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Research paper

A new method for automated discontinuity trace mapping on rock mass 3D surface model

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ABSTRACT

This paper presents an automated discontinuity trace mapping method on a 3D surface model of rock mass. Feature points of discontinuity traces are first detected using the Normal Tensor Voting Theory, which is robust to noisy point cloud data. Discontinuity traces are then extracted from feature points in four steps: (1) trace feature point grouping, (2) trace segment growth, (3) trace segment connection, and (4) redundant trace segment removal. A sensitivity analysis is conducted to identify optimal values for the parameters used in the proposed method. The optimal triangular mesh element size is between 5 cm and 6 cm; the angle threshold in the trace segment growth step is between 70° and 90°; the angle threshold in the trace segment connection step is between 50° and 70°, and the distance threshold should be at least 15 times the mean triangular mesh element size. The method is applied to the excavation face trace mapping of a drill-and-blast tunnel. The results show that the proposed discontinuity trace mapping method is fast and effective and could be used as a supplement to traditional direct measurement of discontinuity traces.

1. Introduction

Discontinuity trace mapping is one of the fundamental tasks for rock mass characterization. Fracture size information (e.g., fracture trace length distribution and discontinuity diameter distribution) is often estimated from trace length measurements (Kulatilake and Wu, 1984; Mauldon, 1998; Zhang and Einstein, 1998, 2000; Li et al., 2014; Zhu et al., 2014). Information on discontinuities has traditionally been difficult, slow, and often dangerous to obtain by direct measurement using a tape and geological compass (Barton et al., 1974; Franklin et al., 1988). Currently, non-contact measuring techniques, such as photogrammetry and Light Detection and Ranging (LIDAR), provide alternative approaches to in situ measurement and allow discontinuities to be measured from photographs and 3D point clouds of rock mass exposures. These non-contact measuring techniques tremendously improve conventional geologic mapping due to the ability to take measurements without direct access to the rock mass and time restrictions, as well as to provide objective records of rock masses.

The two-dimensional image processing method has been used to extract discontinuity traces according to changes of pixel intensities (Crosta, 1997; Reid and Harrison, 2000; Hadjigeorgiou et al., 2003; Lemy and Hadjigeorgiou, 2003). However, the image processing method shows strong dependence on rock textures, illumination conditions, and threshold settings, often resulting in meaningless segments or excessive fragmentation (Ferrero et al., 2009). In addition, the use of the general-purpose image processing method has tended to show two other shortcomings: simultaneous highlighting of shadows and surface markings on the intact rock, and images acquired through uncalibrated cameras suffer from projective distortion and lens distortion that are difficult to rectify.

In recent years, many researchers have been working on the extraction of discontinuity traces from 3D surface models (Roncella et al., 2005; Gigli and Casagli, 2011), i.e., high-resolution 3D point clouds of rock mass surfaces. The photogrammetry technique is capable of obtaining 3D point clouds from pairs of 2D images. LiDAR technology is another solution to obtaining 3D point clouds. The pros and cons of both techniques have been discussed by many authors (Roncella et al., 2005; Potsch et al., 2005). Two main methods can be used to detect traces using a 3D surface model. First, discontinuity traces can be obtained as intersection lines between the fitting planes of rock mass surfaces (Slob et al., 2007; Otoo et al., 2011; Gigli and Casagli, 2011). However, the result is highly dependent on the accuracy of the fitting planes, which is further dependent on the segmentation accuracy of the rock mass surface. Second, traces can be detected based on the principal curvatures of the vertices on the digital surface model (DSM) of the rock mass (Umili et al., 2013).

Automated discontinuity trace mapping is an emerging method because discontinuity surfaces are irregular in shape, occur at any

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orientation, and contain variable amounts of small-scale roughness and large scale undulation (Vöge et al., 2013). This study is motivated by the following difficulties in automated discontinuity trace mapping: (1) feature point detection from 3D point clouds is noise sensitive (feature points are the vertices at the intersections of rock mass surfaces); (2) automated trace detection is prone interruption by uneven rock mass surfaces, resulting in fragmented discontinuity traces; (3) an automated identification process is difficult to achieve because of speculative selection of threshold values (Umili et al., 2013). This paper develops a robust and automated trace mapping method to extract discontinuity traces from the 3D surface model of natural outcrops or tunnel excavation faces. First, the Normal Tensor Voting Theory (Page et al., 2002) is utilized to reduce the interference of noisy data in trace feature point detection. Second, post-processing techniques are proposed to overcome the segmentation of extracted traces and to achieve smooth and continuous traces. Finally, the trace mapping process is streamlined without human intervention and is insensitive to the chosen thresholds.

This paper is organized as follows: an automated discontinuity trace mapping method is introduced in Section 2, sensitivity of the method is analyzed in Section 3, the method is then applied to trace mapping of a tunnel face under construction in Section 4, the application of the method is discussed in Section 5 and some conclusions are drawn in Section 6.

