Computers & Geosciences 68 (2014) 38–52

Contents lists available at ScienceDirect

Computers & Geosciences

journal homepage: www.elsevier.com/locate/cageo

A new approach for semi-automatic rock mass joints recognition from 3D point clouds

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ARTICLE INFO

Article history:
Received 12 October 2013
Received in revised form
19 March 2014
Accepted 20 March 2014
Available online 4 April 2014

Keywords:
LiDAR
Rock mass
Discontinuities
Semi-automatic detection
3D point cloud
Sensitivity analysis

ABSTRACT

Rock mass characterization requires a deep geometric understanding of the discontinuity sets affecting rock exposures. Recent advances in Light Detection and Ranging (LiDAR) instrumentation currently allow quick and accurate 3D data acquisition, yielding on the development of new methodologies for the automatic characterization of rock mass discontinuities. This paper presents a methodology for the identification and analysis of flat surfaces outcropping in a rocky slope using the 3D data obtained with LiDAR. This method identifies and defines the algebraic equations of the different planes of the rock slope surface by applying an analysis based on a neighbouring points coplanarity test, finding principal orientations by Kernel Density Estimation and identifying clusters by the Density-Based Scan Algorithm with Noise. Different sources of information – synthetic and 3D scanned data – were employed, performing a complete sensitivity analysis of the parameters in order to identify the optimal value of the variables of the proposed method. In addition, raw source files and obtained results are freely provided in order to allow to a more straightforward method comparison aiming to a more reproducible research.

1. Introduction

Remote sensors such as Light Detection and Ranging (LiDAR) and Differential SAR Interferometry (DInSAR) have become an essential tool for the landslide analysis over the last decade (Abellán et al., 2014; Jaboyedoff et al., 2012; Oppikofer et al., 2009; Rosser et al., 2005; Viero et al., 2010). LiDAR sensors, also known as laser scanners, allow the acquisition of high resolution (density of points up to 10^4 point/m^2) and high accuracy (std. dev. <1 cm at 100 m) three-dimensional information of the ground surface. Such systems allow obtaining the coordinates (X, Y, and Z) of the points of a surface at high speed (more than 222.000 measurements per second) from a considerable distance of acquisition (up to 6.000 m). This sensor has revolutionized the acquisition of rock slope parameters that play a key role in the global and local stability including the orientation, spacing, persistence and roughness of discontinuities. Not surprisingly, the number of publications dealing with the semi-automatic extraction of 3D features has exponentially grown in the last 5 years (García-Sellés et al., 2011; Gigli and Casagli, 2011; Jaboyedoff et al., 2007; Khoshelham et al., 2011; Lato et al., 2009; Lato et al., 2010; Lato and Voge, 2012; Olariu et al., 2008; Slob et al., 2005; Sturzenegger and Stead, 2009b; Sturzenegger et al., 2011). Nevertheless, in order to enable fast advancement in the application of the sensor in disciplines such as rock mechanics, geotechnics and earth sciences, development of new algorithms is needed (Abellán et al., 2014).

This paper proposes a new approach for the semi-automatic identification and extraction of rock slope planar features – i.e. the discontinuity sets affecting rock mass stability – using 3D point cloud data. The main novel contributions of the proposed method are: (a) the user-supervised removal of noisy points through the creation of a coplanarity test; (b) the semi-automatic identification of discontinuity sets using a Kernel Density Estimation (KDE) Analysis; (c) the automatic extraction of single discontinuities through a density-based clustering algorithm; (d) a complete sensitivity analysis of the parameters playing a key role in the method; and (e) the public availability of the complete 3D RAW and processed data sets used in this publication in order to provide method validation for other researchers in www.3d-landslide.com/projects/discontinuity/.

1.1. Previous studies on discontinuity characterization from 3D point clouds

Rock slope discontinuities play a key role in strength, permeability of rock masses and in the stability of surface and underground excavations (Harrison and Hudson, 2000; Hoek and Bray, 1981). Thus, a thorough understanding of the properties of

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http://dx.doi.org/10.1016/j.cageo.2014.03.014
0098-3004/

discontinuities, included their orientation (i.e. dip and dip direction) is crucial in rock engineering applications.

In order to assess the global quality of a rock mass, several authors proposed the use of geomechanical classifications more than 20 years ago. Rock mass classifications are means for the evaluation of the performance of rock masses based on their most important inherent and structural parameters (Pantelidis, 2009). In practice, a wide number of geomechanical classifications for slopes exist such as those proposed by Bieniawski (1989), Romana (1985), Hack et al. (2003) and Tomás et al. (2007). These classifications require precise information of a series of slope parameters – such as discontinuities orientation, which are classically obtained in tedious fieldwork campaigns using a geological compass. Some well-known techniques, such as the stereo photogrammetry, have allowed the measurement of orientations of individual discontinuities since the 1970s' (Rengers, 1967). In addition, basic photogrammetry principles and pattern recognition routines can be used to model surfaces in 3D, which can be very useful in the rock mechanics field. Unfortunately, these techniques require tedious and time consuming outlining of discontinuities (Slob et al., 2005).

