Performance of Image Correlation Techniques for Landslide Displacement Monitoring

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Abstract
The objective of this work is to present the applicability of image correlation techniques (applied to very-high resolution terrestrial optical photographs and to very dense Terrestrial Laser Scanning (TLS) point clouds) to monitor the displacement of continuously active landslides. The method has been developed to characterize the kinematics of very active landslides with cumulated displacement of several decimeters per year. The data are processed with a cross-correlation algorithm applied on the full resolution images (photographs and DEMs produced from the TLS data) in the acquisition geometry. Then, the calculated 2D displacement field is ortho-rectified with a back projection technique. The method allows to characterize the heterogeneous displacement field of the landslide in time and space, and to produce displacement maps. The performance of the technique is assessed using as reference differential GPS surveys of a series of benchmarks.

The sources of error affecting the results are discussed. Because the proposed methodology can be routinely and automatically applied, it offers promising perspectives for operational applications like, for instance, in early warning systems.

Keywords
Image cross-correlation • Image matching • Time-lapse acquisition • Displacement monitoring • LiDAR, landslide

Introduction
Remote-sensing techniques are interesting tools to obtain spatially-distributed information on landslide kinematics (Delacourt et al. 2007). They give the possibility to discriminate stable and unstable areas and to map sectors within the landslide with different kinematics from a regional to a local scale (Casson et al. 2005; Teza et al. 2008; Oppikofer et al. 2008). Three main categories of remote sensing techniques, either operated from terrestrial or airborne platforms, are used in landslide monitoring: Synthetic Aperture Radar Interferometry (InSAR), Laser Scanning (LiDAR) and Optical Photogrammetry (OP).

The objective of this work is to highlight the possible applications and limitations of cross-correlation techniques applied both on airborne and terrestrial LiDAR point clouds and on very-high resolution optical images. Several datasets
of multi-source images acquired on the La Valette and Super-Sauze landslides (South French Alps) over the period 2007–2010 from different platforms are analysed. The influence of external factors on the precision and the accuracy of the results are discussed.

**Principle of the Image Correlation Technique**

Using matching techniques, two-dimensional displacement fields can be derived by tracking objects in two images acquired at different time. The technique is based on the automatic identification of identical texture patterns within an image by maximizing a correlation function (Lewis 1995). So far, Image Correlation techniques have been applied only on aerial and satellite images (e.g. SPOT, QuickBird, OrbView, EROS) for the creation of landslide displacement maps (Delacourt et al. 2004). Its principle adapted for landslide kinematics analysis is described in Delacourt et al. (2007).

In this work, a sub-pixel hierarchical correlation technique is used (Hild 2003). The original images are first converted in gray-scale images on which a $3 \times 3$ pixel Sobel convolution matrix is applied to highlight the ground surface texture. The gradient values are then correlated. Four successive degradations of the image resolution are applied following a pyramidal approach for changing the physical size of the correlation window and of the explored area by down-sampling the gradient values of the full resolution image (Kumar and Banerjee 1998) (Fig. 1).

The correlation starts with the lowest resolution image in order to determine the largest displacements. Then the location of the pixel with the maximum cross-correlation value is used as the centre of the zone of interest for the next correlation step at a higher resolution. The spatial location of the maximum correlation value in the highest resolution image is thus progressively better estimated (Fig. 1). Ignoring high resolution information at the first computational step decreases the probability to reach a local minimum of the correlation function and, consequently, to obtain a good matching in the correspondence solution (Alaoui and Ibn-Elhaj 2009). In addition, this approach ensures very often a higher probability of detecting a reliable correlation peak. The sub-pixel displacement is computed after the correlation at the highest resolution image. An iterative procedure is used to find the maxima of the correlation function interpolated with a bi-parabolic formula and with a maximization procedure based on the simplex method (Press et al. 1997).

![Fig. 1 Principle of the normalized hierarchical image correlation technique](image)

The correlation results consist in matrices of displacement $\Delta u$ and $\Delta v$ along the $u$- and $v$-axes in the image plane with their associated correlation index (Fig. 1). In case of orthorectified airborne images, the pixel size is constant, only the effective pixel size at the ground has to be calculated to estimate metric displacements. In case of terrestrial images, the pixel size is not constant in the image due to the oblique acquisition; the displacements field correlated in the image plane cannot be directly interpreted in terms of metric displacements and an orthorectification procedure is compulsory for a quantitative analysis.

**Application 1: Image Correlation of Terrestrial Photographs**

A set of images acquired at the Super-Sauze landslide over the period May–July 2008 is used to illustrate the potential of the technique for the characterization of the Kinematics during an acceleration period (Travelletti et al. in press).

Figure 2 presents the monitoring system installed in front of the landslide. The instrumentation consists in a low-cost D70 Nikon reflex digital camera installed on a concrete pillar located at a distance of 300 m from the lower part and 900 m from the main scarp (Fig. 2a, b). The acquisition system is controlled by a datalogger and the power is provided by a 40 W solar panel. Every four days, a series of images is acquired at 11:00, 12:00, 13:00 and 14:00 GMT.

