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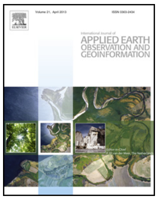

Image-based correlation of Laser Scanning point cloud time series for landslide monitoring

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ABSTRACT

Very high resolution monitoring of landslide kinematics is an important aspect for a physical understanding of the failure mechanisms and for quantifying the associated hazard. In the last decade, the potential of Terrestrial Laser Scanning (TLS) to monitor slow-moving landslides has been largely demonstrated but accurate processing methods are still needed to extract useful information available in point cloud time series. This work presents an approach to measure the 3D deformation and displacement patterns from repeated TLS surveys. The method is based on the simplification of a 3D matching problem in a 2D matching problem by using a 2D statistical normalized cross-correlation function. The computed displacement amplitudes are compared to displacements (1) calculated with the classical approach of Iterative Closest Point and (2) measured from repeated dGPS observations. The performance of the method is tested on a 3 years dataset acquired at the Super-Sauze landslide (South French Alps). The observed landslide displacements are heterogeneous in time and space. Within the landslide, sub-areas presenting different deformation patterns (extension, compression) are detected by a strain analysis. It is demonstrated that pore water pressure changes within the landslide is the main controlling factor of the kinematics.

1. Introduction

Slope monitoring techniques have made a lot of progress in the last decade, especially in the field of ground-based remote sensing platforms (e.g. Ground-Based Synthetic Aperture Radar Interferometry – GB-InSAR, Terrestrial Laser Scanning – TLS, Terrestrial Optical Photogrammetry – TOP). These techniques allow to discriminate stable and unstable slope portions from safe and remote places and to map sectors with different kinematics within a landslide body (Delacourt et al., 2007). These instruments provide the necessary information to analyze quantitatively the slope kinematics (e.g. displacement and deformation fields) and propose a geomechanical understanding of the failure mechanisms (Casson et al., 2005; Teza et al., 2008; Oppikofer et al., 2008). This work focuses on the use of repeated Terrestrial Laser Scanning (TLS) surveys. This type of instrument is currently used in a large variety of applications in earth and environmental sciences, and among them for landslide analysis as underlined by the considerable increase in the number of publications in the last years (Slob and Hack, 2004; Sturzenegger and Stead, 2009; Jaboyedoff et al., 2012). TLS instruments allow a fast (typically thousands of points per seconds), distributed, high resolution (millimetric to centimetric) and dense (several millions) acquisition of 3D information of the terrain through point cloud of 3D point locations and near-infrared reflectance intensity (e.g. X, Y, Z, I).

The instruments typically use 'time-of-flight' (also known as 'pulse-based'), 'phase-based' or 'waveform processing' technology to determine the distance to the targets. The differences in laser light wavelengths, amount and velocity of point data collection, field acquisition procedures, data processing and possible error sources are detailed in Hiremagalur et al. (2007) and in Vosselman and Maas (2010).

Time-of-flight scanners are the most common type of instruments used in geophysical applications because of their longer distance range (typically 100–800 m) and their possible high acquisition frequency. They combine a pulsed laser emitting the beam, a mirror deflecting the beam toward the scanned area and an optical receiver subsystem which detects the laser pulse reflected from the object. Since the speed of light is known, the travel time of the laser pulse can be converted to a precise distance measurement (Vosselman and Maas, 2010). The precision of the technique is mainly affected by instrumental errors (mirror orientation inside

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the scanner), pulse flight-time measurement, laser beam divergence (Petrie and Toth, 2008), point density variations due to surface multiple reflections (Abellán et al., 2009; Hodge et al., 2009) and co-registration of the point clouds (Schürch et al., 2011). The precision is quantified by the standard deviation of each point measurement of typically a centimetric accuracy at a distance range of 100 m (Lichti and Jamtsho, 2006). Taking into account the high spatial density of TLS point clouds, the accuracy of point clouds is higher than the accuracy of single data point measurements (Lindenberg and Pfeifer, 2005).

The usefulness of TLS surveys for the monitoring of geomorphologic processes has been demonstrated in the last years, mainly for defining the structure of rocky slopes susceptible to rockfalls and rockslides (Abellán et al., 2009; Oppikofer et al., 2009; Sturzenegger and Stead, 2009; Kasperski et al., 2010) or for characterizing the dynamics of slow-moving (typically a few centimeters to a few meters per year) slope processes such as ice glaciers (Bauer et al., 2003; Schwalbe et al., 2008; Avian et al., 2009) and landslides (Teza et al., 2007; Prokop and Panholzer, 2009; Travelletti et al., 2008; Aryal et al., 2012). Different techniques exist to analyze the space–time evolution and can be broadly classified in five categories.

Category 1 consists in the analysis of differential Digital Terrain Models (DTMs) and is the most commonly used processing technique to compare different surveys. It is used to quantify accumulation or loss of material (Bitelli et al., 2004; Prokop and Panholzer, 2009; Kasperski et al., 2010; Schürch et al., 2011). This method is not fully adapted for landslide kinematic analysis since it provides only information on changes in the vertical component. Furthermore the interpolation in the horizontal (*X*–*Y*) plane implies a significant loss of information initially contained in the original point clouds if the gridded mesh size is coarse.

