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The use of digital imaging and laser scanning technologies in rock engineering

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Abstract: Rock mass characterization is an integral part of rock engineering design. Much of the information for rock mass characterization comes from field fracture mapping and data collecting. This paper describes two technologies that can be used to assist with the field mapping and data collecting activities associated with rock mass characterization: digital image processing and 3D laserscanning. The basis for these techniques is described, as well as the results of field case studies and an analysis of the error in estimating fracture orientation.

1. Introduction

Rock engineering is involved in the design of tunnels, slopes, bridge and dam foundations, underground and surface mines, and other types of rock excavations. At the heart of designing structures in rocks is a thorough characterization of the rock mass prior to excavation. The results of rock mass characterization go on to be used in blast and excavation design, determination of support requirements, cost analyses, numerical modeling, and many other aspects of the design process. At a minimum, rock mass characterization usually involves borehole logging and sampling, laboratory testing, and field mapping and data collection. Due to access problems, safety concerns, and time and cost concerns, there are many uncertainties and inconsistencies associated with the field mapping and data collection aspects of rock characterization projects. For example, consider the widening of a highway that involves additional excavation along an existing rock slope. It is traditional to conduct cell mapping or scanline surveying to collect rock mass information, which involves making detailed measurements along the slope (Priest, 1993; Nicholas and Sims, 2001). Some information can be gathered from the base of the slope, but if the slope is high, the collection of data may involve repelling down the slope. This is a safety hazard as well as being time consuming and costly. As another example, in NATM tunneling through difficult and varying rock conditions, it is necessary to characterize the rock mass continually as the tunneling progresses in order to properly design the tunnel support. It is difficult with traditional methods to properly characterize the rock mass while at the same time doing it in a timely manner so that the tunneling can progress without delays. As a third example, consider a large open-pit mine. It would useful both for blast design and slope stability to be able to completely characterize the rock on all the exposed rock faces as mining progresses. This information could then be input into the mine database along with geology, grade, throughput, cost and other information. However, because of the large number of new rock faces that are created each week in a large mine, this is an unreachable goal using traditional field methods.

The examples given above illustrate some of the problems with traditional field methods associated with rock characterization. New technologies have the potential for greatly assisting with the field mapping and data collection activities associated with rock mass characterization. Digital image processing is one of these technologies. Digital image processing involves taking digital images in the field and processing these images to obtain various kinds of useful information (Russ, 1999). For instance, by taking digital images at various stages of a mine's comminution cycle (blasting, crushing, grinding) and delineating the rock fragments in the images, the size distribution of the rock fragments at these stages can be estimated (Kemeny et al., 2002). This information is useful to optimize the comminution processes, which are the most energy-intensive processes involved in mining. Figure 1a shows an example of an image of rock fragments, and Figure 1b illustrates the automatic delineation of the fragments in the image. Image processing systems for this purpose are now available commercially from many vendors (e.g., Split Engineering, 2003). Another application of image processing to rock engineering involves imaging exposed rock faces and processing these images to extract fracture information. This involves automatically delineating the fracture traces in the images and then characterizing the trace information. Fracture information that can be determined from the trace information includes fracture orientation, length, spacing, roughness, and other information (Kemeny and Post, 2003). An example of an image of a rock face along with the delineated traces is shown in Figures 2a and 2b, respectively.

