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Ground-based multi-view photogrammetry for the monitoring of landslide deformation and erosion

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ABSTRACT

Recent advances in multi-view photogrammetry have resulted in a new class of algorithms and software tools for more automated surface reconstruction. These new techniques have a great potential to provide topographic information for geoscience applications at significantly lower costs than classical topographic and laser scanning surveys. Based on open-source libraries for multi-view stereo-photogrammetry and Structure-from-Motion, this study investigates the accuracy that can be obtained from several processing pipelines for the 3D surface reconstruction of landslides and the detection of changes over time. Two different algorithms for point-cloud comparison are tested and the accuracy of the resulting models is assessed against terrestrial and airborne LiDAR point clouds. Change detection over a period of more than two years allows a detailed assessment of the seasonal dynamics of the landslide; the possibility to estimate sediment volumes and 3D displacement are illustrated for the most active parts of the landslide. Algorithm parameters and the image acquisition protocols are found to have important impacts on the quality of the results and are discussed in detail.

1. Introduction

Digital Elevation Models (DEMs) are indispensable information sources in many geoscientific studies. Modern remote sensing technologies have greatly facilitated their creation and frequent updating for applications in geomorphology, hydrology, geophysics and natural hazards research. Spaceborne observations are valuable sources for obtaining topographic information at global and regional scales (1:100,000–1:10,000). Measurements at higher spatial resolution and submeter accuracy are required for the investigation at local scales (<1:10,000) where topographic information can be acquired from airborne/terrestrial photogrammetry or laser scanning. In particular Light-Detection and Ranging (LiDAR) is being employed in an increasingly large number of applications providing very accurate surface representations because of its capability to penetrate vegetation and to acquire very dense and precise point clouds (Heritage and Large, 2009; Jaboyedoff et al., 2010). However, the costs of the equipment and the logistics of LiDAR surveys are currently still rather high and acquisitions at high temporal resolution are, therefore, not always feasible. Conventional photogrammetric techniques with metric and non-metric cameras are a frequently employed alternative for a wide range of applications (Fryer et al., 2007) but comprise high demands on the image acquisition geometry, ground control, processing software and the experience of the operator (Henry et al., 2002; Fryer et al., 2007).

Great advances of the photogrammetry and computer-vision communities in pose-estimation and bundle-adjustment (Triggs et al., 2000; Hartley and Zisserman, 2004), camera self-calibration (Fraser, 1997; Pollefeys et al., 1999) as well as feature-based and area-based image matching (Lowe, 2004; Pierrot-Deseilligny and Paparoditis, 2006; Hirschmuller, 2008; Furukawa and Ponce, 2010) have recently converged in a new class of photogrammetric algorithms that enable more flexible 3D surface reconstruction from unordered non-metric image collections. These tools are summarized under the terms ‘Structure-from-Motion’ (SfM i.e. the process of estimating camera parameters and sparse point-clouds; Ullman, 1979) and multi-view stereo (Seitz et al., 2006), (MVS, i.e. the process of deriving dense surface models once the correspondence among multiple cameras has been established). Many proposed approaches for SfM and MVS are implemented in commercial software (e.g., AgiSoft PhotoScan, Pix4D, PhotoModeler Scanner, and Trimble Inpho), web-based services (e.g., Microsoft Photosynth, Autodesk 123D, Arc3D, and Cubify Capture) and in open-source or freely available software packages (Snavely et al., 2008; Furukawa and Ponce, 2010; Deseilligny and Clery, 2011; Rothermel et al., 2012; Wu, 2013).

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The geoscience community has already taken great interest in these new tools (James and Robson, 2012; Westoby et al., 2012; Fonstad et al., 2013) and recent applications in geomorphology include landslide investigation (Niethammer et al., 2011; Lucieer et al., 2014), costal cliff monitoring (James and Robson, 2012), lava flow and volcanic dome analyses (James and Varley, 2012; Bretar et al., 2013), glacial and periglacial processes research (Kääb et al., 2013; Whitehead et al., 2013), gully erosion surveys (Gómez-Gutiérrez et al., 2014), soil microtopography (Ouédraogo et al., 2014) and braided river systems (Javernick et al., 2014).

These studies have shown that among many factors that condition the accuracy of SfM–MVS (e.g. camera, lens, and acquisition geometry, quality of the ground control, illumination, and processing software), the distance to the object is probably the most influential. Imaging distances between <2 m (Bretar et al., 2013) and >2000 m (James and Robson, 2012) have been explored resulting in accuracies that are generally between 0.04 and 1.68 m, respectively. James and Robson (2012) suggested a relative precision of 1:1000 corresponding to an *RMSE* value of 1 m at an imaging distance of 1000 m. However, limited attention has been paid to comparisons of different processing pipelines (Ouédraogo et al., 2014). While several benchmark studies have evaluated MVS algorithms on toy models (Seitz et al., 2006) and architectural outdoor scenes (Strecha et al., 2008; Remondino et al., 2012), there is currently no corresponding information for natural terrain available. Natural scenes yield fundamentally different image characteristics (Torralba and Oliva, 2003) and are typically more challenging in terms of surface features, illumination and constraints on the viewing geometry. For interested users, it is consequently difficult to select the most accurate solution among the variety of available tools. This also applies, to some extent, for the choice of the algorithm parameters whose values are typically not reported in the literature.