At the beginning of the XXI century, some authors suggested the possibility of accurately obtaining discontinuity orientation from 3D point clouds obtained by a total station (Feng et al., 2001). Since then, and thanks to the wide accessibility of 3D sensors like LiDAR, different approaches were developed for obtaining the orientations of discontinuities. Early studies proposed the use of least square method to a subset of points (Abellán et al., 2006; Fernández, 2005; Sturzenegger and Stead, 2009a). Some other authors proposed the calculation of normal vectors to a series of 2.5D interpolated surfaces (Kemeny et al., 2006a; Slob and Hack, 2004). Recently, the calculation of the normal vector associated to a subset of the 3D point cloud is widely accepted (Ferrero et al., 2009; García-Sellés et al., 2011; Gigli and Casagli, 2011; Jaboyedoff et al., 2007). More specifically, Jaboyedoff et al. (2007) proposed the calculation of the normal vector orientation for every point and its coplanar neighbours using the principal component analysis method (hereinafter PCA). This concept is also used to isolate multi-scale objects from LiDAR data (Ioannou, 2012). Other approaches calculate the orientation for each node in the TIN (Slob et al., 2005; Voge et al., 2013) or are based on the searching of volumetric pixels (voxels) and subsequent calculation of the planar orientation (Gigli and Casagli, 2011). Remarkably, any of the above mentioned studies utilize kernels for the estimation of the density function, meaning that those points belonging to less sampled discontinuity sets can potentially be overlooked using commonly used methods.

Most of the current discontinuity detection methods use triangulated irregular network (TIN) to simplify the surface (Gigli and Casagli, 2011; Lato et al., 2009; Slob et al., 2007). Conversely, our proposal uses real 3D information contained in every point and its corresponding neighbours to see the local differences in the geometry of the slope.

Some authors offer commercial software packages, such as Split-FX (Slob et al., 2005) and Coltop-3D (Jaboyedoff et al., 2007). Some recent studies include the use of a Graphic User Interface (GUI) in Matlab environment such as the recently developed DiAna (Gigli and Casagli, 2011) or PlaneDetect (Voge et al., 2013), but the use of these software is not publicly available. Other applications for the geomechanical classifications include: (a) the automatic detection of discontinuity spacing (Slob and Hack, 2004; Slob et al., 2005), which is based on the cluster analysis of sets of discontinuities (Roncella and Forlani, 2005; Turner et al., 2006); (b) the removal of objects characterized by chaotic shapes – such as vegetation – together with the calculation of other parameters of the geomechanical classifications – such as spacing/frequency and persistence – which can also be (potentially) achieved using tools such as 3D-Veros (Brodu and Lague, 2012) and DiAna (Gigli and Casagli, 2011). Unfortunately, only a limited number of benchmarks is publicly available – such as the Rockbech common repository described in Lato et al. (2013), so there is a need for a comparative performance analysis of the existing algorithms mentioned in this manuscript.

The paper is organized as follows: (a) an introduction to LiDAR techniques and their application to discontinuity extraction is presented in Section 1; (b) the methodology for discontinuity extraction and the presentation of the case studies used in this paper are presented in Section 2; (c) Section 3 shows a sensitivity analysis of the method using simple geometries (case study A); Section 4 shows the application of our method to a more complex scenario (road cut slope, case study B). In addition, the methods' parameters are calibrated and then their processing parameters values are proposed. Finally, Section 5 discusses and summarizes the results and explores the future lines of research.

2. Methodology

The proposed method aims to detect structural discontinuities using 3D point clouds than can be typically obtained from LiDAR sensors, 3D digitizers, etc. Unlike other methodologies, our proposal uses, throughout the workflow, the “true” 3D information contained on the LiDAR point cloud, instead of using interpolated 2.5D mesh surface. Given the set of raw data points (X, Y, and Z) from the observed scene (hereinafter ‘P’), if the slope surface is mostly defined by discontinuities, the outcrop points can be appropriately ordered into sets which define planes. These planes define the discontinuity sets.

The method basically performs a compass data acquisition for each point, but only if it is surrounded by other coplanar points. Therefore, there is an obvious advantage: it is possible to obtain millions of virtual compass measurements in a few minutes, even in otherwise non-accessible areas.

The proposed methodology is developed through three main steps (Fig. 1):

a) PART A – Local curvature calculation: this consists of a nearest neighbour search and the determination of the discontinuity orientation in every point. This task is described in Section 2.2.
b) PART B – Statistical analysis of the planes: this consists of the determination of the principal orientations, which represent the different discontinuities sets that affect to the rock mass. The next step is the identification of those points that belong to a common discontinuity set. This part, developed in Section 2.3, requires the user's supervision.
c) PART C – Cluster analysis: localization of the points that define different clusters in the space and calculation of the outcrop plane equations. This last part is explained in Section 2.4.

2.1. Description of the datasets

Two different series of 3D datasets were used in our study: experimental datasets and real outcrop measurements. The first was obtained under controlled laboratory conditions and the second one is a more complex dataset corresponding to a portion of a real rock mass. We discarded using synthetic datasets due to their over-simplistic characteristics.

2.1.1. Case study A

We first scanned a series of well- known geometrical solid objects using a 3D digitizer (Konica Minolta, *Vivid* 9i) from University of Lausanne, Switzerland, including a cube, dodecahedron, icosahedron, octahedron, hexagonal pyramid, hexagonal prism, octagonal prism and a triangular prism. Data acquisition was performed through