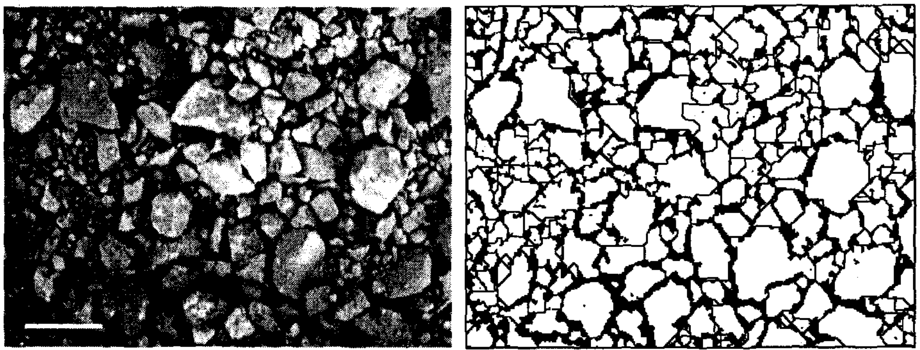

Figure 1. a) Image of primary crusher product. b) Automatic delineation of the fragments. Scale in the image is 6 inches.

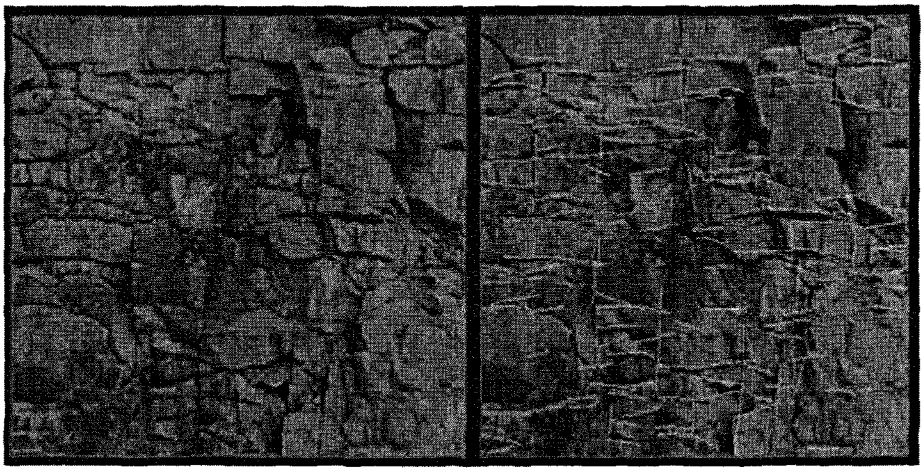

Figure 2. a) Digital image of a rock face. b) Automatic delineation of the fracture traces.

A second new technology that has a great potential to assist with the field activities associated with rock mass characterization involves the use of 3D laserscanners. As their name implies, 3D laserscanners work by taking a closely packed array of laser measurements of a 3D site of interest, in our case an exposed rock face. Current 3D laserscanners are capable of laser measurements spaced 2 mm apart or less, with an accuracy of less than 6 mm, at distances up to 1000 meters or more. A typical scan of a rock face with a million laser measurements takes less than 15 minutes. The array of x,y,z points from the laserscanner is called a point cloud. The point cloud contains valuable information about the fractures in the rock mass, including orientation, size and shape, spacing, and roughness. An example of a point cloud of a rock face is shown in Figure 3. Extracting the 3D fracture information from the point cloud can either be accomplished manually using hand-editing features in the point cloud software, or automatically utilizing automated software that is now being developed by several investigators (e.g., Slob et al., 2002).

The new technologies described above have obvious advantages over the existing manual techniques. First of all, both digital imaging and 3D laserscanning can be conducted from a distance, thus allowing information from the entire rock face to be collected without safety hazards. This also allows much larger databases of information to be acquired. Because data is both collected and processed utilizing automated equipment and software, problems associated with human bias are greatly reduced. Finally, the techniques have the potential for significant reductions in the time and cost associated with field mapping and data collecting.