In susceptible lithologies and landscapes, landslides can dominate the sediment transfer (Hovius et al., 2000; Mackey and Roering, 2011); however, it is in general still challenging to obtain measurements of the kinematics and sediment budgets with high spatio-temporal coverage. Travelletti et al. (2012) and Gance et al. (2014) have recently demonstrated that terrestrial time-lapse photography is a valuable tool for the monitoring of slow-moving landslides; Niethammer et al. (2011) and Lucieer et al. (2014) provided examples for the use of UAV-based SfM–MVS to monitor landslide deformation from two acquisitions. Since terrestrial multi-view photogrammetry does not depend on aerial platforms or fixed permanent terrestrial installation, it could provide a very flexible tool for the monitoring of landslides and other geomorphological processes at high temporal and spatial resolution.

Therefore, the target of this work is to evaluate quantitatively the accuracy of dense point clouds created from several SfM–MVS pipelines (Deseilligny and Clery, 2011; Wu et al., 2011; Deseilligny et al., 2013; Wu, 2013) for 3D landslide surface monitoring including the measurement of surface deformation as well as the quantification erosion rates. The paper is organized as follows: first, the study site (Super-Sauze landslide) is introduced together with the acquisition protocols of the terrestrial photographic surveys, and the ground-control datasets obtained from LiDAR and differential GPS (dGPS) surveys are explained in detail. Second, details of three SfM–MVS algorithms and pipelines are presented. Third, the accuracy of the photogrammetric models is assessed through comparison with LiDAR point clouds. Fourth, change detection methods are applied to quantify the surface changes and the dynamics of the landslide over a period of two years. Finally, current limitations, potentials and possible pitfalls of the processing pipelines and image acquisition protocols are discussed.

2. Study site and data acquisition

The Super-Sauze landslide (Fig. 1) is a clay-rich slow-moving slope movement located in the Southern French Alps. The landslide initially developed in the 1960s through retrogressive failures of the main scarp; at present, its dynamics are controlled by the local hydrology–meteorological conditions and the accumulation of new material from successive failures at the main scarp. During the last decade, several in-situ and remote sensing studies have contributed to a better understanding of the movement pattern (e.g. Malet et al., 2002; Niethammer et al., 2011; Travelletti et al., 2012; Stumpf et al., 2013). For further information on the regional climatic and geological context the interested reader is referred to Flageollet et al. (1999). Multi-technique displacement observations since 1996 suggest average displacement rates of 0.01–0.03 m d^{-1} (Malet et al., 2002) but regularly, daily cumulative displacements larger than 5 m are observed (Travelletti et al., 2012). Such relatively high displacement rates pose challenges for displacement measurements since they often lead to signal decorrelation in the multi-temporal analysis of radar and optical images, and hinder the long-term maintenance of in-situ measurement devices.

The site is characterized by a rugged topography comprising vertical and overhanging cliffs, thalwegs and depressions of various sizes, and quasi-horizontal surfaces. The eastward-adjacent slopes are largely forested, whereas the westward-adjacent slopes consist of badlands and sub-parallel ridges bordering the landslide. Constraints on possible camera view points, low incidence angles and topographic or vegetation occlusion make such type of terrain very challenging for terrestrial photogrammetric measurements.

Acquisitions of terrestrial photographs in an MVS setup have been carried out since October 2011 at regular intervals (Table 1). Field campaigns are typically limited to the time between early May and late October since snow cover prohibits photogrammetric and most other measurements during the rest of the year. A Nikon D700 camera has been used, the focus has been set to infinity, and care has been taken to obtain a good trade-off between sufficiently short exposure time and large depth of field (narrow aperture) for all acquisitions.

Two target zones were monitored by photogrammetry. A first acquisition protocol was setup to reconstruct the evolution of the main scarp (Fig. 1) at five dates for the period October 2011 till July 2013. The images were recorded in a surface-parallel linear array of panoramic shots with distances to the targeted surface between 20 and 200 m. During the first survey images were recorded only at a reduced resolution (2128 × 1416) and in JPEG format, whereas for all subsequent surveys full resolution (4256 × 2832) images were stored in native Nikon (NEF) file-format to avoid information loss. A 60 mm lens was used at all dates except in July 2012 when a 35 mm lens was used to also investigate the influence of the focal length on the reconstruction.

A second acquisition protocol was setup to obtain a full-scene model for the entire landslide on 10-Oct-2012 and 19-Jul-2013. Images were captured in a half circular array along the limits of the landslide (Fig. 1) using a 35 mm lens. Distances to the targeted surface varied between approximately 50 and 1000 m. The latter constitutes a rather great distance for the application of terrestrial photogrammetry and according to James and Robson (2012) an *RMSE* value of 1 m should be expected.

The point clouds used as a reference dataset were acquired with a terrestrial (Optech ILRIS-3D) and an airborne (Riegl LMS-Q560) laser scanner. To provide full coverage of the main scarp, multiple terrestrial scans were acquired from different view angles and aligned subsequently using the Iterative Closest Point (ICP) algorithm implemented in PolyWorks (Innovmetric, 2010). The scans were performed at average distances between 3 and 800 m resulting in a ground-point density of ca. 100 points m^{-2}. The scan accuracy (standard deviation) of the terrestrial LiDAR scans (TLS) varies between ~0.01 m at 100 m and ~0.02 m at 2000 m (Abellán et al., 2013), whereas the alignment error amounts to an *RMSE* value of 0.02–0.03 m (Travelletti, 2011). The airborne LiDAR scan (ALS) was acquired on 29-Aug-2012 with an average flight height of 800 m above the surface resulting in an average ground-point density of approximately 90 points m^{-2}. The accuracy of the