Category 2 consists in the analysis of point pairs in consecutive point clouds (Oppikofer et al., 2009), and in the calculation of displacement vectors of selected objects. This technique has important limitations as it is very difficult to track exactly the same point in consecutive point clouds. Therefore its precision strongly depends on the point clouds resolution, on the deformation pattern of the tracked objects (rigid, elastic or plastic). Further, this method does not exploit all the geometric information contained in the point clouds, and can represent a fastidious processing task for very large datasets.

Category 3 consists in the analysis of point clouds with shortest distance methods (e.g. for instance the Hausdorff metric) to estimate the differences between two surfaces in every direction (Besl and McKay, 1992; Chen and Medioni, 1992; Oppikofer et al., 2009; Vosselman and Maas, 2010). If average displacement vectors of the landslide are known, the algorithm can be constrained to identify points located in the sliding direction and provide a rough estimation of the magnitude of the displacements (Travelletti et al., 2008). However, the reliability of the computed displacements strongly depends on the slope topography relative to the sliding direction. Therefore this method remains rather qualitative.

Category 4 consists in the analysis of point clouds with the Iterative Closest Point (ICP) and Least Squares 3D Surface Matching methods (LSSM). The ICP (Besl and McKay, 1992) and LSSM (Gruen and Akca, 2005) methods are among the most efficient algorithms for the automatic characterization of 3D displacement fields. Their application to landslide monitoring has been demonstrated by Teza et al. (2008) and Monserrat and Crosetto (2008). Teza et al. (2007) presented an automatic calculation method using an ICP-based piecewise alignment method. The method calculates the roto-translational matrix describing the displacement and the rotation of an object considering a high amount of points. The accuracy of the displacement measure is limited by the presence of shadow zones (unscanned areas) and vegetation or important soil deformation. Because this method uses an iterative procedure to identify the optimal rotation and translational components, it can be relatively time consuming without necessarily any convergence in the calculation.

Finally, category 5 consists in the analysis of high resolution DTMs (computed from the original point clouds) using cross-correlation functions. This method, commonly applied for the analysis of time series of laboratory or field optical images (White et al., 2003) is still poorly exploited to monitor continuously active slope processes (Corripio, 2004; Travelletti et al., 2012). The first application in the literature was proposed by Duffy et al. (2004), who quantified the migration of submarine sand dunes by applying a 2D cross correlation on sun-illuminated values computed on a DTM. The elevation data were measured with a multibeam echo sounder. Because the computed displacement field was shown to be dependent on the azimuth of the virtual sun, slope values of the topography were finally correlated instead of the sun-illuminated values. Duffy and Hughes-Clarke (2005) found that displacement rates computed from the slope values are more robust since there is no extra parameter in the slope calculation. A second application was proposed by Schwalbe et al. (2008) who monitored glacier movements; they developed a method in which the point clouds are projected in a regular horizontal (*X*–*Y*) grid. First raster images are defined in such a way that each pixel containing a TLS point is filled with a gray intensity value depending on the relative elevation of the point; then, a 2D cross-correlation function is used to track features between two acquisitions. The morphological structures of the glacier (represented by pixels of different gray intensity values) are iteratively dilated to favor confidence to the pixels containing many TLS information for the correlation procedure. This complex iterative procedure allows minimizing the influence of shadow zones in the correlation computation and improved the determination of the velocity field. A third application is proposed by Aryal et al. (2012) for the analysis of the displacement pattern of the Cleveland Corral landslide; the authors correlated a series of DTMs interpolated from the original point clouds in which the relative elevation values (*Z*) are computed in the horizontal (*X*–*Y*) plane. The authors highlighted the development of lateral shear zones and of a non-rigid behavior of the landslide. This approach allows a continuous spatial estimation of the displacement but is limited to still relatively low displacement rates as it is necessary to preserve a relative similar aspect of the DEMs at the different dates.

The objective of this work is to propose a method to measure the 3D displacement field and to estimate the deformation pattern of landslides using high density repeated TLS point clouds. The aim of the method is to be applicable to large displacements and important changes in the morphology of the slopes.

The method uses a normalized cross-correlation function in order to exploit the full geometrical information available in consecutive point clouds. The hypothesis is that for objects scanned from a unique viewpoint, relatively simple 2D correlation functions as largely used in digital photogrammetry (Debella-Gilo and Kaab, 2011) can be applied on multi-temporal point clouds with an accuracy comparable to complex and time-consuming 3D Surface Matching algorithms. Numerous examples demonstrated the efficiency of 2D correlation functions to detect the displacement field of landslides from satellite, airborne and terrestrial optical images (Casson et al., 2005; LePrince et al., 2008; Travelletti et al., 2012), but only little work has been carried out to develop efficient methodologies for TLS point clouds (Travelletti et al., 2008; Schwalbe et al., 2008; Aryal et al., 2012). The performance of the method is tested on datasets acquired at the Super-Sauze landslide (South French Alps) over a period of three years (October 2007–May 2010).

First, the main geomorphological and kinematical characteristics of the landslide are presented. Second, the principles of the