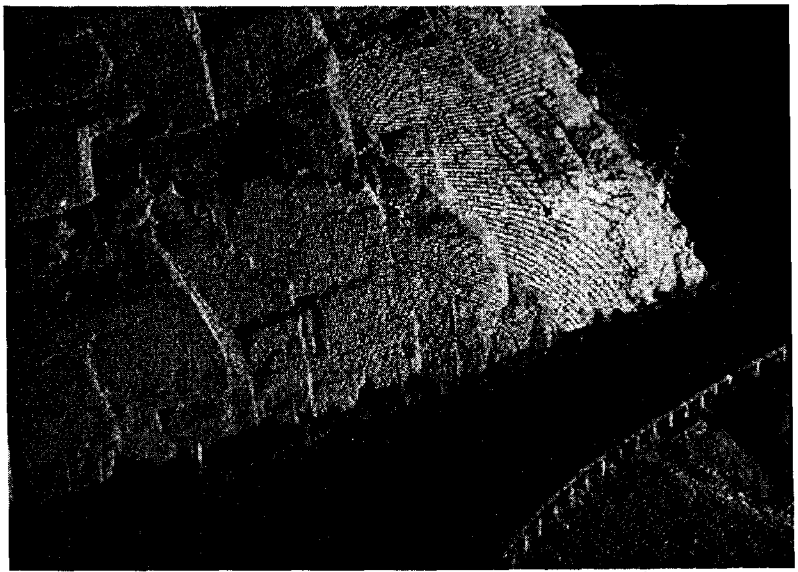

Figure 3. Point cloud of a road and a rock slope taken with a 3D laserscanner.

This paper describes progress that has been made on developing the new techniques for field data collection associated with rock mass characterization. In Section 2, progress on the digital imaging technique is described. In Section 3, progress on the 3D laserscanning technique is described. Conclusions and future work are described in Section 4.

2. Digital image processing techniques for rock mass characterization

Figure 2a is an example of a digital image of a rock face. Digital images of exposed rock faces, like the one shown in Figure 2a, contain an abundance of features that can be used to extract information related to rock mass characterization. First of all there are the presence of fracture traces in the image. Figure 2b shows the delineation of the traces in Figure 2a. If the fracture traces are separated by joint set, they can be processed to give information specific to each joint set, including distributions of fracture orientations, lengths, spacings, and roughnesses. Details of the mathematical and image processing algorithms involved in analyzing fracture traces are described in Kemeny and Post (2003) and Kemeny et al. (2003). If the fracture network is analyzed as a whole (i.e., the traces are not separated by joint set), then the network can be processed to given information on block size distribution. Another important piece of information related to the fracture network is the presence of rock bridges. A rock bridge is defined as a small bridge of rock separating parallel or non-parallel discontinuities. Rock bridges can be seen in digital images such as Figure 2a. The rock bridges play an important role in stabilizing the removal of rock blocks.

In addition to the presence of fracture traces, there are a number of other features in digital images of rock faces that provide rock characterization information. Texture, for example, can be used to give information on the weathering of the intact rock and the condition of the fractures. Standard texture operators are being used to correlate rock and rock fracture weathering with texture. Finally, color can be a used to extract additional rock characterization information. Fracture fill and the occurrence of different rock types can often be identified using color segmentation.

The information described above can also be combined to calculate a rock mass classification index. Popular rock mass classification schemes being used today include the Rock Mass Rating (RMR), the Mining Rock Mass Rating (MRMR), the Slope Mass Rating (SMR), and the Rock Quality Index (Q), among others (Hudson and Harrison, 2000). Here we introduce the Digital Rock Mass Rating (DRMR), which is a method for estimating the rock mass rating from digital images of rock faces. The DRMR utilizes most of the image information described in the previous paragraphs. In particular, the equation for DRMR utilizes 7 pieces of information automatically calculated from digital images:

DRMR = F1 + F2 + F3 + F4 + F5 + F6 + F7, where

- F1 is based on the number of joint sets
- F2 is based on the distribution of joint lengths
- F3 is based on the distribution of joint spacings
- F4 is based on the distribution of large scale roughnesses
- F5 is based on the rock block size distribution
- F6 is based on the rock bridge size distribution
- F7 is based on the rock texture classification

An additional factor based on joint orientation can be used to correct the DRMR for slopes and underground excavations. Additional details on the DRMR will be described in a separate paper.

