Three-Dimensional Laser Imaging for Rock Mass Characterization

by

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Abstract

Three-dimensional (3D) laser imaging has recently emerged as a tool for rock mass characterization. An image is composed of millions of 3D points which are collectively termed point cloud data. Each image is a digital representation of the rock face containing information for rock mass characterization. The objective of this research project was to (1) measure joint orientation and (2) surface roughness from 3D data. The third objective was to (3) remove the obstructive wire mesh from 3D data.

In an above ground field trial, joint orientation was measured using two methods: a 2.5D method using a triangular irregular network and a 3D pole density contouring method using a fully 3D triangular surface discretization model. In each method, the normal vector of each triangle was used to determine the strike and dip. The fully automated 3D method was very accurate in a validation test against manual measurements. The effect of image resolution, triangle size, and joint face geometry were also assessed.

In an underground field trial, surface roughness was measured from point cloud data using principal component analysis (PCA). For geo-referencing, joint orientation was first measured using the normal vector from the PCA best fit plane. A 2D surface profile was generated and the maximum asperity amplitude was measured to estimate the Joint Roughness Coefficient. The methodology was successfully validated against manual measurements and applied to generate a surface roughness map from the entire image. Surface roughness anisotropy was also evaluated.

In underground mining, support elements such as wire mesh are imaged in front of the rock face. Two filters were developed to remove the wire mesh. The first was based on the instrument noise, measured in-situ from rockbolt face plates, and an estimate of the maximum asperity amplitude. The second was based on the amplitude distance of each point from the PCA best fit plane. In a third field trial, these filters were applied with success. For joint orientation, the presence of wire mesh had minimal impact. Once removed, surface roughness measurements were successfully made using the same methodology as in the previous field trial.

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Preface

The following is an integrated thesis consisting of two peer-reviewed journal articles and a third manuscript currently in review on the subject matter of three-dimensional (3D) laser imaging for purposes of rock mass characterization. For the research described in each article, I had the primary role in the formulation of the problem to be addressed, the design and execution of the field trials as well as analysis of the acquired data and final interpretation. As the first author, I took a leadership role in developing the content of each article and in making the supporting figures and tables. For each article, co-authors Samson and McKinnon provided guidance during the field trials, image analysis, and interpretation of the results. Samson and McKinnon provided detailed comments on the form and content for each article provided herein. Co-author Thibodeau reviewed the content from an operational mining perspective.

For each article, the text and figures are reproduced in whole. Table and figure numbers have been updated in accordance with the thesis document. Figure titles have been added where none was inserted and are clearly identified. References have been consolidated in accordance with the thesis document. Complete bibliographical details for each article are listed below.

1. Mah J^a, Samson C^a, McKinnon SD^b, 3D laser imaging for joint orientation analysis.

International Journal of Rock Mechanics and Mining Sciences. 2011;48:932-941.

2. Mah J^a, Samson C^a, McKinnon SD^b, Thibodeau D^c, 3D laser imaging for surface roughness analysis. International Journal of Rock Mechanics and Mining Sciences. Accepted 10 August 2012.
3. Mah J^a, McKinnon SD^b, Samson S^a, Thibodeau D^c, Wire mesh filtering in 3D laser image data. International Journal of Rock Mechanics and Mining Sciences. Submitted August 17 2012.

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Statement from Prof. Claire Samson (co-supervisor):

The information provided by Jason Mah in the preface above regarding my role as a co-author of the three journal articles presented in this thesis is correct.

Statement from Prof. Stephen McKinnon (co-supervisor):

The information provided by Jason Mah in the preface above regarding my role as a co-author of the three journal articles presented in this thesis is correct.

1.0 Introduction

Rock mass classification systems, such as the Rock Tunneling Quality Index Q [1] and Rock Mass Rating (RMR) [1], are widely used in mining engineering to estimate the quality of the rock mass. These classification systems consider several characteristics of the rock mass such as the number of joint sets and surface roughness.

The number of joint sets and their orientation are significant factors influencing excavation stability. Joint orientation is defined by the strike and dip of the rock surface. Strike and dip are measured at the rock face with a compass. Typically a large number of joint orientation measurements are made and plotted in a stereonet for analysis. Statistical analysis of the pole clusters in the stereonet is conducted to determine the number of joint sets and the orientation of each joint set.

Surface roughness has a direct impact on the shear strength of joints and the overall rock mass strength. Surface roughness is a difficult parameter to quantify and classical methods, such as Barton's reference roughness profiles [2-5], are based on a qualitative visual analysis. In a more quantitative approach, a mechanical profilometer (profile comb) can be used to provide a two-dimensional (2D) surface profile. The instrument consists of a line of pins which conform to the joint surface. From the 2D surface profile, the Joint Roughness Coefficient (JRC) is estimated by correlating the maximum asperity amplitude to the profile length on Barton's empirical surface roughness relations [3]. The surface roughness is used directly in the Q system (Joint

roughness number) whereas the RMR only considers the surface roughness as part of the joint condition evaluation.

It can be challenging to make both joint orientation and surface roughness measurements at a rock face. The region of interest may not be accessible. Manual measurements at the rock face may also be hazardous if the rock mass is unstable. A large number of manual measurements are required to fully characterize the rock mass, which is a laborious task. Manual measurements are also subject to human error and may not be repeatable.

1.1 Three-dimensional laser imaging: a concise literature review

Terrestrial laser imaging has recently emerged as an effective tool for rock mass characterization [6-9]. For each acquired image, a digital representation of the rock face is captured, composed of a high density of three-dimensional (3D) points. There are several practical benefits to using 3D laser imaging for rock mass characterization. Image data can be acquired in inaccessible locations. Images can be acquired from a safe distance without the need to come in contact with the rock face. The field of view for a single scan can cover a large area with minimal effort. The amount of manual labour required to collect sufficient data for rock mass characterization is therefore reduced. The data is processed efficiently and provides robust measurements. The data also serves as a permanent digital record of the rock mass that can be re-examined at later dates.

There are different types of terrestrial laser scanners. Research has been conducted to characterize rock mass using time-of-flight (TOF) light detection and ranging (LiDAR) laser systems [10-15]. In the TOF principle, the distance between the laser scanner and the target is determined by measuring the time for the laser pulse to be projected and reflected back to the scanner [16]. TOF scanners can acquire data from 5-800 m away from the target with an accuracy of 3-5 mm [16]. The challenge for TOF scanners is that, at short ranges (less than 5 m), specialized electronics is required to measure the extremely short reflection times.

Triangulation-based 3D laser scanners have also been used successfully to characterize rock mass [6,7,17,18]. After the laser beam is projected onto the target, the reflected beam is focused onto a linear detector array. Depending on the target distance, the reflected beam illuminates the linear detector array at different positions. The precise geometry of the projected and reflected beam paths are used to triangulate and calculate the target distance. Triangulation-based laser scanners have been used to acquire images in an underground mine [6, 17] and to measure the bulk volume of meteorites in a laboratory environment [19].

The overall workflow in the application of 3D laser imaging for joint characterization utilized in this research is: (1) image acquisition, (2) noise filtering, and (3a) measurement of joint orientation and surface roughness directly from the image. However, the workflow can be branched to (3b) generation of a triangular mesh model of the surface and (4) determination of joint sets and their orientation.

Image acquisition refers to the test setup and scanning of the rock face. An image is typically composed of millions of individual points consisting of three spatial coordinates (X, Y, Z). The scanner may also acquire the grayscale light intensity (I) or color data in the red, green, blue wavelengths (RGB). A collection of 3D points compose point cloud data. It is advantageous to acquire and merge images of the rock face at more than one location to minimize shadow zones. A shadow zone is generated when an object blocks the line of sight of the laser beam, causing data occlusion. Acquiring an image at different incidence angles creates a new line of sight for the laser beam, which can fill the shadow zone. Overlapping images can be aligned and merged to fill shadow zones.

After images are acquired, a critical step prior to measuring the joint characteristics is to filter any noisy data. Instrument noise is the primary source of noise. It depends on the optical and mechanical design of the laser scanner. The environment and objects in the field of view are also sources of noise. Sunlight can contaminate the intensity or color measurement. Dust and water vapour can physically disrupt the laser beam, leading to a weak and diffuse reflected beam [20]. Water in the field of view on the rock face has a similar effect of beam diffusion [20]. Edges are another source of measurement noise which occurs when the laser beam is split and attempts to measure the range of two different surfaces. A discontinuity of the range measurement is recorded, causing an error. Man-made objects are also a source of measurement noise in the sense that they may partially block the rock face during scanning and must be

filtered before any characterization can be performed. They are also an additional source of edge effect noise. In an underground mine, the installation of wire mesh for ground support purposes causes challenges for joint orientation and surface roughness measurements. A number of studies have been conducted to smooth the image data before measuring surface roughness [21-24].

After any data filtering is completed, the joint orientation and surface roughness can be measured directly from the point cloud data. This workflow avoids the generation of a triangular mesh model where minor interpolation errors can be introduced. Measuring directly from the point cloud data also permits the operator to measure the joint orientation or surface roughness in-situ at the field site, immediately after an image is acquired, and thus minimizes data processing time and effort. Joint orientation can be measured using Principal Component Analysis (PCA) [7, 18, 25, 26]. A variety of methods have been proposed to measure surface roughness [18, 27-32].

Alternatively, a triangular mesh model can be generated using a discretization process. Images can be aligned and merged to fill shadow zones, increasing the quality of the data and providing more rock face area for characterization [6, 11, 13, 14, 17]. As opposed to analyzing the point cloud data of a single scan, analyzing merged data in a triangular mesh model can be more comprehensive and cover a larger area. Two triangular mesh models can be generated: a 2.5D triangular irregular network (TIN) or a 3D model. In a 2.5D TIN, it is not possible to have multiple Z values for a pair of X and Y coordinates. A TIN is not fully 3D due to this limitation. However, a TIN is more than 2D

because of the Z-coordinate measurement. Geological features such as overhangs and concavities cannot be represented. In contrast, overhangs and concavities are discretized properly in a 3D model.

1.2 Objectives

The objective of this research is to evaluate 3D laser imaging for rock mass characterization. More specifically, 3D images are acquired and analyzed to measure joint orientation and surface roughness. This integrated thesis combines three articles that fulfill this objective. Table 1-1 lists each article and its current status, and establishes the correspondence between articles and thesis chapters. Figure 1-1 displays the workflow proposed and the theme of each article.

The objective of article 1, “3D laser imaging for joint orientation analysis”, was to measure joint orientation from a discretized triangular mesh model. The orientation (strike and dip) of each triangle were measured and plotted in a stereonet to identify joint sets. The impact of point density, triangular mesh element size, and rock face geometry were examined to optimize the discretization process.

The objective of article 2, “3D laser imaging for surface roughness analysis”, was to measure surface roughness directly from the point cloud data. The first step however, is to measure the joint orientation. This serves to geo-reference the surface roughness measurement. The impact of scale on surface roughness measurement was examined as well as the surface roughness anisotropy. The ability to merge the joint orientation and surface roughness and present the results on a single image was demonstrated.

The objective of article 3, “Wire mesh filtering in 3D laser image data”, was to examine the impact of the wire mesh and edge effects on joint orientation and surface

roughness measurements made from 3D images. Two thresholds were developed to distinguish and filter the wire mesh from the rock mass. The first threshold was based on the instrument noise plus an estimate of the maximum asperity amplitude. The second threshold was based on the normalized amplitude which is the distance of each point from the best fit plane determined by PCA analysis. In a proof of concept, the wire mesh filter was applied successfully in cases where a single and double wire mesh layers were present. With the wire mesh removed, surface roughness was measured.

Table 1-1: Article Summary

Article	Thesis Chapter	Title	Journal	Status
1	3	3D laser imaging for joint orientation analysis	International Journal of Rock Mechanics and Mining Sciences	Published September 2011
2	4	3D laser imaging for surface roughness analysis	International Journal of Rock Mechanics and Mining Sciences	Accepted on 10 August 2012
3	5	Wire mesh filtering in 3D laser image data	International Journal of Rock Mechanics and Mining Sciences	Submitted 17 August 2012

Figure 1-1: 3D laser imaging workflow and theme of each article.

2.0 Methodology

Each article in this integrated thesis follows a methodology with common elements described in the following section.

2.1 Field trials

For each article, a field trial was conducted to acquire images for analysis. Images were acquired at a road cut in article 1 as a precursor to the underground field trials conducted and described in articles 2 and 3. The above ground field trial was conducted at Ivy Lea, along Provincial Highway 137, approximately 45 km east of Kingston, Ontario, Canada [6,33]. The underground field trial for article 2 was conducted at Vale's T1 nickel mine located in Thompson, Manitoba, Canada [34]. The underground field trial for article 3 was conducted at Vale's 175 Orebody mine located in Sudbury, Ontario, Canada [34].

2.2 Instrument

The selection of the 3D laser scanner used in this research program was critical as underground field trials present numerous challenges. Underground rock faces have limited exposure and display subtle features. The underground environment also contains dust and water, and limited space in mine drifts.

A triangulation-based laser scanner was selected for this research project. The Laser Camera System (LCS), developed by Neptec Design Group [35] is a robust instrument, and operates with sub-millimeter accuracy at short distances (less than 10 m) [7, 16]. The LCS is immune to the ambient lighting conditions and acquires point

cloud data with Cartesian coordinates (X, Y, Z) as well as the grayscale reflection intensity (I).

2.3 Validation of Results

In each field trial, manual joint orientation and surface roughness measurements were made. The purpose of the manual measurements was to conduct validation studies in a controlled manner by comparing the results from manual and laser measurements made at the exact same location. This validation step confirmed that the image processing methods were reliable before automating the processes and applying them to the entire images.

3.0 Article 1: 3D laser imaging for joint orientation analysis

The first article summarizes the results of an above-ground field trial to measure joint orientation. Images were acquired at a road cut and the point cloud data was discretized into 2.5D TIN and 3D model for joint orientation analysis.

The article was published in volume 48 (2011) of the International Journal of Rock Mechanics and Mining Sciences. The article text and figures are reproduced in whole. The table and figure numbers have been updated in accordance with the thesis document. A description of the algorithm is presented in Appendix C and the source files are provided in a DVD.

3.1 Abstract

This paper evaluates the application of three-dimensional (3D) laser imaging to measure joint orientation. A field trial was conducted at a road cut with 3 well expressed joint sets. Using 3D point cloud data, joint orientation was evaluated using two methods: a 2.5D method, commercially available, based on a triangular irregular network (TIN) and a new 3D pole density contouring method where the orientation of each triangular mesh element in the 3D model is determined. Validated against field measurements, the 2.5D and 3D methods were applied manually and the resultant average angular differences were 13.3° and 3.8° , respectively, indicating that the 3D method is very accurate. When automated, the 2.5D and 3D methods yielded results with average angular differences of 14.4° and 9.9° . The effects of image resolution (an image acquisition parameter), triangular mesh element size (an image processing parameter), and joint face geometry (a geological parameter) on the performance of the 3D pole density contouring method were reassessed. Image resolution had minimal effect on measurement accuracy. Increasing triangular mesh element size had an adverse effect because holes started to appear in the 3D model.