2. Methodology

The method for discontinuity trace mapping is divided into five steps: (1) trace feature point detection: vertices of the traces are identified and labeled as feature points; (2) trace feature point grouping: adjacent feature points are grouped for further processing; (3) trace segment growth: trace segments composed of a continuous chain of feature points are generated using a growth algorithm; (4) trace segment connection: segments that belong to a trace are connected; (5) redundant trace segment removal: feature points that do not lie in the main direction of the traces are removed to improve the quality of trace lines. The flow chart of the method is illustrated in Fig. 1.

2.1. Description of the datasets

Two 3D point cloud datasets are used in our study: the publicly available LiDAR data of a rock cut and the DSM of a rock tunnel excavation face. The first is used to make a comparison with previous studies and the second is for field application.

2.1.1. Case study A

Case study A uses LiDAR data at the Rockbench open repository (Vöge et al., 2013). The complete 3D RAW data is available from www.3d-landslide.com/projects/discontinuity/ (Riquelme et al., 2014). The case is a rock cut located in Ouray, Colorado, USA (Fig. 2). This point cloud has 1,515,722 points and the resolution of the point is approximately 2 cm. The scanning took about 15 min using an Optech Ilris3D scanner.

2.1.2. Case study B

Case study B is a highway rock tunnel situated in Yuexi County, Anhui Province, China. The tunnel was excavated using the drill and blast method. The total length of the tunnel is 7.548 km, and the lithology along the tunnel is primarily granite and gneiss. The 3D point cloud data were obtained using overlapping photographs (Roncella et al., 2005; Haneberg, 2008; Sturzenegger and Stead, 2009) to create 3D surfaces. Examples of commercial photogrammetry software for geological mapping include Sirovision, ShapeMetrix3D, 3DM Analyst, and Agisoft Photoscan. Fig. 3 (a) shows a picture of the tunnel excavation face and Fig. 3 (b) shows the reconstructed 3D point cloud with color after binocular 3D reconstruction.

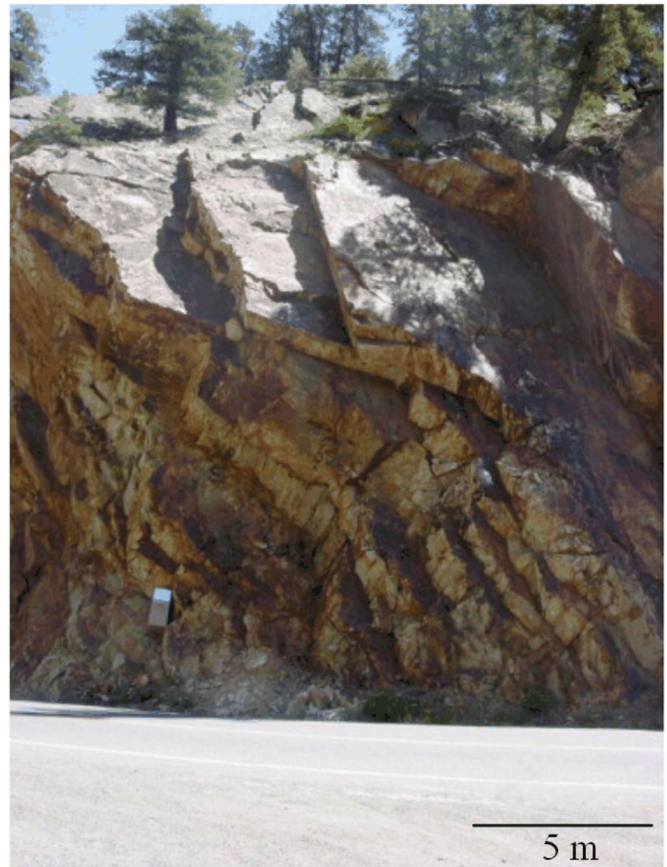

Fig. 2. Image of a road cut slope from the Rockbench repository.

2.2. Automated trace mapping method

2.2.1. Preprocessing of the dataset

The raw data that contain vegetation, unnecessary and sparse points will affect the precision of trace detection and also increase processing time. The first step is to remove these points to focus on the region of interest. As shown in Fig. 4, some holes (marked using red circles) are caused by the presence of vegetation and occlusions. In addition, the point cloud is noisy because of instrument errors, dust and dynamic disturbances in the open field (Slob, 2008). Therefore, the preprocessing of the point cloud is performed in the following steps: vegetation removal, point cloud resampling, noise reduction and triangulation.

First, the point cloud is resampled with a minimum distance of 3 cm to preserve rock mass geometry features and improve

Fig. 1. Flow chart of the proposed discontinuity trace mapping method.