3. 3D Laserscanning Techniques for Rock Mass Characterization

3D laserscanners are being used for a number of purposes, including civil and architectural design, surveying and modeling, scene reconstruction, volume calculations, and other applications. Their use in geoengineering is showing a rapid increase in popularity, with mining, geotech, civil and environmental applications. This paper focuses on the use of 3D laserscanners to extract fracture information for use in rock mass characterization. For this purpose, laserscanners are extremely easy to use, and they provide a detailed three-dimensional point cloud of the rock face, as shown in Figure 3.

Techniques are being developed by a number of researchers for automatically extracting fracture information from point clouds (Ahlgren et al., 2001; Slob et al., 2002). In general there are two methods being considered for point cloud fracture extraction, the 3D Hough transform and calculating surface normal vectors. Details of the use of the 3D Hough transform for the extraction of planar surfaces are described in Vosselman and Dijkman (2001). The primary disadvantage of this method is that it is computationally intensive and time consuming. The use of normal vectors is described in Slob et al. (2002). The primary disadvantage of this method involves the noisiness of the normals, especially in the case of surveys with a high density of laser points. The use of normal vectors involves first meshing the 3D surface using Delaunay triangulation or other methods (Slob et al., 2002). Normals are then calculated for each element of the meshed surface, followed by the grouping of similar normals that represent flat "patches". Some of these patches represent portions of fracture surfaces. Others will be erroneous and need to be removed. The orientation of the fracture patches is important, but the size and shape are not necessarily representative of the discontinuity as a whole. This is where the incorporation of information from the digital image is necessary, including fracture trace information and possibly color. The authors are currently developing algorithms for the extraction of fracture surfaces from point clouds using the normal vector technique described above. Additional details will be presented in a separate paper.

An important aspect of the use of 3D laserscanners for rock mass characterization is understanding the errors associated with 1) the instrument, 2) the procedures for scanning in the field, and 3) processing the resulting point clouds. First of all, there is a significant range in accuracies associated with different 3D laserscanners. A review of 14 3D laserscanners is given in Poboline (2003). In terms of scanning accuracy, there are three important parameters: distance accuracy, position accuracy and beam diameter. All three of these parameters vary with distance, so they are usually either stated for a given distance or a formula is given for their variation with distance. At a distance of about 50 meters, the stated distance and position accuracies vary from 4 to over 10 mm (±) between the 14 reviewed scanners. At a distance of about 30 meters, the beam diameters range from 3 mm to over 30 mm. Another important difference between scanners is the maximum range. The maximum range varies from 2 to 2000 meters between the 14 scanners. The actual maximum range for a particular scan depends of the reflectivity of the material being scanned. In general most rock faces can be scanned at distances over half the stated maximum range. A parameter that can be varied by the user when scanning is the scan resolution, which is the distance or angle between individual laser rays. The minimum scan increment varies from .001 to .07 degrees between the 14 scanners.

For extracting fracture information from point clouds, a key measure of accuracy is the error in the estimation of a fracture's strike and dip (or dip and dip direction). For a typical scan of a rock face, often over 1000 laser points will intersect large fracture surfaces, while less than 50 points may intersect smaller surfaces. It is important to understand how the number of laser points intersecting a fracture surface and the error of the laser impact the accuracy in the estimation of the strike and dip of the plane. For this purpose a computer model has been developed to determine the error in the calculation of strike and dip, based on a laserscanner with given distance and position accuracies and a fracture plane with a given size and distance from the scanner. Below we show results for a 1 m x 1 m fracture plane at a distance of 100 meters from the scanner with a dip of 62.581 degrees and dip direction of 26.565. For scanner accuracy, position and distance accuracies of ± 1.5 cm were used. This is a large error, and most 3D laserscanners are capable of scan accuracies less that this. Two cases were considered. In the first case 91 laser points intersected the plane, and in the second case only 11 laser points intersected the plane.