3.2 Introduction

Terrestrial laser imaging has recently been recognized as a tool for rock mass classification [8,9]. The technology reduces the amount of manual labor involved. It enables a large amount of data to be acquired efficiently at a safe distance from potentially hazardous rock faces or areas that otherwise would be inaccessible. The data

can be processed quickly resulting in a digital model from which rock mass characteristics can be extracted. The resulting model also serves as a permanent digital record that can be re-examined at later dates.

The majority of research on terrestrial laser imaging for rock mass classification has focused on time-of-flight (TOF) LiDAR [10-15]. In TOF LiDAR systems, the distance to the target is calculated by measuring the time for the laser pulse to be projected and reflected back to the camera. TOF systems can acquire 3D data from targets approximately 5-800 m away from the instrument with constant accuracy in the order of 3-5 mm [16]. Other LiDAR systems operate using phase-shift principles where the phase shift of the projected and reflected laser pulse is measured to determine the distance to the target. The result is higher range accuracy compared to TOF systems.

There are limitations to LiDAR systems. The specialized electronics required to measure TOF are highly sensitive to a variety of influences such as thermal and atmospheric effects [16]. Sensitivity to ambient lighting conditions is low to moderate. At distances less than 5 m, accuracy is limited as the electronics cannot measure extremely short reflection times. This is a serious constraint in confined spaces, for example, in underground mine tunnels.

Triangulation-based 3D laser imaging is an emerging technology for rock mass characterization [17]. These laser cameras are short-range systems designed to operate at distances less than 10 m from the target, that is, close to the lower operational limit of LiDAR systems [6]. With these systems, a laser beam is projected on to the target and

the reflected beam is focused onto a linear detector array. The precise geometries of the projected and reflected beam paths are known and triangulated to calculate the distance to the target with sub-millimeter accuracy [16]. This concept is illustrated in Figure 3-1. There have been a small number of case studies using triangulation-based 3D laser imaging in geological applications: a survey to acquire images in an underground mine [17], and laboratory investigations to measure the bulk volume of meteorites [19].

A voxel is a volumetric image element composed of three spatial coordinates (X, Y, Z) and a collection of voxels form a point cloud. To study discontinuities, the workflow transforms point cloud data into a triangular mesh before measuring joint orientation. Two methodologies have been developed to transform the point cloud data into either a 2.5D triangular irregular network (TIN) or 3D polygonal model. Assuming the Z-axis measurement is the distance from the laser camera to the target, it is not possible within a 2.5D TIN to have multiple Z values for a given pair of X- and Y-coordinates. As a result, overhangs and concavities within a rock mass cannot be represented. A TIN is not fully 3D because of this limitation but, at the same time, a TIN is more than 2D because it contains a Z-coordinate measurement. A common term in describing a TIN is therefore "2.5D". The commercial software Split-FX evaluates joint orientation by generating a 2.5D TIN [36]. This software has been used in several successful case studies at open pit mines, road cuts, and at an underground mine [10-12,17].

Figure 3-1: Auto-synchronous triangulation 3D laser scanning principle.

The projected laser beam is controlled by two mobile mirrors, the X-axis and Y-axis mirrors, mounted on high-precision galvanometers. The reflected laser beam is focused onto a linear detector array.

The point cloud data can also be transformed into a 3D polygonal model comprised of triangular elements, which is capable of modeling overhangs and concavities. In this paper, use is made of the Polyworks [37] software package to perform this discretization. Polyworks is a high density 3D point cloud software package capable of aligning and merging multiple images into a single 3D polygonal model [11,12,17]. This is highly beneficial in minimizing holes in the 3D polygonal model, which are generated when the laser camera has poor coverage of the rock face from a single position. The bias and measurement error associated with poor coverage zones have recently been studied using Polyworks [14]. COCONE is another software tool that can transform 3D point cloud data into a 3D polygonal model using Delaunay surface triangulation. In one study, a subset of the 3D model generated by COCONE was used to measure joint orientation but results were not validated against field measurements [13,38].

3.2.1 Objectives

Here, we describe a new method of acquiring and analyzing 3D laser images to measure joint orientation, taking into account operational constraints. In the 2.5D method, Split-FX is used manually and compared to field measurements from a survey site in a controlled validation step. In the new 3D pole density contouring method, multiple images are aligned and merged to form a single 3D polygonal model. By removing the Z-axis constraint on the 2.5D TIN method, a fully 3D triangular mesh model is constructed from the point cloud, and used directly to estimate strike and dip.

The pole orientation of every triangular mesh element in the 3D polygonal model is contoured to identify emerging peaks corresponding to the dominant joint sets. The results are compared to field measurements and the 2.5D method. The impact of image resolution, triangular mesh element size, and joint face geometry are evaluated to optimize the method and provide guidelines for its practical application.

Our primary domain of application for this method of joint orientation determination is underground mines, where operational constraints require mapping work to be carried out rapidly. This environment presents a number of challenges, including limited target distance (typically less than 5 – 10 m), low or negligible lighting, and typically dusty and dirty working conditions. We therefore chose to acquire images with a ruggedized triangulation-based laser camera which has proven accuracy at short range and is immune to ambient lighting conditions. Prior to using the equipment in the harsh underground mining environment, an above ground survey site was selected for the pilot study reported in this paper.

3.3 Field trial

A field trial was conducted at a quartzite road cut along Provincial Highway 137 at Ivy Lea, approximately 45 km east of Kingston, Ontario, Canada [33]. The survey site, which covers an area 4.6 m width by 2.4 m height, was selected based on its accessibility and good exposure of joint sets (Figure 3-2). From visual inspection, it can be noted that the block size decreases from left to right while the spacing between joint sets increases.

The triangulation-based 3D laser camera used for this field trial is the Laser Camera System (LCS) developed by Neptec Design Group of Ottawa, Canada [35,39]. Operation is based on an auto-synchronous triangulation scanning principle first proposed by the National Research Council of Canada (Figure 3-1) [40]. LCS specifications are listed in Table 3-1.

The LCS was mounted on a tripod 1.8 m above the ground, 3.0 m directly in front of the rock face. The rock face was divided into a grid of 6 images, 3 images across by 2 images high. Figure 3-2 shows the grid of images acquired by panning and tilting the LCS on the tripod. Given the target distance of 3 m and the 30° x 30° field of view, the central image in the grid is approximately 1.6 m by 1.6 m while the outer images are approximately 1.9 m by 1.6 m. Adjacent images overlapped one another by approximately 25% for image alignment and merging purposes. To geo-reference the data, the strike and dip of the laser camera head was measured when acquiring each image. Image characteristics are listed in Table 3-2.

Figure 3-2: Field measurements made at the Ivy Lea survey site.

The location of the 160 field measurements is displayed and color coded. The sub-vertical joint set 1 in yellow, (71 measurements) is the best expressed geologically. Joint set 2, in blue (42 measurements), is also sub-vertical and has developed in a strike perpendicular to that of joint set 1. The sub-horizontal joint set 3 (47 measurements) is in green. The scan grid, 3 images across by 2 images high, is displayed. Each scan overlapped one another and the total scan area was 4.6m x2.4 m. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 3-1: LCS specifications

	Value
Physical Characteristics	
Enclosure Dimensions (cm ³)	18.8 x 25.4 x 27.9
Mass (kg)	12.1
Optical Characteristics	
Focusing distance (m)	1.2
Laser spot size at focusing distance (mm)	0.8
Depth resolution at focusing distance (mm)	0.5
Precision (1 standard deviation) (mm)	0.8
Source wavelength (nm)	1500
Linear detector array sensitivity (nm)	1500 +/- 3
Imaging Characteristics	
Maximum field of view (degree)	30 x 30
Maximum image resolution (voxel)	1024 x 1024
Integration time (μs)	20 – 500
Maximum acquisition rate (voxel/s)	5000

Table 3-2: Image characteristics

	Value
Field of View (degree)	30 x 30
Average target distance (m)	3
Image size (m ²)	1.6 x 1.6 (central images) 1.6 x 1.9 (outer images)
Image resolution (voxel)	1024 x 1024
Integration time (μs)	488
Distance between adjacent voxels (cm)	0.16
Point cloud concentration (voxel/cm ²)	41
Acquisition time (minute)	≈ 15
Number of images acquired (image)	6
Image resolution (voxel)	1024 x 1024
Total number of voxels acquired (voxel)	6 291 456

An important step in the study was to validate the joint orientation results by comparing the 3D laser measurements to conventional field measurements, as any new technique should be evaluated in the context of its performance against an established technique, especially when it is still widely used. Although we use the term “validation”, it is recognized due to the potential high accuracy of determining planar orientations from laser acquired point cloud data, the manually determined orientation values may be the least accurate in this comparison.

A total of 160 field measurements were completed at the survey site using a compass. For each measurement, the exact location on the rock face was recorded (Figure 3-2). Using the Dips software package [40], the field measurements were analyzed using the Fisher distribution method about the mean pole orientation [41]. The pole density contours were plotted on a lower hemisphere stereonet (Figure 3-3). Selection envelopes were formed around the 3 principal joint sets at clusters with a minimum concentration of 2%. The strike and dip of joint sets 1, 2, and 3 in degrees are 056/80, 139/88, and 154/01, respectively.

Rock mass characterization was conducted for the survey site. The RMR_{1976} is approximately 82 based on the following ratings: (1) strength of intact rock of 100 to 200 Mpa, 12 points, (2) Rock Quality Designation greater than 90%, 20 points, (3) joint spacing of 0.3 to 1 m, 20 points, (4) joints are rough with some separation, 20 points, (5) dry condition, 10 points. An RMR_{1976} value of 82 is equivalent to an RMR_{1989} of 87 [4].

The Q index for the survey site is approximately 9.7. The definitions for RMR and Q index are provided in Appendix A. (paragraph added)

Figure 3-3: Stereonet generated from 160 field measurements

3.4 Image alignment and merging

Each image was imported into Polyworks as a point cloud [37]. The point cloud was interpolated onto a 2D parametric grid to generate a 3D triangular mesh. The point cloud data were edited and cropped to remove outliers and vegetation. After importing all six images, the central top image was locked in place in order to preserve its spatial location for geo-referencing at later stages. In a rough alignment, the adjacent images were first manually aligned by selecting common voxels in the overlapping regions. To achieve a more accurate alignment, an iterative closest point algorithm [43] was then executed to minimize the mean 3D distance in the overlapping regions.

The next step in Polyworks consisted of generating a single best fitting 3D polygonal model by merging the six images together. First, all overlapping regions were merged into a single non-redundant surface. Second, the 3D polygonal model was smoothed to reduce the impact of noise in the image data. The third step was to minimize the size distribution of the triangular mesh elements so that the surfaces are represented by triangles of approximately equal size. At the same time, the geometry of the triangles was adjusted to generate equilateral triangles that uniformly sample the surface. The final output is a seamless digital 3D polygonal model of the rock face composed of triangular mesh elements with an intensity measurement at each vertex (Figure 3-4).

Figure 3-4: 3D polygonal model (title added)

Images are merged to generate a final 3D polygonal model in Polyworks (triangular mesh element size = 0.1 cm^2). Coverage is complete except in occluded areas, near overhanging features, on the sub-horizontal planes that were illuminated at grazing incidence angles by the laser beam, and in the vegetation at the base of the rock face.

In this study, several 3D polygonal models of varying triangular mesh element sizes were generated and analyzed using the 2.5D TIN and 3D pole density contouring method. Figure 3-5 presents a flow chart summarizing the different processing steps and analysis methods, and Table 3-3 summarizes the results. The following sections examine each branch of the flow chart in detail and contrast the advantages and limitations of the various methods.

Figure 3-5: Flow chart to acquire, process, and analyze 3D data (title added)

Flow chart outlines the methodology used to acquire, process, and analyze the 3D data.

Images are acquired by the LCS at the maximum image resolution and later decimated.

The point clouds are edited to remove outliers. Images are aligned and merged to form

a single 3D polygonal model. A 3D polygonal model with the smallest triangular mesh

elements (0.1 cm^2) is analyzed using the 2.5D TIN method in a manual validation step

against the field measurements. A 3D polygonal model with triangular mesh elements of

0.9 cm^2 is processed automatically using the 2.5D and 3D methods, and the respective

results are compared against the field measurements as well as against each other. In an

optimization study, images at resolutions of 1024 by 1024, 512 by 512, and 256 by 256

are processed to generate 3D polygonal models of varying triangular mesh element size.

The 3D polygonal model was also sub-sampled in a region of large cubic and smaller

platy cubic blocks to determine the impact of the physical geometry of the rock mass on measured joint orientation.

3.5 Image analysis: 2.5D TIN method

To estimate the joint orientations in a rock mass, 3D polygonal models are imported as point clouds into Split-FX [36]. This software package has been used extensively; it generates a 2.5D TIN, and its operational parameters have been explored [10-12, 17]. Rotating the image in 3D reveals that the resulting 2.5D TIN is in fact an irregular mesh of triangular elements of varying size (Figure 3-6). This type of mesh fails in certain locations to capture fine details by oversimplifying the topology of the surface using relatively large triangles. Split-FX delineates patches for orientation determination, which can be inserted manually or automatically.

3.5.1 Validation against field measurements

A 3D polygonal model was generated in which the average size for a triangular element was 0.1 cm^2 . This model would not be used in practice because it takes very long to process. It was used here so that patches generated in Split-FX could be manually inserted at the same location as the 160 field measurements. The average triangular mesh element size in the 2.5D TIN was 1.7 cm^2 . The average size for each patch was 13.6 cm^2 . In comparison, the contact area of the compass used for the manual measurements is approximately 7 cm^2 .

Figure 3-7 shows the resulting stereonet, which can be directly compared with Figure 3-3. The results derived from the 3D laser image data (044/88, 141/81, 184/19) are consistent with the field measurements (056/80, 139/88, 154/01). Note that there are variations introduced by physical registration of the compass on the rock face, and a

small error potentially introduced during compass measurement of the laser camera head orientation.

Figure 3-6: Comparison between 2.5D and 3D methods (title added)

(A) A comparison of the 2.5D TIN (left) and 3D pole density contouring (right) methods for a specific region of the rock face. (B) The 2.5D TIN and 3D fine mesh models are displayed from the camera's perspective. For the 2.5D method, a photo is draped over the point cloud data for clarity. The 2.5D TIN is generated by overlaying a flat 2D grid over the point cloud data. The 3D mesh model is generated by fitting triangular elements of different orientations to conform to the changes in topology in the point cloud data. (C) The 2.5D TIN and 3D models are rotated to reveal their differences.

Figure 3-7: Stereonet from manual 2.5D TIN method (title added)

Stereonet for the 2.5D TIN manual method in Split-FX with an average mesh element size of 1.7 cm^2 . A total of 160 patches were inserted in to the 2.5D TIN at the exact location of each field measurement.

Figure 3-8: Stereonet from automatic 2.5D TIN method (title added)

Stereonet for the 2.5D TIN automatic method in Split-FX with an average mesh element size 11.3 cm^2 . The pole markers are scaled in accordance with the surface area of each patch.

3.5.2 Automatic patch delineation

A 3D polygonal model was generated with the smallest practical mesh element size of 0.9 cm^2 . The model was imported into Split-FX and the 2.5D TIN was generated. To estimate joint orientation Split-FX measures the normal vector of a patch, which is a plane representing a group of mesh elements. Patches were delineated using the values of 10° and 5 triangular mesh elements for the tolerance angle of the normal vectors and the minimum patch size, respectively. These were the recommended values from previous research using LiDAR [10,11]. An extensive investigation, testing a range of input parameter values and filter settings, was also performed to confirm these values. The automatic process generated 144 patches with an average size of 250 cm^2 . The patches represent 25.7% of the total surface area of the 2.5D TIN. The estimated joint orientations determined from these automatic patches are 039/81, 141/88, and 183/25 (Figure 3-8).

3.5.3 Discussion of 2.5D TIN method

The angular difference between the 2.5D manual and automatic methods with respect to the manual field measurements is rather large at 13.3° and 14.3° , respectively (Table 3-3). The discrepancy is most probably caused by the oversimplification in generating the 2.5D TIN within Split-FX. It is largest for joint set 3, which is sub-horizontal and a challenge to image. Sub-horizontal planes are illuminated at grazing incidence angles by the projected laser beam. In such cases, the reflected laser beam

tends to be deflected out of plane at wide angles, leaving only sparse signals returning to the camera for data acquisition. Orientation measurements of a sub-horizontal joint would have a high angular difference regardless of the laser camera and processing technique [15]. Similarly, high strike errors in conventional mapping have been associated with shallow dipping surfaces [43,44].

Table 3-3: Joint orientation results (strike/dip in degrees) from the 2.5D and 3D methods.

	Field Measurements	2.5D TIN Method		3D Statistical Method	
		Manual method	Automatic method	Manual method	Automatic method
Image Alignment and Merge: 3D Polygonal Model					
Average triangular mesh element size (cm ²)		0.1	0.9	0.9	0.9
Number of mesh elements		1 245 945	165 462	165 462	165 462
Total mesh area (cm ²)		165 425	150 027	150 027	150 027
Average number of voxels per mesh element		1.6	12.4	12.4	12.4
Model Analysis					
Model Type		2.5D TIN	2.5D TIN	3D Model	3D Model
Number of mesh elements		93 167	12 448	165 462	165 462
Total mesh area (cm ²)		156 649	140 341	150 027	150 027
Average mesh element size (cm ²)		1.7	11.3	0.9	0.9
Joint orientation analysis					
	strike / dip	strike / dip	strike / dip	strike / dip	strike / dip
Joint set 1	056 / 80	044 / 88	039 / 81	051 / 80	043 / 84
Joint set 2	139 / 88	141 / 81	141 / 88	138 / 89	132 / 86
Joint set 3	154 / 01	184 / 19	183 / 25	143 / 06	154 / 10
Angular difference with respect of the field measurements in degrees					
Joint set 1		14.4	16.8	4.9	13.5
Joint set 2		7.3	2.0	1.4	7.3
Joint set 3		18.1	24.1	5.0	9.0
Average angular difference (degree)		13.3	14.3	3.8	9.9
Effort (minute)					
Image acquisition (15 min per image, 30 min setup/takedown)		120	120	600	120
Image alignment		120	100	100	100
Image merge		90	50	50	50
Model analysis		30	30	30	30
Total effort		360	300	780	300

When the patches were inserted manually, the average angular difference with the field measurements was 13.3° . The 2.5D manual patch insertion method, however, required the careful attention of a skilled user and significantly more time than the automatic method. In comparison, the average angular difference for the automatic approach was slightly higher at 14.3° . The difference between the 2.5D manual and automatic methods is only 1%, indicating that the 2.5D automatic method is quite robust. Furthermore, the same degree of point cloud mesh discretization was not necessary for the automatic method to generate accurate results as indicated by the fact that the triangular mesh element size was 0.9 cm^2 for the automatic method versus 0.1 cm^2 for the manual method. However, the 2.5D automatic method requires a priori extensive testing of the input parameters and filter settings. These parameters are critical to patch generation. If the parameters are too constraining, a limited number of patches are delineated. If the parameters are too wide, erroneous patches are delineated. These parameters are interlinked in the algorithm underlying Split-FX and it is a challenge to isolate the impact of each of them on the stability of the orientation results.

3.6 Image analysis: 3D pole density contouring method

A 3D pole density contouring method was developed in MATLAB [45] to further automate and enhance joint orientation analysis using a full 3D polygonal model rather than a 2.5D TIN approximation. This method analyzes the 3D polygonal model directly; each triangular mesh element is considered to be a plane where strike and dip can be

determined. The only user specified input is the laser camera head geo-referencing information. A 3D polygonal model with an average mesh element size of 0.9 cm^2 was analyzed using the 3D pole density contouring method. This was the same 3D polygonal model used for the 2.5D TIN automatic method to allow for a direct comparison of the results.

3.6.1 Validation against field measurements

Triangular mesh elements were manually selected at the exact location of each field measurement. Each group contained an average of 10.7 triangles and the average group size was 10.0 cm^2 . The strike and dip for all the triangles in the group was averaged, which is displayed in Figure 3-9 and can be directly compared to Figure 3-3. The strike and dip of joints 1, 2, and 3 are 051/80, 138/89, and 143/06, respectively.

3.6.2 Automatic joint orientation analysis

The 3D polygonal model was geo-referenced and strike and dip for each mesh element was determined automatically. On the resulting stereonet shown in Figure 3-10, three envelopes were formed around the 3 principal joint sets at clusters with a minimum concentration of 2%. For joint sets 1, 2, and 3, the orientation results are 043/84, 132/86, and 154/10, respectively.

3.6.3 Discussion of 3D pole density contouring method

In comparing the results of the manual and automatic 3D pole density contouring method to the manual field measurements, the average angular differences are 3.8° and 9.9° , respectively. For all joint sets, the results from the manual 3D pole

density contouring method are very close ($<5^\circ$) to the field measurements, indicating the method can provide a high level of accuracy. However, the approach is operationally impractical because it is performed manually and requires a high level of effort.

Figure 3-9: Stereonet from manual 3D pole density contouring method (title added)

Stereonet validating the 3D pole density contouring method against the manual field measurements. The average mesh element size is 0.9 cm^2 . A total of 160 measurements were made at the exact location as the manual field measurements.

Figure 3-10: Stereonet from automatic 3D pole density contouring method (title added)

Stereonet generated by the automatic 3D pole density contouring method. The average mesh element size is 0.9 cm^2 .

The automatic 3D pole density contouring method is much more suitable for joint orientation measurements in an operational environment. For all joint sets, the orientation measurements are within the second standard deviation of the manual orientation measurements. Discrepancies can be attributed to a combination of sampling population and surface roughness.

In the manual 3D approach, 1703 triangular mesh elements were measured representing only 1% of the total area of the 3D polygonal model. In the automatic 3D approach, 165 462 triangular mesh elements were measured representing the entire area (100%) of the scanned rock mass. A large sample population converges to more representative averages of the joint set orientations. Therefore, the 3D automatic method is believed to be more accurate because there is less sampling bias [46]. With respect to discontinuity spacing, the relationship between measurement accuracy and sample population has been explored with a similar effect [47]. The error in mean discontinuity spacing decreases with the number of samples.

Surface roughness is also known to increase the spread of strike and dip measurements made in the field because of its effect on the local variability of joint plane orientation [44, 45, 46]. In addition, scatter in orientation measurements increases as the base length of the measurement tool decreases [48]. The field measurements are made using a compass that covers approximately 7 cm^2 . The much smaller mesh elements for which strike and dip have been measured using the 3D pole density contouring method have an average size of only 0.9 cm^2 and are therefore more

sensitive to roughness effects. The average joint orientation is therefore influenced not only by variations in the mean planar orientation of each joint, but by the variation introduced by the surface roughness.

The results of the automatic 2.5D TIN and 3D pole density contouring methods can also be compared, where the average angular difference with field measurements is 14.3° and 9.9° , respectively. The difference is likely related to the inability of the 2.5D TIN to record multiple Z-axis values for a given pair of X- and Y-coordinates in complicated areas of the rock face such as overhangs and concavities [25]. The automatic 3D pole density contouring method performed especially well for sub-horizontal joint set 3 (angular difference of 9.0° versus 24.1°) demonstrating its superior capability in areas with sparse laser coverage.

There are common sources of error between the automatic 2.5D TIN and 3D pole density contouring methods. One potential source could be a slight misorientation of the laser camera head [11]. However, this source of error can be discounted since the angular difference is not consistent between all joints. Similarly, the obliquity of the rock face to the line of sight of the laser camera poses a challenge to both methods as it tends to decrease point cloud concentrations [14].

3.7 Optimization of 3D pole density contouring method

An optimization study was performed to assess the impact of three important parameters on the measurement accuracy of the 3D pole density contouring method: image resolution, triangular mesh element size, and joint face geometry. Angular

difference was used as the metric for accuracy in the optimization study. This choice has to be approached with care considering the various errors affecting field measurements, namely under-sampling and error related with the physical registration of the compass on the rock face.

3.7.1 Effect of image resolution and triangular mesh element size

Image resolution is an operational parameter directly related to the acquisition of 3D laser images in the field. The advantage to acquiring images at high resolution is the fine detail of the rock face captured. However, this is done at the expense of long acquisition and processing times. For each decrease in image resolution from 1024 to 512 voxels and from 512 to 256 voxels, the quantity of data is reduced by a factor of 4. This represents a significant time saving when multiple images are acquired.

The images acquired at a resolution of 1024 by 1024 voxels were decimated in a systematic fashion to simulate data at 512 by 512 and 256 by 256 resolutions. This is equivalent to reducing the point cloud concentration from 41 voxel/cm² to 10 voxel/cm² to 2.5 voxel/cm² for a target distance of 3 m. The decimation was performed on the acquisition raster pattern where every fourth voxel was saved to avoid any bias or averaging affects. For each of the 3 image resolutions, 15 polygonal models were generated representing various triangular mesh elements sizes (0.9, 5, 11, 20, 29, 38, 50, followed by 25 cm² increments up to approximately 250 cm²), for a total of 45 models [49]. This was performed in Polyworks using the surface sampling step parameter, which controls the density of mesh vertices and the size of the triangular

mesh elements. As the triangular mesh element size increases, the 3D image data are interpolated over larger areas, which decreases the level of detail in the 3D model.

Figure 3-11 shows a plot of the average angular difference with the field measurements versus the triangular mesh element size plotted on a logarithmic scale. The overall trend observed is that the average angular difference increases as the triangular mesh element size increases. This supports the concept that joint orientation measurements are scale dependent [44,46]. On closer review, it appears the overall trend can be divided into two zones. In the first zone, with the lowest triangular mesh element sizes, the average angular difference remains constant regardless of triangular mesh element size. In the second zone, the average angular difference tends to increase with triangular mesh element size after an optimal size is passed.

The optimal triangular mesh element size at the transition is the critical size yielding results with the highest accuracy in the shortest period of time. From Figure 3-11, this optimal triangular mesh element size is approximately 10.0 cm^2 . Figure 3-11 shows the average angular difference for 256 by 256, 512 by 512, and 1024 by 1024 resolutions. The plot reveals that image resolution has a minimal impact on angular difference. This indicates that results with high accuracy can be obtained with an image resolution of 256 by 256 voxels, which corresponds to 12 voxels per triangular mesh element. The level of effort to acquire images, develop and analyze the 3D model with the lower resolution of 256 by 256 voxels resulted in a significant time savings of approximately 45%.

Figure 3-11: Angular difference compared to triangle size (title added)

Angular difference between field measurements and 3D imaging results for 45 polygonal models (15 different triangular mesh element sizes for image resolutions 1024 by 1024 voxels, 512 by 512 voxels, and 256 by 256 voxels). The solid line corresponds to the average angular difference for all image resolutions combined.

3.7.2 Effect of joint face geometry

The size and shape of the rock blocks imaged are determined by site geology and characteristics of the excavation process that exposed the rock face. These characteristics of the rock face also influence the fidelity with which a 3D model conforms to the topology of the rock face. In the optimization study, it was observed that as the triangular mesh element size increased, anomalous holes appeared in the 3D polygonal models where a high intersection angle between surfaces was present. The impact of this characteristic was quantified in Figure 3-12 which shows the ratio of the number of boundary vertices to the total number of vertices as a function of triangular mesh element size. Boundary vertices represent vertices at the edge of the 3D polygonal mesh, including along the perimeter of holes. A large ratio is indicative of a degraded model where triangles conform poorly to the joint face. From Figure 3-12, the overall trend observed is an increasing ratio with increasing triangular mesh element size. The ratio is in the range of 25-40% at the critical mesh element size (10 cm²). In a conservative manner, a boundary to total vertices ratio of 25% can be used as a guideline to identify a reliable and accurate 3D model. Beyond 25%, the overall measurement accuracy begins to decrease. An added benefit of using this ratio is that regions of data occlusion due to shadow zones are considered in the number of boundary vertices. Therefore, a high ratio can also indicate that some joint faces are missing and that the 3D model is not a good representation of the rock mass.

Figure 3-12: Ratio of boundary to total number of vertices compared to triangle size

(title added)

Left vertical axis: ratio of the number of boundary vertices to the total number of vertices. High values are indicative of degraded models. Right vertical axis: angular difference between field measurements and 3D imaging results from Figure 3-11.

In Figure 3-11, the angular difference also appears to oscillate in a sinusoidal manner with increasing triangular mesh element size. The sinusoidal oscillations are subtle in the 10 cm^2 - 70 cm^2 range but there is a clear local maxima at 125 cm^2 and minima at 175 cm^2 . The local maxima and minima are present for all image resolutions. This appears to be related to the ability of the triangular mesh elements to conform in a discrete manner to the topology of the rock mass, as shown in Figure 3-13. For cases A and C, the triangular elements conform well to the rectangular area. The majority of the vertices line up along the perimeter of the rectangular area. These cases would yield accurate joint orientation measurements. For case B, in which the triangular mesh element size is between those of cases A and C, the triangular elements do not conform as well to the rectangular area. In such a case, poor joint orientation measurements would be made along the perimeter of the rectangular area because of edge effects.