The program works by first calculating the exact intersections between the laser rays and the plane. x, y and z errors are then added to each intersection xyz, based on a uniform random number with bounds ± the laser accuracy. Figure 4 shows the distribution of radial error (i.e., the distance between the actual intersection point and the one with the xyz errors added) for the case of 91 laser points hitting the plane. It shows that most of the radial errors vary from 1.5 to 3 cm for this case. A least squares plane is then fit through the intersection points with the error, and the dip and dip direction of this plane is calculated and compared with the actual orientation. This process is repeated in a Monte Carlo fashion. Figures 5a and 5b show the distributions of dip and dip direction for 30 Monte Carlo simulations for the case of 91 laser points hitting the plane. It shows variations in dip of about ±0.18 degrees from the actual, and variations in dip direction of about ±0.1 degrees from the actual. Figures 6a and 6b show the distributions of dip and dip direction for 30 Monte Carlo simulations for the case of only 11 laser points hitting the plane. It shows variations in dip of about ±0.5 degrees from the actual, and variations in dip direction of about ±0.35 degrees from the actual. Overall these results are very promising and indicate that errors in the strike and dip less than 0.5 degrees should be able to be attained with fractures containing as little as 20 laser intersections and using almost any of the laserscanners available today. It should be noted that the model does not consider some important sources of possible error, including atmospheric and temperature errors. It also does not include the error associated with spatially orienting the point cloud, which is discussed below.

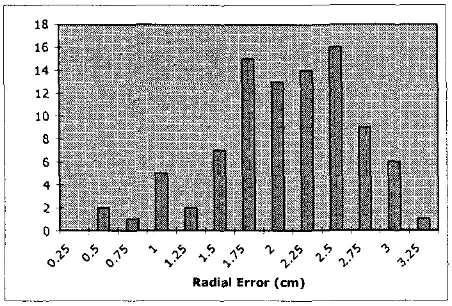

Figure 4. Distribution of radial error for a simulation of 91 laser points hitting a fracture plane with a scan accuracy of ±1.5 cm.

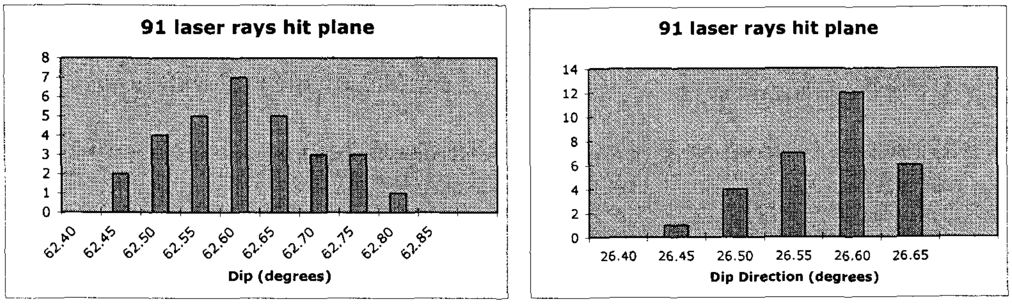

Figure 5. Distributions of dip and dip direction from 30 Monte Carlo simulations, where 91 laser rays hit the fracture plane and using a scan accuracy of ±1.5 cm.