Figure 3-13: Fit of triangular mesh element to a rock face (title added)

Rectangular area is used to represent a rock face in the 3D polygonal model. The area is fitted with triangular mesh elements of three different sizes. For case A, the area is fitted with 4 elements across and 8 elements high. For case C, the area is fitted with 3 elements across and 6 elements high. The triangular mesh elements conform well to the rectangular area in cases A and C because the vertices line up with the perimeter. For case B, with a triangular mesh element size between those of cases A and C, the vertices do not line up with the perimeter. The orientation of elements on the edges would not capture the joint orientation accurately.

The results shown in Figure 3-11 and Figure 3-12 imply that the shape and size of the joint faces in conjunction with the mesh element size affect the joint orientation accuracy. To further test this hypothesis, the Ivy Lea rock mass was segregated into two regions exhibiting different block sizes and shapes. These regions correspond to the two leftmost and two rightmost images acquired by the LCS (Figure 3-2). The region on the left is mainly composed of larger cubic blocks while the region on the right exhibits smaller platy blocks [33]. The average spacings for joint set 3 were approximately 0.6 m and 0.4 m in the left and right regions, respectively. Joint orientation was estimated using the 3D pole density contouring method for a total of 90 models (2 regions x 3 image resolutions x 15 triangular mesh element sizes) and compared to field measurements.

Figure 3-14 displays the average angular difference for both regions. The right region has typically larger difference than for the left region, and follows a steeper growth trend. The larger features of the cubic blocks (average size $\approx 0.6 \text{ m} \times 0.8 \text{ m} \times 0.9 \text{ m}$) of the left region can be adequately represented using a wide range of triangular mesh element sizes. The left region exhibits a trend similar to the average angular difference in Figure 3-11. For smaller triangular mesh element sizes, the angular difference remains relatively constant. The optimal triangular mesh element size for this region of the rock mass was approximately 20 cm^2 . Conversely, the complicated geological structure of the small platy blocks (average size $\approx 0.4 \text{ m} \times 0.8 \text{ m} \times 0.9 \text{ m}$) of the right region can only be modeled with high fidelity using the small triangle size of 1

cm^2 . The angular difference increases immediately, indicating the optimal triangular mesh element size has already been exceeded.

Figure 3-14: Rock face geometry and angular difference compared to triangle size (title added)

Angular difference from 3D imaging results for right and left regions (image resolutions: 1024 by 1024 voxels, 512 by 512 voxels, and 256 by 256 voxels) compared to field measurements.

If the optimal mesh element size is considered to be 20 cm^2 and 1 cm^2 for the left and right regions respectively, a guideline can be proposed with respect to block geometry. The optimal triangular mesh element size is $\approx 1 \text{ cm}^2$ when the smallest block dimension is on the order of a few tens of centimetres, and $\approx 20 \text{ cm}^2$ when it approaches one metre. An effective formula to estimate the triangular mesh element size is $A \approx 2/3 \ell^2$ where A represents the triangular element size and ℓ represents the shortest edge length of the joint face. This length can be measured directly from the 3D polygonal model.

3.8 Conclusions

In this study, triangulation-based laser imaging was used in a field trial to acquire 3D image data from a road cut from a distance of 3 m. The short-range instrument was selected to demonstrate its capability and potential to measure joint orientation in an underground mine. As a baseline reference, manual field measurements of strike and dip were made at the survey site.

Two 3D image processing methods were evaluated and validated against the manual field measurements. When both methods were applied automatically, the angular difference of the new 3D pole density contouring method was 9.9° while the angular difference for the 2.5D TIN method was 14.3° .

An optimization study was performed, using the 3D pole density contouring method, to examine the effect of image resolution, triangular mesh element size, and joint face geometry on the strike and dip measurements. The study found that (1) image

resolution had little impact on the accuracy of the joint orientation measurements and (2) the overall angular difference remains relatively constant up to an optimal triangular mesh element size beyond which the angular difference increases. Operationally, low resolution images can significantly reduce image acquisition and processing times. In this study, accurate results were obtained with a point cloud concentration as low as 2.5 voxel/cm².

Two guidelines are proposed to estimate the optimal triangular mesh element size to maximize measurement accuracy and minimize processing time. The first guideline is to maintain a ratio of less than 25% between boundary to total number of vertices to avoid large holes in the 3D model. The second guideline relates the shortest edge length of the joint face to the triangular mesh element size, expressed as $A \approx \frac{2}{3} \ell^2$ where A is the triangular mesh element size and ℓ is the shortest edge length of the joint face. If both guidelines estimate different sizes, a conservative approach can be taken where the user selects the smaller triangular mesh element size. Additional testing of both guidelines will be required in different geological settings for validation purposes.

3.9 Acknowledgements

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4.0 Article 2: 3D laser imaging for surface roughness analysis

Following the success of the above ground field trial in article 1, the research moved to an underground field trial with a focus on surface roughness. However, prior to measuring surface roughness, the joint orientation needed first to be measured in order to geo-reference the surface roughness measurements. The triangular discretization process from article 1 was applied with only moderate success due to the limited exposure of the rock faces. To circumvent this problem, in article 2, the triangular discretization process was removed from the work flow and the joint orientation and surface roughness were measured directly from the point cloud data.

The article was accepted for publication on 10 August 2012 in the International Journal of Rock Mechanics and Mining Sciences. The article text and figures are reproduced in whole. The table and figure numbers have been updated in accordance with the thesis document. Additional information supporting this article is provided in Appendix B. A description of the algorithm is presented in Appendix C and the source files are provided in a DVD.

4.1 Abstract

Three-dimensional (3D) images of rock faces contain key information for rock mass characterization. In an underground field trial, 3D laser imaging is used to measure surface roughness. A controlled validation study is performed comparing surface roughness measured manually and from the 3D data. At the same location as the manual measurements, joint orientation is first measured from the 3D point cloud data using principal component analysis. This process calculates the best fitting plane and its associated normal vector to the imaged joint surface. The normal vector being known, a 2D surface profile can be generated along the strike and dip. The profile length of the maximum asperity amplitude measured from the 3D data is used to estimate the Joint Roughness Coefficient (JRC). In addition, the 3D point cloud data contains a wealth of information typically not available. The surface roughness measurements can be made across the entire image to generate a surface roughness map. Joint characteristics such as surface roughness anisotropy can be evaluated efficiently.

4.2 Introduction

Rock mass rating systems, such as Q and RMR, are well established and widely used to estimate rock mass quality and strength [1]. The shear strength of joints is an important factor contributing to the overall rock mass strength, and it is strongly influenced by the surface characteristics of joints, including roughness. The influence of roughness is accounted for either directly (using the joint roughness number in the Q

system) or indirectly (as part of the joint condition evaluation in RMR), but its measurement in the field is challenging.

One method of measuring surface roughness is to use a mechanical profilometer, also known as a profile comb. The instrument consists of a line of pins which conform to the joint face, which can then be traced to obtain a 2D surface profile. To characterize surface roughness, the 2D surface profile is typically compared visually to Barton's reference roughness profiles to estimate JRC [2-5]. A more quantitative method is to use a straight edge of known profile length and place it against the rock face. The operator estimates the location of the maximum asperity amplitude normal to the straight edge and measures the amplitude using a second ruler or a caliper. Knowing the profile length and maximum asperity amplitude, JRC can be determined using Barton's empirical surface roughness relations [3].

Three-dimensional (3D) laser imaging is emerging as a practical tool in rock mass classification [7,17]. Image acquisition is performed at a safe distance eliminating the need to come in contact with the rock face. 3D data can also be acquired from regions that would typically be inaccessible. In a single image, millions of high accuracy 3D data points are acquired in Cartesian space [16]. The quantity of 3D data acquired is several orders of magnitude greater than the amount of data that can be acquired manually. These data are processed efficiently by automatic algorithms, reducing the amount of manual labour required, leading to robust estimates of joint characteristics.

Using 3D laser imaging, several innovative strategies to measure surface roughness are being developed to replace the traditional manual methods. 3D laser profilers are used to estimate surface roughness using mathematical morphology [50]. Computed tomography methods are used to investigate surface roughness and fluid flow in rock fractures [27]. Most of this research is being conducted in laboratory environments which allows for controlled validation studies using rock samples [28-31, 51]. A few outdoor field trials have been conducted that examined image processing techniques to measure surface roughness [31, 21, 32].

4.3 Objective and Methodology

In this paper, we show how 3D laser imaging can efficiently acquire reliable surface roughness data. A methodology is proposed to measure surface roughness from the 3D image and presented as a proof of concept. A field trial is conducted where the sidewalls of a drift in an underground mine are scanned. In a controlled validation exercise, surface roughness measurements were made manually and computed from the 3D data at the same locations to allow a direct comparison. The study is further extended by examining the impact of scale on surface roughness measurement. Exploiting the large quantity of data acquired in a single 3D image, a surface roughness map is derived as a new data product. The ability to measure surface roughness anisotropy is also examined and demonstrated in the computation of an anisotropy map. Potential applications of the anisotropy map as a geological and engineering resource are explored. The proposed methodology provides a general procedure for

surface roughness measurement which can be further optimized with additional research and field trials.

4.4 Underground Field Trial

An underground field trial was conducted at Vale's T1 nickel mine located in Thompson, Manitoba, Canada. The mine is located in the Thompson Nickel Belt, which is approximately 100 km long, 5 to 30 km wide. The Thompson Nickel Belt has a northeast trend and is bounded by the Archean Superior Province to the east and the Trans-Hudson Orogen to the west. The Thompson Nickel Belt is composed of Archean gneisses, Proterozoic rocks, and ultramafic sills which host the nickel deposits [57].
(paragraph added)

Images were acquired of a rock face in the sidewall of a 5 m wide x 4 m high lightly arched roof access drift, located 1524 m (5000 ft) underground. The upper region of the rock face was supported with mesh and bolts. The survey site consisted of mafic and metamorphosed rocks. Mineral foliation was observed in the metamorphosed rocks. The rock face featured undulating features with a wavelength and amplitude of approximately 150 mm and 16 mm respectively. The survey site also contained blast fracture surfaces. The survey site was in the vicinity of a magnetic ore body. The RMR₁₉₈₉ for this site is 72 [59] (paragraph modified).

The selection of the 3D laser scanner was critical as imaging underground presents numerous challenges. Rock face features can be very subtle and difficult to map due to their limited exposure as opposed to the exposure of large blocks commonly

observed in natural outcrops or road cuts. This requires a laser scanner with high depth resolution. The conditions underground also have dust, dirt, water, and limited lighting and space. To address these challenges, a triangulation-based laser scanner was utilized. These systems are designed to operate at distances less than 10 m from the target. They differ from light detecting and ranging (LiDAR) time-of-flight and specular reflection laser scanners in that the distance to the target is measured by triangulating the projected and diffusely reflected beam paths, at sub-millimeter accuracy [16].

The instrument selected for this study was the Laser Camera System (LCS), developed by Neptec Design Group. This instrument had been used previously in both above ground [5] and underground field trials [17, 18, 39]. The LCS is immune to ambient lighting conditions by using a laser and detector in the infrared part of the electromagnetic spectrum, and has a depth resolution of 0.5 mm. The laser source and linear detector array both reside in the same enclosure. The LCS acquires 3D point clouds with Cartesian spatial coordinates (X, Y, Z) and grayscale reflection intensity (I) of points on the surface of the target.

The LCS was set up approximately 3 m away from the rock face, with the projected beam direction perpendicular to the face segment to be imaged. Seven overlapping (20% of the surface) images were acquired covering an area 5.3 m wide by 2.0 m high. Images were acquired at the full resolution, 1024 by 1024 points, which corresponds to a point cloud concentration of approximately 41 points per square centimetre. Each image took approximately 10 minutes to acquire. For each image

acquired, the orientation of the laser scanner was measured for geo-referencing purposes. Figure 4-1 shows the test setup.

For validations purposes, 18 joint orientation measurements were made using a compass. At the exact location of the joint orientation measurements, 32 surface roughness measurements were made along the strike and dip directions with a straightedge and a caliper at varying profile lengths, ranging from 0.08 m to 0.61 m (Figure 4-2).

4.5 Image Analysis

A common image processing strategy is to align and merge the point cloud data to generate a surface using a triangular discretization process, in this case, a 3D triangular mesh model where triangles of different sizes and orientations conform to the topology. The orientation of each triangle was measured using its normal vector and plotted on a stereonet where statistical groupings were used to identify joint sets [7, 10-12, 17]. This strategy was applied to the 3D triangular mesh model for the test site (Figure 4-2) and three joint sets were identified. The strike/dip of joint sets 1, 2, and 3 are 011/52, 136/83, and 204/65, respectively. A stereonet generated from the manual measurements is provided in Appendix B.

Figure 4-1: Laser scanner underground test setup.

Figure 4-2: Test site (title added)

The location of the 18 manual orientation and surface roughness measurements.

In this study, the joint orientation measurement strategy described above was streamlined by measuring joint orientation directly from the 3D point cloud data. The proposed methodology does not require the generation of a 3D triangular mesh model. While there are several benefits in generating a 3D triangular mesh model, it is a time consuming process and alignment errors may be introduced. For a 3D model composed of 6 images, removing this step can reduce processing time by up to 50% [7]. In addition, a measurement can be made directly from the 3D point cloud data on site in a matter of minutes, immediately after an image has been acquired.

4.5.1 Joint Orientation Measurement

Measuring joint orientation directly from the point cloud data is the first step in the proposed methodology. The user chooses a point in the 3D point cloud and all 3D points falling within a 30 mm radius of this center point are selected. For direct comparison, the locations of these joint orientation measurements coincided exactly with those of the manual measurements. The size of the circle surface was chosen as it corresponds approximately to the contact area of a Brunton compass, which is commonly used for joint orientation measurement. A principal component analysis (PCA) is performed which uses a least-squares method to determine the best fitting plane to the selected 3D points. The strike and dip are calculated from the normal vector to this plane. This methodology has been used successfully to measure joint orientation [18, 25,26]. Figure 4-3 displays the best fit plane from the PCA analysis for

site #7. The x-axis represents the North-South direction while the horizontal and vertical grid lines of the plane indicate the direction of the strike and dip.

Figure 4-3: Principal component analysis (title added)

Principal component analysis is used to compute the best fitting plane to the point cloud at measurement site #7. Points in red and green are above and below the plane, respectively.

4.5.2 Surface Roughness Measurement

After measuring the joint orientation, a rectangular subset of 3D points is selected along a particular orientation (strike or dip orientation) and length (0.08 m to 0.61 m) corresponding to that used in the manual measurements. The width of the rectangular subset is 12.7 mm (0.5 inch). From this subset of points, a 2D surface profile is generated by binning the points along the length of the profile and computing the average offset of all points falling within each bin. Wider bins, containing more points, would cause the surface profile to progressively become featureless. Statistical methods such as moving or weighted averages may also overly smooth the profile and remove detail. In contrast, narrower bins, containing fewer points, are influenced by measurement noise and outliers. The average bin width is 6.35 mm (0.25 inch), corresponding to an average point density of 65 points per bin. The bin width was selected as a compromise to minimize these effects. A constant bin width was applied to all surface roughness measurements regardless of the profile length to maintain any smoothing effects and other bin width errors constant.

On the resulting 2D surface profile, a straight line is generated between the two local maxima to simulate a straightedge apposed on an irregular rock face. The normal distance from the line to the 2D surface profile is calculated to determine the maximum asperity amplitude (Figure 4-4). Knowing the profile length and the maximum asperity amplitude, the JRC is read from Barton's empirical graphs [3], provided in Appendix B.

Figure 4-4: 2D surface profile (title added)

The 2D surface profile averaged from binned point cloud data at measurement site #3, along strike.

4.6 Validation of Results

Validation of the surface roughness measurements is accomplished by comparing the maximum asperity amplitude and corresponding JRC for the 32 manual and 3D laser measurements (Table 4-1). The majority of measurement sites have minor variations in the maximum asperity amplitude with the 3D laser measurements being an average 0.3 mm greater than the manual measurements. This results in a difference in JRC of 0.1. The 3D laser measurements are plotted on Barton's empirical graph in Appendix B [3].

The difference in JRC measurements could be caused by a fundamental difference between the manual and 3D laser joint orientation measurements. In manual measurements, the joint orientation is measured by placing the compass on the surface of the rock face. However, with the 3D data, the joint orientation is measured by PCA analysis which determines the best fitting plane. Approximately half the 3D data should be above and below the plane. The PCA analysis measures the joint orientation through the surface as opposed to manual measurements which are taken on the surface. This may cause differences in joint orientation measurement. Subsequently, the orientation of the generated 2D profile may not match the orientation of the manual measurement resulting in a difference in JRC.

Table 4-1: Surface roughness results (title added)

Maximum asperity amplitudes and JRC values from manual and 3D laser measurements.

Site Number	Direction	Length of profile m	Manual measurement		Laser measurement		Difference (laser to field)	
			Amplitude mm	JRC	Amplitude mm	JRC	Amplitude mm	JRC
1	dip	0.15	6.20	17	6.10	16	-0.10	-1
2	strike	0.30	16.30	20	15.60	20	-0.70	0
	dip	0.30	15.70	20	18.70	20	3.00	0
3	strike	0.15	5.80	16	6.50	18	0.70	3
4	strike	0.30	1.80	3	2.50	3.5	0.70	1
5	strike	0.15	5.30	14	5.20	14	-0.10	0
6	strike	0.15	6.20	17	5.60	15	-0.60	-2
	strike	0.30	5.70	8	5.30	7.5	-0.40	-1
	dip	0.30	13.10	20	11.60	18	-1.50	-2
7	strike	0.15	1.10	3	1.10	3	0.00	0
	dip	0.15	2.50	7	2.80	7.5	0.30	1
	strike	0.41	12.40	13	18.90	19	6.50	6
8	strike	0.30	1.90	3	1.80	2.5	-0.10	0
	dip	0.30	1.70	3	2.20	3	0.50	1
9	strike	0.25	5.50	9	6.10	10	0.60	1
	dip	0.15	3.50	10	5.20	14	1.70	5
10	strike	0.15	3.50	10	3.10	8	-0.40	-2
	dip	0.28	4.30	7	3.60	5.5	-0.70	-2
11	strike	0.61	21.50	16	23.20	18	1.70	2
12	strike	0.30	4.30	7	5.30	7.5	1.00	1
	dip	0.15	3.50	10	2.80	7.5	-0.70	-2
13	strike	0.15	3.80	10	3.90	10	0.10	0
14	strike	0.30	5.50	8	4.50	6.5	-1.00	-2
	dip	0.23	3.50	6	4.00	7	0.50	1
	dip	0.15	4.00	11	2.70	7.5	-1.30	-3
15	strike	0.08	1.20	5	1.10	5	-0.10	0
	dip	0.08	1.70	10	1.70	10	0.00	0
16	dip	0.15	5.80	16	6.00	16	0.20	1
	strike	0.30	7.20	11	9.50	14	2.30	4
17	strike	0.30	2.70	5	2.60	4	-0.10	-1
	dip	0.30	2.90	5	1.50	2	-1.40	-3
18	strike	0.15	3.80	10	2.60	7	-1.20	-3

Errors can occur when manual measurements are made if the location of the maximum asperity amplitude is not correctly identified. This can easily happen underground with limited lighting, dirty rock faces, and awkward accessibility. For the surface roughness measurements with a profile length of 40.64 mm (1.6 inch) and 60.96 mm (2.4 inch), it is also possible that the straightedge flexed during the measurement. Manual measurements may also be limited by the accuracy of the measurement tools. For the 3D measurements, noisy data or outliers can introduce errors, as well as non-optimal choice of the bin width used in the computation of the 2D surface profiles. For both manual and 3D laser measurements, another source of error is introduced if the surface roughness measurements are not exactly made along the strike or dip.

The presence of the magnetic ore body had a negligible impact on results under the assumption that the magnetic gradient was short and therefore the deflection was constant for all compass measurements. The compass measurements might have been slightly inaccurate in the absolute sense but were consistent in the relative sense.

4.7 Characterization and Mapping

The benefit of 3D laser imaging is that a wealth of information can be extracted from the point cloud data, allowing detailed analysis of surface roughness characteristics. For instance, at each measurement site, 2D surface profiles can easily be computed for different profile lengths. Figure 4-5 shows the maximum asperity amplitude for varying profile lengths ranging from 0.08 m to 0.60 m along the strike direction for the rock face under study. The joint set associated with each measurement

is identified by color and reference lines for JRC 1, 10 and 20 are displayed. The analysis of 3D laser imaging data has allowed Figure 4-5 to be populated with many more data points than the sparse manual measurements.

Figure 4-5: Maximum asperity amplitude versus profile length (title added)

Maximum asperity amplitude versus profile length for each of the 18 measurement sites. The three joint sets cannot be distinguished based on surface roughness along the strike due to significant overlap in JRC.

Figure 4-6 displays the JRC as a function of profile length along the strike direction for each of the 18 measurement sites. For each measurement site, the average range in JRC was 4. No consistent bias was observed towards increasing or decreasing JRC with respect to increasing profile length. In some cases, the location and magnitude in the maximum asperity amplitude remained unchanged resulting in a decreased JRC with increasing profile length. In other cases, a new, larger maximum asperity amplitude was detected over the extended profile, resulting in an increased JRC.

Figure 4-6: Joint set JRC versus profile length (title added)

JRC to profile length for each of the 18 measurement sites.

Surface roughness measurements derived from 3D laser imaging data can be presented in various innovative ways. Figure 4-7 merges joint orientation and surface roughness information, providing a comprehensive map. A 3D grid, with approximately 0.10 m x 0.10 m spacing, was generated following the topology of the rock face and superimposed onto the point cloud image. Grid units with corners, edges, and mesh wire were removed. In the grid, joint set number and surface roughness are represented by the fill color and its intensity, respectively. For JRC 1 to 20, the color transitions from translucent to near opaque. Regions with high and low surface roughness are identified immediately and can be correlated with geological features.

Figure 4-7: Surface roughness map (title added)

Joint orientation and surface roughness along the strike is mapped for an entire image.

Joint sets and surface roughness are distinguished by color and color intensity.

4.8 Anisotropy

To measure surface roughness anisotropy, rectangular subsets of 3D points were selected at 10° azimuthal increments. Each rectangular subset is 152.4 mm long by 12.7 mm wide. The associated 2D profiles are generated, maximum asperity amplitude measured, and corresponding JRC estimated. Figure 4-8 shows the surface roughness anisotropy polar plot for measurement site #12, for a profile length of 152.4 mm. The figure clearly shows a direction of high roughness with a rake of approximately 30°, with low roughness at all other orientations. Plotting the anisotropy in this manner also allows for the detection of higher orders of anisotropy, which would be represented by multiple axes of high JRC.

Figure 4-8: Surface roughness anisotropy (title added)

Surface roughness anisotropy at measurement site #12 is displayed as a polar plot with the long axis at approximately 211 degrees azimuth and the short axis perpendicular at 301 degrees. The strike, dip, JRC 20, and JRC 10 are displayed as the horizontal axis, vertical axis, outer circle, and inner circle, respectively.

Figure 4-9 displays anisotropy polar plots superimposed on the 3D image of the rock face permitting further characterization of the joint sets. The surface roughness is measured with a profile length of 152.4 mm. Overall, joint set 1 has a relatively low JRC (< 10). In the lower portion of the rock face, the surface roughness of joint set 1 shows *minor anisotropy with the long axis consistently oriented in the dip direction*. In the upper portion of the rock face, anisotropy is in different orientations. Joint set 2 has a relatively high JRC, close to 20 in several orientations. Joint set 3 has a relatively low JRC (< 10) in most orientations.

Figure 4-9: Surface roughness anisotropy map (title added)

Surface roughness anisotropy is mapped to study the anisotropic nature of the joint sets. Each anisotropy polar plot is color coded with joint set 1, 2, and 3 in yellow, green, and blue. The outer circle represents JRC 20 and is scaled according to the profile length (152.4 mm).

The surface anisotropy map can provide pertinent information for both engineering and geological perspectives. The directional strength of joint set can be assessed quickly. Fracture analysis can be conducted to determine the number of fracture events, the type of fracture, and the fracture propagation direction. Variations in fracture characteristics can be related to geological processes occurring at the time of slip. Direction indicators can reveal subsequent reactivation and later changes in directions of slip. Effectively, a history of the geological processes occurring from the time of joint formation is displayed. These details have not been examined as part of this study, but the data acquisition and analysis technique presented open up new possibilities to study aspects such as these.

In the current practice, manual surface measurements are made along the strike and dip. In contrast, the anisotropy plot from 3D data is a consolidation of surface roughness measurements made at 5° increments. Comparing the two methods, Figure 4-9 shows several anisotropy plots where the maximum JRC resides in directions other than the strike and dip. This indicates the current practice, to measure surface roughness along the strike and dip, is biased. The anisotropy plot removes this bias and provides a complete assessment of the anisotropy. (paragraph added)

4.9 Conclusions

It has been shown that 3D laser imaging can be used to successfully measure not only joint orientation, but surface roughness and surface roughness anisotropy. Manual

measurements are laborious, which limits the number of measurements that can be acquired whereas 3D image data are recorded quickly, processed efficiently, and can be used to further characterize the rock mass. The 3D image data present opportunities for new data products such as maps in which surface roughness and its anisotropy are superimposed on images. This allows for a visual correlation of this information with geological features.

An analysis of the image data showed that joints can exhibit considerable anisotropy in roughness. Because of the limited number of measurements that can be made manually, this can lead to biasing of results, which would translate into inaccurate estimates of joint surface frictional strength. The analysis method described provides a means of quantifying this directional roughness. Anisotropy appears to vary spatially and may not be a unique characteristic of a joint set, although analysis of a larger data set is required to verify this result.

4.10 Acknowledgements

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5.0 Article 3: Wire mesh filtering in 3D laser image data

Following the success of both field trials, the research project sought to investigate in more detail the operation issues related to 3D laser imaging in underground mines. The installation of wire mesh on rock walls, effectively restricting access and masking part of the surface, was a prominent challenge to both manual and laser measurements. Identification and filtering of the wire mesh on 3D laser images was the focus of the third article.

The article was submitted on 17 August 2012 to the International Journal of Rock Mechanics and Mining Sciences. The article text and figures are reproduced in whole. The table and figure numbers have been updated in accordance with the thesis document. A description of the algorithm is presented in Appendix C and the source files are provided in a DVD.

5.1 Abstract

Three-dimensional images contain an element of measurement noise that negatively impacts the characterization of the rock mass. In a mining environment, support elements such as wire mesh are a source of measurement noise. In this study, two filters are developed to remove the wire mesh enabling joint orientation and surface roughness measurements to be made: a second derivative filter and a baseline filter. After completing a principal component analysis of the point cloud data, plotting the normalized amplitude reveals a sharp inflection point, segregating the legitimate rock face data and the noisy data. The threshold for the second derivative filter is based on characteristics of the normalized amplitude curves of these two data sets. The baseline filter accounts for the instrument noise and the maximum asperity amplitude of surface roughness. Flat rockbolt face plates provide an opportunity to characterize the instrument noise in the field under operational conditions. The presence of wire mesh has minimal impact on joint orientation measurements. Surface roughness measurements are more sensitive to noise. After the mesh is removed, surface roughness measurements can be made from a 2D surface profile generated along the strike, dip, and other directions to study anisotropy.

5.2 Introduction

Three-dimensional (3D) laser imaging is an emerging practice in rock mass characterization [6, 8, 11, 12, 17-19, 25, 52]. A single image, composed of millions of geo-referenced 3D data points, can cover a large surface area that would typically

require significant amounts of time to map manually. Image acquisition can be performed from a safe distance, without any contact with the rock face. Data can be acquired in regions difficult or impossible to access. The data is composed of a set of 3D Cartesian coordinates with the laser scanner at the origin and intensity measurements in either greyscale or color, termed “point cloud” [16].

The well-established rock mass rating systems, Q and RMR, consider joint characteristics to estimate rock mass quality and strength [1], including parameters such as the number of joint sets, joint spacing, surface roughness, nature and degree of infilling or surface weathering, and the presence of water. Many of these parameters are amenable to quantification through laser imaging. After image acquisition, the point cloud data requires processing to measure the surface characteristics of interest. The challenge is in developing robust, unbiased methodologies that can measure these parameters automatically. Successful case studies have been conducted where laser imaging was used to measure joint orientation [6, 8, 10-12, 17, 25, 52]. Surface roughness in a controlled lab environment [28-30] and in outdoor field trials [21, 31-32] has also been measured using imaging methods. Most joint orientation and surface roughness measurements are single, localized measurements but, with a robust processing method, an entire image can be analyzed to generate a joint orientation or surface roughness map [7].

In mining and geology, laser scanners are challenged to operate in harsh conditions that can increase noise in the data. Measurement noise is defined as the

deviation between the measured and true range measurement. In our application, any factor that disrupts measurement of the range to the rock face is considered to be a source of measurement noise.

During image acquisition, there are several sources of measurement noise. The first source of measurement noise lies with the instrument. Instrument noise is inherent to the scanner and is dependent on its optical and mechanical design.

In the field, environmental factors such as sunlight, dust, and water vapour can also contribute to measurement noise [20]. Water on a surface often causes diffusion of the reflected laser beam and a decrease in the precision of the range measurement.