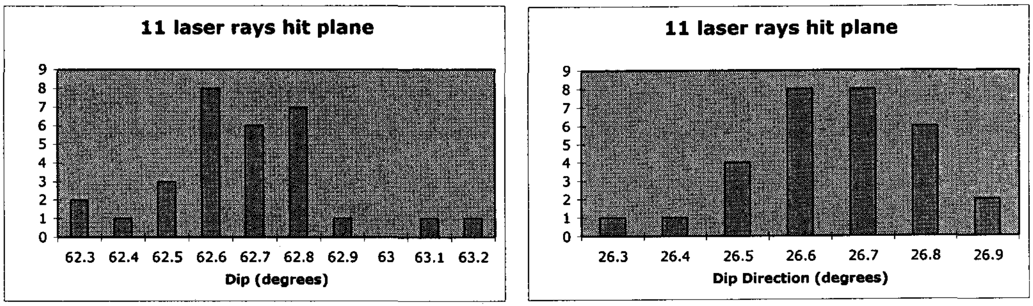

Figure 6. Distributions of dip and dip direction from 30 Monte Carlo simulations, where 11 laser rays hit the fracture plane and using a scan accuracy of ±1.5 cm.

One of the most important steps in processing the point cloud is reorienting the point cloud to the real world coordinate system. This is typically done by placing targets in the images and using standard surveying equipment such as a total station or laser rangefinder. There are several problems associated with this technique. First of all, this can be a costly and time consuming step, especially if scanning surveys are conducted in remote areas. Secondly, there could be safety hazards associated with putting targets on the rock faces. To alleviate some of these problems, an alternative method has been developed. For the purpose of fracture characterization, the point cloud needs to be oriented correctly, but not necessarily positioned correctly. For such cases, a technique has been developed where the orientation of a flat object in the image is measured accurately using a compass. The flat object can either be a natural object already in the image, or a non-natural object can be placed in the image. The placed object does not have to be on the rock face being scanned. The accuracy of this technique should be as good as the accuracy in measuring the orientation of the flat object with a compass, about ±1 degrees. A test using this technique was conducted on the University of Arizona campus. A flat rock surface was scanned from several orientations and distances. In each scan, a flat object with known orientation was placed in a position so that it would be part of the point cloud. Figure 7 shows the results of this test on a lower hemisphere stereonet. It shows the actual orientation of the object as well as the results from the scans. The scanned results are within 2-4 degrees from the actual orientation. This is higher than expected, but could be do to the fact that both the measurement of orientation of the flat surface and the control measurement of orientation of the rock fracture each has an error of about ±1 degrees. Additional tests using this technique are being conducted to see if the error can be reduced.

4. Conclusions

This paper describes two new technologies that are being developed to assist with the field mapping and data collection activities associated with rock mass characterization. The first technology, digital image processing, involves first taking digital images of rock faces. The fracture traces are then automatically delineated, from which information on fracture orientation, length, spacing and roughness can be extracted. Rock weathering and joint condition information can also be extracted from digital images using texture operators. Finally, the Digital Rock Mass Rating (DRMR) can be determined by combining the information described above. The second technology involves first scanning a rock face using a 3D laserscanner. The resulting array of millions of individual distance measurements is called a point cloud. The fracture information from the point cloud is extracted automatically using algorithms that are being developed. Computer models and experiments have shown that the orientation of individual fractures in the point cloud can be determined within a few degrees of their actual orientation.

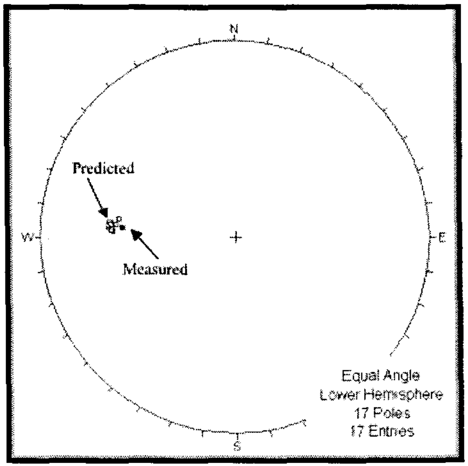

Figure 7. A comparison between the actual orientation of a rock face, and numerous measurements using a 3D laserscanner positioned at different angles and distances from the face. The point cloud was oriented using a technique where a flat object of known orientation was placed in the scan.

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