The setup of the laser scanner and image acquisition strategy can also influence data quality. If the laser scanner is setup at a high incidence angle with respect to the rock face, the point cloud data may exhibit line-of-sight bias and joint distance variability [49, 14, 53]. At high incidence angles, some regions of the rock mass may be preferentially illuminated whereas overhangs may cause shadow zones where no data is acquired.

Objects in the field of view may also be a source of measurement noise. The reflectivity of the object and edges are known to cause measurement noise. Reflectivity is dependent on the laser wavelength, therefore reflective objects may not necessarily be identifiable by the human eye. In some instances, a highly reflective surface may exceed the limit of the detector array and saturate the intensity measurement [20]. Alternatively, an object may have poor reflectivity, causing a low intensity

measurement. Low intensity measurements can be avoided by increasing the laser power. Edge effects cause measurement noise when the laser beam is split at a physical edge and the instrument attempts to measure the range of two different surfaces, introducing erratic data in both range and intensity measurements.

In this application, man-made objects in the field of view can also be classified as noise because they interfere with the characterization of the rock face. These objects are further classified as either partially or fully obscuring. In a mining environment, partially obscuring objects include support elements such as wire mesh and rockbolts. Since the rock face is still visible when these objects are in the field of view, useful information can be extracted from laser images. Other objects, such as shotcrete, ventilation tubing, and service supply pipes, commonly found in mining excavations, completely obscure the rock face. This eliminates the possibility of any form of discontinuity characterization, and images containing such objects are not considered further.

Ideally, the environmental factors and man-made objects in the field of view should be avoided to minimize measurement noise. However, this is not always possible, resulting in reduced accuracy in joint orientation and surface roughness measurements. The impact is particularly detrimental to surface roughness measurements where surface profiles contain an element of measurement noise leading to an overestimation of the surface roughness [21]. A number of successful methods to minimize the impact of noise on surface roughness have been proposed:

wavelet de-noising [21], scattered data interpolation [22], interpolation to increase the data density [23], and moving least squares [24]. Other methods to reduce measurement noise have concentrated on camera calibration in a controlled environment [54-56].

5.3 Objective

In underground mining, wire mesh and rockbolts are commonly used as standard support. In these instances, specialized image processing techniques are required to derive accurate measurements from the 3D laser image data. In this paper, the impact of wire mesh on joint orientation and surface roughness measurements is evaluated. Two filters are developed to distinguish between the rock mass and noise. Without affecting the rock mass data, these filters are applied to remove the data associated with the wire mesh. The filters take into consideration the instrument noise, the maximum asperity amplitude of the discontinuity surface, and the amplitude of each point to the best fit plane from principal component analysis (PCA). The wire mesh filters are applied as a proof of concept with test cases demonstrating the operational realities observed in the field. When the mesh is removed, the joint orientation and surface roughness can be measured accurately. Figure 5-1 shows the point cloud from a segment of a rock face with the wire mesh and edge effects.

Figure 5-1: Segment of a rock face with wire mesh present.

The wire mesh and noisy data (mostly associated to edge effects) are shown in red. The size of the wire mesh is approximately 10 cm by 10 cm.

5.4 Underground field trial

An underground field trial was conducted in a drift at Vale's 175 orebody mine located in Sudbury, Ontario, Canada. The drift was 1524 m below ground surface, 5 m wide by 4 m high, with a slightly arched roof. Images of a rock face were acquired at the end of the drift and along the sidewall leading to this rock face. The rock mass at this site featured joints, undulated features, and blast fracture surfaces. The upper region of the rock face and sidewalls were supported by mesh and bolts.

The RMR_{1989} for this site was 80 [4]. The rating of the five RMR parameters were: (1) strength of intact rock of 100 to 250 Mpa, 12 points, (2) Rock Quality Designation approximately 90%, 18 points, (3) joint spacing of 60 to 200 mm, 10 points, (4) joints are slightly rough with slight weathering, 25 points, (5) dry conditions, 15 points.

In an underground environment, selection of the laser scanner is critical. The rock faces tend to be small with limited exposure, and features on the rock face can be subtle and difficult to measure. This is in contrast to larger blocks commonly observed in natural outcrops, road cuts, and open pit mines. A laser scanner with a high depth resolution is required that is minimally affected by the dust, dirt, water, low lighting, and the limited space constraints of underground excavations.

Considering these factors, the Laser Camera System (LCS), developed by Neptec Design Group, was selected for this study based on its successful heritage in above

ground [6] and underground field trials [7, 17, 18]. The LCS stores both a laser source and linear detector array inside a robust enclosure. An infrared laser is used, making the LCS immune to the ambient lighting conditions. By triangulating the projected laser beam and its reflection on the detector array, the LCS measures the distance to the target at sub-millimeter accuracy [16]. In ideal laboratory conditions, the LCS has a depth resolution of 0.5 mm at a range of 3 m. The 3D point cloud data recorded by the LCS is composed of Cartesian coordinates (X, Y, Z) and grayscale reflection intensity (I). Table 5-1 lists the LCS specifications.

The LCS was set up on a tripod, approximately 3 m away from the rock face and images were acquired facing *normal* to the rock face as well as at oblique incidence angles greater than 30°. Five images were acquired at full resolution, 1024 by 1024 voxels, at different locations along the drift. Each image was approximately 1.6 m wide by 1.6 m high, corresponding to a point cloud concentration of approximately 41 points per square centimeter. The integration time of the detector array and the laser power were adjusted based on the reflectivity of the rock face. Each image took approximately 10 minutes to acquire. For geo-referencing purposes, the orientation of the LCS enclosure was measured at each scan location. For validation purposes, 4 manual joint orientation measurements were made in a roughly blasted, blocky region by climbing a ladder and placing a compass through the mesh support. Figure 5-2 shows an intensity view of two 3D images.

Table 5-1: Surface roughness results (title added)

LCS Specifications		
Enclosure Dimensions	cm ³	18.8 x 25.4 x 27.9
Mass	kg	12.1
Maximum field of view	degree	30 x 30
Image size	m	1.6 x 1.6
Maximum image resolution	voxel	1024 x 1024
Depth resolution at 3 m	mm	0.5
Laser wavelength	nm	1500
Maximum acquisition rate	voxel/s	5000
Scan time	min	10

Figure 5-2: Two images in intensity view (approximately 1.6 m x 1.6 m).

Image A displays locations where the wire mesh filter was applied (numbered circle), manual joint orientation measurements were made (dashed circle), and instrument noise was measured (square outline). Image B displays locations where the wire mesh filter was applied (numbered circle) and instrument noise measured (square outline). The images show instances where there is a single mesh (locations 1-4,9) and a double mesh (locations 7, 8).

5.5 Methodology

5.5.1 Validation of joint orientation measurements

A validation study was first conducted to verify that accurate joint orientation measurements could be made from the point cloud data. The wire mesh was manually removed from the image to eliminate any influence it might have on the measurements. Joint orientations were estimated using *principal component analysis (PCA)* at the same exact four locations where manual measurements were made. These locations are indicated by dashed circles in Figure 5-2A.

PCA is a statistical method that determines the best fitting plane to the selected point cloud data. PCA analysis has been applied successfully in previous case studies [6, 55]. Since the measurements are made directly from the point cloud data, results are available immediately after an image is acquired and processing errors in the discretization process to generate a surface model are avoided [6]. The angular difference between the manual and laser measurements at the four locations used in the validation study are presented in Table 5-2. The average angular difference is 6.1° which is in the accepted range of manual joint orientation measurements [6].

Table 5-2: Angular difference between manual and laser measurements

Measurement Number	Manual measurement strike/dip (degree)	Laser measurement strike/dip (degree)	Angular difference (degree)
1	200/60	207/52	9.9
2	300/90	302/86	4.5
3	303/89	299/90	4.1
4	236/84	241/81	5.8
		Average	6.1

5.5.2 Distinguishing between rock face and wire mesh data using normalized amplitude

As illustrated in Figure 5-1, selecting a portion of the image of the rock face situated behind wire mesh will include points representing the rock face, wire mesh, and edge effects. In this study, we use PCA analysis to segregate between the legitimate data and the wire mesh data. PCA analysis generates two data sets: above and below the best fit plane (Figure 5-3). Amplitude is defined in this context as the distance from the best fit plane. For each data set, the amplitude data is first sorted from smallest to largest and then normalized by computing the ratio between the amplitude of each point and the maximum amplitude in each respective data set (Figure 5-3, right). This allows the two data sets to be compared to one another.

The presence of the wire mesh causes the best fit plane to become offset from the rock face. The data below the best fit plane, nevertheless, is for the most part rock face data. The corresponding normalized amplitude curve is therefore mainly a function of the surface roughness. Since the maximum amplitude of the data below the best fit plane is less than that of the data above the best fit plane, the curve exhibits a larger radius of curvature (Figure 5-3, right). Since the below data is predominantly rock face data, we can assume the below data does not require filtering.

The data above the best fit plane, containing the wire mesh, tends to be a smaller data set. A point of inflection is observed in its normalized amplitude curve

(Figure 5-3, right). We interpret the point of inflection as marking the boundary between legitimate rock face data and wire mesh and edge effect data. We assume that the inflection is due to the *higher amplitude of the data points from the wire mesh* in comparison to the amplitude of the data points from the rock surface.

Figure 5-3: A cross sectional view of the rock face at location 4 (left) and corresponding normalized amplitude plot (right).

The PCA best fit plane (solid black line) computed using PCA analysis is used to distinguish between two data sets: the data below (red) and above (green) the plane.

5.5.3 Filter design

Two filters are developed to remove the wire mesh. The second derivative filter attempts to identify the location of the inflection point by discretizing the normalized amplitude data. The baseline filter is independent of the amplitude data and based on instrument noise and surface roughness.

5.5.3.1 Second derivative filter

In-order to identify the inflection point, the normalized amplitude data is discretized in 5% increments. A central finite difference approximation of the first derivative is computed to examine the rate of change in the amplitude data. The first derivative of function $f(x)$ is defined as:

$$f'(x) \approx [f(x+h) - f(x-h)] / 2h \quad (1)$$

where h represents the step size. The same equation is applied again to determine the second derivative. The point where the second derivative is a maximum represents the location where the slope data is changing the fastest. To reduce the chances of selecting legitimate data for removal, the normalized amplitude corresponding to the next discretized point on the second derivative curve is selected as the filter threshold (Figure 5-4). The filter removes all points with a normalized amplitude greater than the threshold.

Figure 5-4: Sketch illustrating the concept of the second derivative filter.

The second derivative filter is used to estimate the location of the inflection point marking the boundary between rock face and wire mesh data for location 4. In a conservative manner to avoid removing legitimate data, the threshold is chosen as the first point on the normalized amplitude curve (indicated by a green arrow) after the maximum second derivative (indicated by a light blue arrow). Points with a normalized amplitude greater than this threshold are eliminated.

5.5.3.2 Baseline filter

The baseline filter takes into consideration instrument noise and surface roughness (Figure 5-5).

5.5.3.2.1 Instrument noise

The level of instrument noise is usually a specification provided by the manufacturer. Published values, however, are typically established in a controlled and favorable environment such as a clean lab. The published values also apply to a specific target range. During field operations, the reflectivity of the target, water, dust and humidity may all impact the instrument noise. The distance between the laser scanner and rock face will also vary depending on experimental setup. Therefore, the manufacturer's specifications may not be representative of the actual instrument noise observed in the field.

In this field trial, the flat rockbolt face plates used to secure the wire mesh provide an opportunity to measure the instrument noise in-situ, without the need to place a cooperative target on the rock face. The face plate is inspected in the point cloud data to ensure that it is flat and not buckled or dished, and not significantly corroded. A region on the face plate is subjected to PCA analysis to determine the best fit plane. Assuming that the face plate is flat, the distance of each point to the plane can be analyzed statistically to estimate the level of instrument noise. This approach provides a data-driven quality control check of the instrument noise in operational

conditions. Variations in instrument noise can also be examined as a function of range and are ideally measured on a per scan basis. Other objects besides face plates may be used to measure the instrument noise and could be inserted into the field of view. In the event that no flat object is available, manufacturer's specification provided by the manufacturer can be used as a lower bound estimate.

Figure 5-5: Sketch (not to scale) illustrating the concept of the baseline filter.

The threshold consists of the instrument noise and half the maximum asperity amplitude corresponding to a JRC of 20. Points with a normalized amplitude greater than this threshold are removed.

For nine face plates, the instrument noise was calculated using a region of 20 mm radius (corresponding to a surface of 1256.6 mm²). This was the largest region in the rock bolt faceplate that could be selected and contained an average of 318 points. As different laser scanners have different point cloud concentrations, the number of points selected may vary. In this case, the standard deviation varied from 0.9 mm to 3.2 mm for ranges increasing from 3.2 m to 4.2 m. Figure 5-2 shows three face plates selected for instrument noise measurement.

5.5.3.2.2 Maximum asperity amplitude

An intrinsic geological property, surface roughness consists of the natural undulations of the rock face topography. The best fit plane measured from PCA analysis on a rock surface should ideally be centered around these undulations. As mentioned in Section 5.5.2, when the wire mesh is present, the best fit plane becomes biased. Due to this bias, the undulations of the rock surface may reside off the plane and the asperity amplitude of the rock face cannot be measured accurately. We therefore have to assume a certain surface roughness. In a conservative manner, we have chosen to use a joint roughness coefficient (JRC) of 20 and the corresponding maximum asperity amplitude for a given profile length [2-5]. Since PCA analysis determines the best fitting plane through the 3D point cloud data above and below the plane, only half of the maximum asperity amplitude is required.

The baseline filter is calculated by adding the instrument noise with half the maximum asperity amplitude as displayed in Figure 5-5. Points with a normalized amplitude larger than this threshold are assumed to be noisy data.

5.5.4 Wire mesh removal

Figure 5-6 illustrates the three step process for wire mesh removal. To avoid removing legitimate rock data, the second derivative and baseline filters are compared, and the filter with the highest threshold is used. The process is iterative, the data kept becomes the input to the following iteration. With each iteration, the number of points above and below the best fit plane gradually becomes similar. When the number of points in both data sets is within 6% of one another, the data sets are merged and analyzed jointly, following the same iterative process.

The iterative process is stopped as soon as one of the two following criteria is met. A first criterion is established using the percentage of data removed between successive iterations. When this percentage is less than 5%, the process is stopped. The second criterion examines the change in the second derivative filter. When the percentage difference in the filter threshold between iterations is less than 5%, the process is stopped.

Figure 5-6: The steps to remove the wire mesh are illustrated for location 4.

Step 1: the best fit plane computed using PCA analysis is used to distinguish between data below (red) and above (green) the plane. Step 2: the normalized amplitude curve is plotted for the data above the best fit plane. The thresholds for the second derivative and baseline filters are calculated. Step 3: noisy data is selected for removal. The process is iterative until most noisy data is removed and a stopping criterion is achieved.

Figure 5-7 plots the normalized amplitude curves at location 4 for each iteration until a stopping criterion is achieved – in this case, this happens on the fourth iteration when the percentage of data removed between successive iterations is less than 5%. As the noisy data is removed, the radius of curvature of the curves increases and the sharp inflection point is no longer observed. This is an indication that the wire mesh and edge effects are gradually being removed from the data. Figure 5-7 also shows that the filter thresholds increase with each iteration. This is because the maximum amplitude is decreasing with respect to the mean amplitude.

5.6 Joint orientation measurement after wire mesh filtering

The impact of the wire mesh on joint orientation measurement was evaluated at 11 locations in which a variety of wire mesh installation geometries were used. Table 5-3 lists characteristics of each measurement location along with pertinent details of the rock face and wire mesh. At these locations, the rock face varied between blocky and roughly blasted to smooth and rippled. Standard mesh panel installation practice involved overlapping of panel edges, presenting double layers of mesh. Due to common occurrence of these potentially more complex mesh/rock images, several of these locations were selected. The distance of the wire mesh to the rock face varied from 5 mm to over 100 mm, depending on the irregularity of the face and how the mesh was tightened to the face by rockbolts. The general orientation of the wire mesh, parallel or diagonal to the rock face, also varied and was recorded.

Figure 5-7: The normalized amplitude curves for five iterations (title added)

The normalized amplitude curves at location 4 are plotted for five iterations. The above and below data is merged at iteration 4. The iterations stop after the percentage of data removed between successive iterations is less than 5%. The thresholds for the second derivative and baseline filters are shown as squares and circles respectively. Iterations 1, 2, and 3 involve the data above the best fit plane only (solid lines). Iterations 4 and the final step involve all the data (dotted lines). After each iteration, the wire mesh data is removed resulting in (1) an increase in the radius of curvature and (2) an increase in the magnitude of both filters.

Table 5-3: Measurement location

Measurement number	Rock face characteristics	Mesh Characteristics		
		Single / Double	Distance to rock face, min - max (mm)	General orientation with respect to rock face
1	Blocky, roughly blasted	Single	10 - 40	Parallel
2	Blocky, roughly blasted	Single	10 - 50	Parallel
3	Blocky, roughly blasted	Single	10 - 60	Diagonal
4	Blocky, roughly blasted	Single	10 - 60	Diagonal
5	Blocky, roughly blasted	Single	30 - 100	Diagonal
6	Blocky, roughly blasted	Double	5 - 30	Parallel
7	Blocky, smooth	Single	5 - 80	Diagonal
8	Blocky, smooth	Double	5 - 30	Parallel
9	Blocky, smooth	Double	20 - 40	Parallel
10	Blocky, smooth	Double	20 - 40	Parallel
11	Blocky, smooth	Double	10 - 30	Parallel

For the 11 locations, PCA analysis was used to calculate the initial joint orientation without any noise filtering. The joint orientation was re-calculated after the wire mesh and edge effects were removed and the angular difference between the two results was computed. In addition, the impact of the noisy data was examined as a function of the PCA measurement radius. The PCA analysis was conducted for an initial radius of 20 mm and was increased by 10 mm increments to the maximum allowable radius in practice, which is a site-dependent function of joint surface exposure. The maximum PCA measurement radius used was 100 mm.

Table 5-4 lists joint orientation measurements. The average percentage of points removed at measurement sites with a single and double mesh was 9.5% and 16.7% of the initial data, respectively. For measurements with a single mesh, the percentage of points removed for measurement 1 was higher at 19.0%. A visual inspection of the point cloud data revealed a reference ruler captured in the point cloud data. Although the filters were developed to remove the wire mesh, the ruler was also successfully removed. Without measurement 1, the average percentage difference of points removed for the single mesh is reduced to 7.6%. The percentage of points removed for the double mesh cases is higher as the second mesh causes additional obstruction. Results did not vary significantly based on the measurement size. For measurement 5, the percentage of points removed was lowest at 4.5%. A visual inspection of the point cloud data revealed that there was less wire mesh present and the majority of the noisy data consisted of edge effects.

Table 5-4: Joint orientation and surface roughness measurements

Measurement number	Joint orientation results						Surface roughness results			
	PCA measurement radius	Strike, for the max radius	Dip, for the max radius	Average points removed	Angular difference (pre versus post filter)		Profile length	Along strike	Along dip	Average points removed
	min - max (mm)	(degree)	(degree)	(%)	Average (degree)	Max (degree)	(mm)	JRC	JRC	(%)
1	20 - 70	293	87	19.0	6.2	10.2	70	10.4	18.7	7.1
2	20 - 100	334	83	11.5	2.2	4.4	100	5.9	7.1	8.3
3	20 - 70	221	57	5.4	1.7	2.7	70	6.4	4.2	1.3
4	20 - 90	266	86	6.3	2.0	3.6	90	6.2	17.5	1.4
5	20 - 100	244	86	4.5	0.5	1.4	100	12.3	10.4	5.6
6	20 - 80	327	85	22.4	7.2	37.6	80	15.7	7.2	3.5
7	20 - 100	241	90	10.4	2.4	3.6	100	9.5	14.5	12.1
8	20 - 80	248	77	17.0	2.1	7.2	80	20.0	20.0	3.2
9	20 - 100	249	90	16.6	1.5	4.5	100	13.3	20.0	5.7
10	20 - 100	244	85	14.7	2.0	4.5	100	14.5	7.0	5.8
11	20 - 100	249	90	12.7	0.6	2.0	100	20.0	11.7	6.3
Average				12.8	2.6	7.4	Average 5.5			

For the PCA joint orientation analysis, despite the presence of the noisy data, the angular difference between the initial and final joint orientation measurements was small. The average angular difference for all 11 measurement locations and measurement sizes was 2.6° . For measurement 6, the maximum angular difference for measurement radii 20-80 mm was significantly higher (37.6°). This angular difference was observed for the 20 mm radii. A detailed review of this data set revealed the presence of a double mesh approximately 5-30 mm from the rock face. The combination of a small measurement radii and double mesh in close proximity resulted in the significantly higher angular difference. Despite this single instance, these results indicate PCA joint orientation analysis is robust and accurate measurements can be made even with the presence of wire mesh and edge effects.

5.7 Surface roughness measurement after wire mesh filtering

Although noisy data had a minimal impact on joint orientation, its removal remains a pre-condition for more detailed analyses such as surface roughness measurements. To maintain consistency, the points selected for PCA analysis are used for surface roughness measurement. For each measurement radius, the surface profile of the rock face can be measured by selecting a rectangular subset and binning the data. The average amplitude is calculated for each bin yielding a 2D surface profile which can be used to measure the JRC based on Barton's empirical graphs [3] provided in Appendix B. This is a technique that has been applied with success in laboratory and field environments [7, 18, 30, 51].

Previous studies have smoothed the data using various methods to improve the precision of the surface roughness measurement. In this study, we apply the instrument noise measured in-situ to filter any remaining effects due to the wire mesh. Assuming that the instrument noise follows a Gaussian distribution, three standard deviations represents 99.73% of the data. Any data points beyond three standard deviations can be assumed to be noise and removed. This instrument noise filter can be applied in each bin to remove any localized noisy data. After this filter has been applied, the surface roughness can be measured at different orientations to study anisotropy. Anisotropy of higher orders can be detected in this manner, enabling a directional strength of the rock face to be assessed and presented in a polar plot [7, 18, 30, 51].

Table 5-4 lists surface roughness measurements. The average percentage difference of points removed for the single and double mesh is 4.9% and 5.8% respectively. Measurement 7 had the highest percentage of points removed. It is also the furthest location measured and has therefore has the highest instrument noise. Figure 5-8 displays a surface roughness anisotropy plot superimposed on the point cloud data. The surface roughness is measured in 5° azimuthal increments and the plot gives a simultaneous impression of the roughness anisotropy and surface topography of the rock face. The plot, of a localized area, shows ripple effects in various directions. If this technique is applied over a larger area covering the entire rock face, features over the entire topography can be displayed for evaluation. As described in [7], there are various applications of this information, including an assessment of directional roughness

related strength, and an examination of the tectonic history of slip, through the memory of damage induced by relatively movement of the opposing surfaces.

Figure 5-8: Surface roughness anisotropy plot (title added)

Surface roughness can be calculated for azimuths between 0° and 360° in increments of 5° to generate an anisotropy polar plot, as shown by this example from location 4. The horizontal and vertical axes represent the strike and dip directions, respectively. The inner and outer circles represent JRC 10 and 20.

For surface roughness measurements, an additional assumption must be made that the occlusion of data in the shadow of the wire mesh is negligible. The number of occluded data points will vary according to the distance between the wire mesh and the rock face. A larger separation between the wire mesh and rock face will generate a wider shadow. For example, at location 4, the total measurement area is 25 447 cm² and the occluded area is estimated to be 1 931 cm² (7.6%). Although removal of the noisy data is necessary, omitting 7.6% of the measurement area may be significant in some circumstances. Any distinguishable features such as fracture or infilling may be lost. The location of the measurement must therefore be selected carefully to minimize the impact of the occluded data.

5.8 Summary and conclusions

In an underground field trial, the proposed filtering methodology was successful in removing noise, consisting of the wire mesh and edge effects, from the 3D image data used for localized joint orientation and surface roughness measurements. The approach combines a second derivative filter and a baseline filter. After completing a PCA analysis of the point cloud data, plotting the normalized amplitude revealed a sharp inflection point, segregating the legitimate surface data and the noisy data. The threshold for the second derivative filter is based on characteristics of the normalized amplitude curves of these two data sets. The baseline filter accounts for the instrument noise and the maximum asperity amplitude of surface roughness. The instrument noise was estimated by analyzing variations in the range measurements on images of rock bolt face plates.

The maximum asperity amplitude was estimated in a conservative manner by assuming a surface roughness corresponding to a JRC of 20. The filters were successful in selecting noisy data for removal in an efficient and unbiased manner.

The study has shown that the presence of the wire mesh and edge effects has minimal impact on the accuracy of the joint orientation measurement when calculated using PCA analysis. This is an indication that PCA analysis for joint orientation analysis is robust, efficient, and insensitive to noise effects caused by the presence of wire mesh. Surface roughness, on the other hand, is significantly more sensitive to noise. Therefore, additional care, in the form of an instrument noise filter, needs to be taken to remove any remaining wire mesh or edge effects before surface roughness measurements were made. In addition, this approach allows the joint surface anisotropy to be examined to determine the magnitude and direction of anisotropy to a degree of resolution not possible with manual measurements.

With the success of the wire mesh filter for localized measurements, it may be possible to apply the filter over an entire image. Similarly, it may also be possible to adapt the filter to remove other sources of noisy data such as water and highly-reflective objects.

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6.0 Conclusion

In this research project, new methodologies to measure joint orientation and surface roughness using 3D laser imaging were successfully developed and demonstrated. The main innovative contributions are the analytical methods developed to measure joint orientation and surface roughness, and to remove the wire mesh, captured in novel algorithms. These algorithms are independent of the sensor used to acquire 3D image data and therefore equally applicable to data recorded by triangulation-based scanners and LiDAR systems.

6.1 Summary

The 3D polar density contour method was developed to measure joint orientation from each triangle in a 3D triangular model. For a 3D triangular model of a survey site, which is typically composed of hundreds of thousand triangles, this method effectively removes measurement bias introduced in manual measurements since it is based on a large sample population. Optimization of the 3D polar density contour method also provided guidelines to determine if the triangular mesh element size was applicable for the site geology. The algorithms for the 3D polar density contour method are presented in Appendix C.

PCA analysis is an alternate method of making joint orientation measurements using 3D image data proposed in this thesis. This method measures the orientation for specific regions in the image directly from the point cloud without the need to generate a 3D triangular model. This method allows individual orientation measurements to be

made, immediately after an image is acquired. However, to fully assess the joint orientation, a number of measurements are required using this PCA method. In comparison, the 3D polar density contour method requires significantly more post-processing efforts but results in a comprehensive joint orientation analysis.

This thesis also presents a new method to measure surface roughness from 3D images based on the classical method of determining JRC on a graph of maximum asperity amplitude versus profile length. A 2D surface profile was generated from point cloud data and the maximum asperity amplitude was measured off a straight line joining local maxima. This method proved successful and was extended to study anisotropy. The current practice of measuring surface roughness is to perform manual measurements only along strike and dip, which introduces a bias in the data. The new polar anisotropy plots capture anisotropy in all azimuths and give a more complete representation of the situation.

For underground operations, a common support element is the wire mesh, which can partially occlude images of rock faces. This thesis features two new filters to remove the wire mesh from point cloud data. The baseline filter is partially based on the instrument noise, which was measured in-situ making an opportunistic use of the rockbolt faceplates as planar elements. The second derivative filter is based on the normalized amplitude data from PCA analysis.

6.2 Future work

Before 3D laser imaging becomes a widely accepted practice for rock mass characterization, more extensive testing is required. The analytical methods presented in this thesis should be used to analyze 3D image data acquired from a variety of geologies environments and survey sites. At the same time, the 3D image data should be acquired at different distances and incidence angles. Evaluating the analytical methods in this manner would test their robustness.

The performance of the 3D pole density contouring method should be further be evaluated. While this method is accurate, characterization of its precision is required. Error propagation from point cloud data, to triangular mesh model, to joint orientation analysis should be examined. Additional triangle discretization methods could also be explored. The relationship presented relating the triangle size to the shortest edge length of the joint face requires additional validation.

For surface roughness measurement, the error in the 2D surface profile should be evaluated and related to the instrument noise. The methodology should also be optimized to determine key parameters such as bin size. At the same time, 3D laser imaging presents an opportunity to develop a new standard to measure surface roughness based on 3D surface profiles rather than 2D surface profiles.

The research on wire mesh filtering could be expanded to test if the intensity data may be valuable for this purpose. At the same time, the wire mesh filter can be merged with other filters to remove undesirable objects from the field of view.

The RMR and Q system both contain additional parameters that can be characterized using 3D laser imaging. The Rock Quality Designation (RQD) is a parameter that can be evaluated from 3D laser images of core samples using 2D surface profiles in a similar manner to those generated for surface roughness measurements. The RQD measurements, however, may require the addition of the image intensity data to distinguish the fractures from the core fragments. Another parameter is the degree of joint infilling. Research could be conducted to automatically measure the distance between faces and the degree of infilling from 3D images. Finally, an important parameter is the presence of water. Water is known to decrease the precision of the instrument [20]. Research to detect the presence of water may consider the instrument noise and intensity data.

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Appendix A Rock mass characterization systems

The Rock Mass Rating system was developed for the purpose of support design. There are five parameters considered as well as an adjustment based on the discontinuity orientation. The following tables show the Rock Mass Rating classification parameters.

A. CLASSIFICATION PARAMETERS AND THEIR RATINGS

Parameter			Ranges of values						
1	Strength of intact rock material	Point-load strength index (MPa)	>10	4 - 10	2 - 4	1 - 2	For this low range, uniaxial compressive test is preferred		
		Uniaxial compressive strength (MPa)	>250	100 - 250	50 - 100	25 - 50	5 - 25	1 - 5	<1
		Rating	15	12	7	4	2	1	0
2	Drill core quality RQD (%)		90 - 100	75 - 90	50 - 75	25 - 50	<25		
		Rating	20	17	13	8	3		
3	Spacing of discontinuities		>2m	0.6 - 2m	200 - 600mm	60 - 200mm	<60mm		
		Rating	20	15	10	8	5		
4	Condition of discontinuities		Very rough surfaces Not continuous No separation Unweathered wall rock	Slightly rough surfaces Separation <1mm Slightly weathered wall rock	Slightly rough surfaces Separation <1mm Highly weathered wall rock	Slickensided surfaces or Gouge <5mm thick or Separation 1 - 5mm Continuous	Soft gouge >5mm thick or Separation >5mm Continuous		
		Rating	30	25	20	10	0		
5	Groundwater	Inflow per 10m tunnel length (l/min)	None	<10	10 - 25	25 - 125	>125		
		ratio (joint water pressure)/(major principal stress)	0	<0.1	0.1 - 0.2	0.2 - 0.5	>0.5		
		General conditions	Completely dry	Damp	Wet	Dripping	Flowing		
		Rating	15	10	7	4	0		

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B. GUIDELINES FOR CLASSIFICATION OF DISCONTINUITY CONDITIONS

Parameter	Ratings				
Discontinuity length (persistence)	<1m	1 - 3m	3 - 10m	10 - 20m	>20m
	6	4	2	1	0
Separation (aperture)	None	<0.1mm	0.1 - 1.0mm	1 - 5mm	>5mm
	6	5	4	1	0
Roughness	Very rough	Rough	Slightly rough	Smooth	Slickensided
	6	5	3	1	0
Infilling (gouge)	Hard filling			Soft filling	
	None	<5mm	>5mm	<5mm	>5mm
	6	4	2	2	0
Weathering	Unweathered	Slightly weathered	Moderately weathered	Highly weathered	Decomposed
	6	5	3	1	0

C. EFFECT OF DISCONTINUITY ORIENTATIONS IN TUNNELLING

Strike perpendicular to tunnel axis			
Drive with dip		Drive against dip	
Dip 45 - 90	Dip 20 - 45	Dip 45 - 90	Dip 20 - 45
Very favourable	Favourable	Fair	Unfavourable
Strike parallel to tunnel axis		Irrespective of strike	
Dip 20 - 45	Dip 45 - 90	Dip 0 - 20	
Fair	Very unfavourable	Fair	

D. RATING ADJUSTMENT FOR DISCONTINUITY ORIENTATIONS

Orientations of Discontinuities		Very Favourable	Favourable	Fair	Unfavourable	Very Unfavourable
Ratings	Tunnels & mines	0	-2	-5	-10	-12
	Foundations	0	-2	-7	-15	-25
	Slopes	0	-5	-25	-50	-60

E. ROCK MASS CLASSES DETERMINED FROM TOTAL RATINGS

Rating	100 - 81	80 - 61	60 - 41	40 - 21	<20
Class no.	I	II	III	IV	V
Description	Very good rock	Good rock	Fair rock	Poor rock	Very poor rock

F. MEANING OF ROCK MASS CLASSES

Class no.	I	II	III	IV	V
Average stand-up time	20yr for 15m span	1yr for 10m span	1wk for 5m span	10h for 2.5m span	30min for 1m span
Cohesion of rock mass (kPa)	>400	300 - 400	200 - 300	100 - 200	<100
Friction angle of rock mass (deg)	>45	35 - 45	25 - 35	15 - 25	<15

[58]

The Q system was developed by the Norwegian Geotechnical Institute. The equation for Q is the following:

$$Q = (RQD / J_n) * (J_r / J_a) * (J_w / SRF) \quad [4]$$

The following tables show the Rock Mass Rating classification parameters.

Rock Quality Designation, RQD	a: Very poor b: Poor c: Fair d: Good e: Excellent	RQD 0-25 25-50 50-75 75-90 90-100	Where RQD is reported or measured as 10 (including 0), a nominal value of 10 is used to evaluate Q RQD intervals of 5, i.e., 100, 95, 90, etc., are sufficiently accurate
Joint Set Number, J_n	a: Massive, none or few joints b: One joint set c: One joint set plus random d: Two joint sets e: Two joint sets plus random f: Three joint sets g: Three joint sets plus random h: Four or more joint sets, random, heavily jointed 'sugar cube', etc. j: Crushed rock, earthlike	J _n 0.5-1.0 2 3 4 6 9 12 15 20	For intersections, use (3.0 × J _n). For portals, use (2.0 × J _n)
Joint Roughness Number, J_r	(I) Rock wall contact and (II) Rock wall contact before 10cm shear a: Discontinuous joint b: Rough or irregular, undulating c: Smooth, undulating d: Slickensided, undulating e: Rough or irregular, planar f: Smooth, planar g: Slickensided, planar (III) No rock wall contact when sheared h: Zone containing clay minerals thick enough to prevent rock wall contact j: Sandy, gravelly, or crushed zone thick enough to prevent rock wall contact	J _r 4 3 2.0 1.5 1.5 1.0 0.5 1.0 1.0	Add 1.0 if the mean spacing of the relevant joint set is greater than 3m. J _r = 0.5 can be used for planar slickensided joints having lineation, provided the lineations are favourably orientated. Descriptions b to g refer to small-scale features and intermediate-scale features, in that order.
Joint Alteration Number, J_a	(I) Rock wall contact a: Tightly healed, hard, nonsoftening, impermeable filling, i.e., quartz or epidote b: Unaltered joint walls, surface staining only c: Slightly altered joint walls. Nonsoftening mineral coatings, sandy particles, clay-free disintegrated rock, etc. d: Silty or sandy clay coatings, small clay fraction (nonsoftening) e: Softening or low-friction clay mineral coatings, i.e., kaolinite, mica. Also chlorite, talc, gypsum, and graphite, etc., and small quantities of swelling clays (discontinuous coatings, 1-2mm or less in thickness) (II) Rock wall contact before 10cm shear f: Sandy particles, clay-free disintegrated rock, etc. g: Strongly over-consolidated, nonsoftening clay mineral fillings (continuous, <5mm in thickness) h: Medium or low over-consolidation, softening, clay mineral fillings (continuous, <5mm in thickness) j: Swelling clay fillings, i.e., montmorillonite (continuous, <5mm in thickness). Value of J _a depends on percentage of swelling clay-sized particles, and access to water, etc.	J _a 0.75 1.0 2.0 3.0 4.0 4.0 6.0 8.0 8.0-12.0	φ, (approx.) Values of φ, are intended as an approximate guide to the mineralogical properties of the alteration products, if present 25°-35° 25°-30° 20°-25° 8°-16° 25°-30° 16°-24° 12°-16° 6°-12°

[4]

Joint Alteration Number, J_a	<p>(iii) No rock wall contact when sheared</p> <p>k: Zones or bands of disintegrated or rock and clay (see g, h, j; for description of clay condition)</p> <p>l: Zones or bands of silty clay, small clay fraction (nonsoftening)</p> <p>m: Thick, continuous zones or bands of clay (see g, h, j; for description of clay condition)</p>	<p>6.0, 8.0 or 8.0-12.0</p> <p>5.0</p> <p>10.0, 13.0 or 13.0-20.0</p>	6°-24°
Strain Reduction Factor, SRF	<p>(i) Weakness zones intersecting excavation, which may cause loosening of rock mass when tunnel is excavated</p> <p>a: Multiple occurrences of weakness zones containing clay or chemically disintegrated rock, very loose surrounding rock (any depth)</p> <p>b: Single weakness zones containing clay or chemically disintegrated rock (excavation depth <50 m)</p> <p>c: Single weakness zones containing clay or chemically disintegrated rock (excavation depth >50 m)</p> <p>d: Multiple shear zones in competent rock (clay-free), loose surrounding rock (any depth)</p> <p>e: Single shear zones in competent rock (clay-free) (depth of excavation <50 m)</p> <p>f: Single shear zones in competent rock (clay-free) (depth of excavation >50 m)</p> <p>g: Loose open joints, heavily jointed or 'sugar cube', etc. (any depth)</p> <p>(ii) Competent rock, rock stress problems</p> <p>h: Low stress, near surface</p> <p>j: Medium stress</p> <p>k: High-stress, very tight structure (usually favourable to stability, may be unfavourable for wall stability)</p> <p>l: Mild rock burst (massive rock)</p> <p>m: Heavy rock burst (massive rock)</p> <p>(iii) Squeezing rock; plastic flow of incompetent rock under the influence of high rock pressures</p> <p>n: Mild squeezing rock pressure</p> <p>p: Heavy squeezing rock pressure</p> <p>(iv) Swelling rock; chemical swelling activity depending on presence of water</p> <p>q: Mild swelling rock pressure</p> <p>r: Heavy swelling rock pressure</p>	<p>SRF</p> <p>10.0</p> <p>5.0</p> <p>2.5</p> <p>7.5</p> <p>5.0</p> <p>2.5</p> <p>3.0</p> <p>2.5</p> <p>1.0</p> <p>0.5-2.0</p> <p>5-10</p> <p>10-20</p> <p>5-10</p> <p>10-20</p> <p>5-10</p> <p>10-15</p>	<p>Reduce these SRF values by 25-50% if the relevant shear zones only influence but do not intersect the excavation</p> <p>σ_3/σ_1 σ_2/σ_1</p> <p>>200 >13</p> <p>200-10 13-0.66</p> <p>10-5 0.66-0.33</p> <p>5-2.5 0.33-0.16</p> <p><2.5 <0.16</p> <p>Few case records available where depth of crown below surface is less than span width. Suggest SRF increase from 2.5 to 5 for such cases</p> <p>For strongly anisotropic stress field (if measured): when $5\sigma_3/\sigma_1 \leq 10$, reduce σ_3 and σ_2 to $0.8\sigma_1$ and $0.8\sigma_3$; when $\sigma_3/\sigma_1 > 10$, reduce σ_3 and σ_2 to $0.6\sigma_1$ and $0.6\sigma_3$ (where σ_3 = unconfined compressive strength, σ_1 = tensile strength (point load), σ_2 and σ_3 = major and minor principal stresses)</p>
Joint Water Reduction Factor, J_w	<p>a: Dry excavations or minor inflow, e.g. 5 l/min locally</p> <p>b: Medium inflow or pressure, occasional outwash of joint fillings</p> <p>c: Large inflow or high pressure in competent rock with unfilled joints</p> <p>d: Large inflow or high pressure, considerable outwash of joint fillings</p> <p>e: Exceptionally high inflow or water pressure at blasting, decaying with time</p> <p>f: Exceptionally high inflow or water pressure continuing without noticeable decay</p>	<p>J_w</p> <p>1.0</p> <p>0.66</p> <p>0.5</p> <p>0.33</p> <p>0.2-0.1</p> <p>0.1-0.05</p>	<p>Approx. water pressure (kg/cm²)</p> <p><1</p> <p>1.0-2.5</p> <p>2.5-10.0</p> <p>2.5-10.0</p> <p>>10.0</p> <p>>10.0</p> <p>Factors c to f are crude estimates. Increase J_w if drainage measures are installed</p> <p>Special problems caused by ice formation are not considered</p>

[4]

Appendix B Supporting documentation

Barton's JRC plot.

Article 2: Surface roughness measurements overlaid on Barton's JRC plot.

Modified from [3]

Article 2: Stereonet for manual joint orientation measurements

From 18 manual joint orientation measurements, the strike/dip of joint sets 1, 2, and 3 are 001/72, 145/81, and 198/24, respectively.

The strike/dip of joint sets 1, 2, and 3 are 011/52, 136/83, and 204/65, respectively.

Appendix C Algorithm descriptions

Article 1: 3D pole density contouring algorithm

The algorithm for article 1 analyzes the 3D triangular model exported from Polyworks in binary format. The primary output is a text file composed of strike and dip measurements that can be plotted using stereonet software. The source code is provided in the attached dvd.

Inputs:

1. Binary file (*.bin) of 3D triangular model (export from Polyworks)
2. Orientation file (*.txt) for laser scanner

Outputs:

1. Strike/dip text file (*.txt)

Article 2: Surface roughness algorithms

The algorithm for article 2 analyzes the point cloud data from an image. The algorithm (1) selects a region of interest, (2) measures the orientation using PCA analysis, and (3) measures the surface roughness along the strike, dip, or any azimuthal direction. The source code is provided in the attached dvd.

Inputs:

1. Input file (*.txt) with the following parameters:
 1. Input size
 2. Scan number
 3. Measurement number
 4. Scanner strike
 5. Scanner dip
 6. X-axis data
 7. Y-axis data
 8. Z-axis data
 9. Surface roughness: length of profile along strike
 10. Surface roughness: width of profile along strike
 11. Surface roughness: length of profile along dip
 12. Surface roughness: width of profile along dip
2. Scan file (*.txt) with the following parameters:
 1. X-axis data
 2. Y-axis data
 3. Z-axis data
 4. Intensity data

Outputs:

1. Text file (*.txt) with the following parameters:
 1. Measurement number
 2. Strike
 3. Dip
 4. Profile length
 5. Maximum asperity amplitude
 6. 2D surface profile

Article 3: Joint orientation, Surface roughness, Filter algorithms

The algorithm for article 3 analyzes the point cloud data from an image. The algorithm (1) selects a region of interest, (2) measures the orientation using PCA analysis, and (3) removes the wire mesh, and (4) measures the surface roughness along the strike, dip, or any azimuthal direction. The source code is provided in the attached dvd.

Inputs:

1. Input file (*.txt) with the following parameters:
 1. Input size
 2. Scan number
 3. Measurement number
 4. Scanner strike
 5. Scanner dip
 6. X-axis data
 7. Y-axis data
 8. Z-axis data
 9. Surface roughness: length of profile
 10. Surface roughness: width of profile
2. Scan file (*.txt) with the following parameters:
 1. X-axis data
 2. Y-axis data
 3. Z-axis data
 4. Intensity data

Outputs:

1. Text file (*.txt) with the following parameters:
 1. Measurement number
 2. Strike
 3. Dip
 4. Profile length
 5. Maximum asperity amplitude
 6. 2D surface profile
2. Updated point cloud with wire mesh removed