Figure 3 shows an example of displacement rates (in pixel day$^{-1}$) of the ground surface in the image plane derived from image pairs of 20–28 May 2008, 1–4 June 2008 and 9 June–13 June 2008. The reference is the image
of 20 May 2008. The contrast in displacement rates between the landslide area and the stable area gives confidence on the calculated velocity field. One can notice that the pattern of displacement rate is heterogeneous spatially and temporally.

The upper part of the landslide displays the highest velocity ranging from 1 to 7 pixels day\(^{-1}\) while the lower part displays velocity of less than 4 pixels day\(^{-1}\). From the 20 May to the 13 June, cumulated displacements up to 110 pixels are observed in the upper part. The maximum of displacement rate is observed around the 1st June. Then the landslide decelerates to displacement rate of about 1 pixel day\(^{-1}\). No quantitative comparisons can be carried out at this stage because the pixel sizes vary strongly in the image.

The displacement fields computed in the image plane are then orthorectified in a local geographic coordinate system using the collinearity equations (Krauss and Waldhäusl 1994). The details of the methodology are explained in Travelletti et al. (in press). Figure 4 presents the amplitude of the 3D orthorectified displacement rates for the period 1-4 June. The difference of kinematics between the upper (until 3 m day\(^{-1}\)) and the lower (until 1 m day\(^{-1}\)) parts is important. The geometrical effect induced by the presence of the stable in-situ crest on the landslide kinematics is also clearly pointed out.

The precision of the computed displacements is assessed by performing a null hypothesis on the stable areas. Only the points with a correlation coefficient \(r > 0.8\) are taken into account. In the image plane coordinate system, the average error \(\mu\) ranges from 0.5 to 0.9 pixels with standard deviation \(\sigma\) of 0.3 to 1.2 pixels for the image pairs between the 20 May and the 25 June 2008. In the local coordinate system, the average error \(\mu\) ranges from 0.03 to 0.11 m with standard deviation \(\sigma\) of 0.10-0.31 m for the image pairs between the 20 May and the 25 June 2008.

The performance of the method has been evaluated by comparing the displacements derived from the image correlation, and the displacement monitored by dGPS on several benchmarks distributed in the stable parts and on the landslide. A correlation coefficient of \(r = 0.95\) is found on 219 measurements and an average relative accuracy of 20 % is determined (Travelletti et al. in press).

Application 2: Image Correlation of Terrestrial LiDAR Point Clouds (TLS)

The potential of terrestrial LiDAR (TLS) 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. 2008) or characterizing the dynamics of ice glaciers (Avian et al. 2009) and landslides (Teza et al. 2008). Automatic matching algorithms applicable to TLS data have started to be developed because of their capability to fully exploit all the geometric information available in the point clouds. The approach is to find correspondences among typical features located in multi-temporal point clouds assuming that the tracked object has a constant geometry in time and/or a perfectly rigid behaviour.

Correlation techniques can be applied on repeated TLS acquisitions in order to characterize the 3D displacement field. The hypothesis is that for objects scanned from a unique view point, simple 2D correlation functions can be applied on multi-temporal point clouds and yield the same range of accuracy than complex and time-consuming 3D surface matching algorithms (Teza et al. 2008). The performance of the cross-correlation algorithm is tested on datasets acquired at the toe of the Super-Sauze landslide. A long-range terrestrial laser scanner Optech ILRIS-3D has been used for the monitoring (Travelletti et al. submitted).
Ten acquisitions were acquired between October 2007 and May 2010 for the same base station at an average distance of 100 m from the landslide toe (Fig. 5). At this distance, the laser diameter on the ground surface is estimated between 3 and 5 cm. Only the last return pulse is registered to maximize the number of points reflected on the ground surface. The average point density at the ground surface varies from 153.0 to 234.9 pts m\(^{-2}\) with a standard deviation up to 351.7 pts m\(^{-2}\) and a maximal density of 1,148.3 pts m\(^{-2}\).

Filtering of vegetation and co-registration of the point clouds have been carried out with the software Polyworks 11 (Innovmetric 2009). A projective transformation is used to represent the entire geometrical information in a plan perpendicular to the viewing direction of the laser scan using the collinearity equations Kraus and Waldhäufl (1994).

The point density varies from 0.78 to 0.94 pt pixels\(^{-1}\) with a relatively low standard deviation of 0.18 pt pixel\(^{-1}\). The distance between the point clouds to the position of the laser scanner is then determined and linearly interpolated in a regular grid.

Because the correlation function gives better results where the input data contains regions of rapidly varying pixel information, the norm of the 2D gradient in \(u\) and \(v\) directions of the distance between the point clouds and the TLS station is calculated for emphasizing the morphology of the landslide. The generated images are then converted in grey-scale values (16 bits) and are used as inputs for the image correlation algorithm (Fig. 6).

The computed displacements are generally well reproduced for all periods of acquisition. Two acquisition periods (July–October 2008, July–October 2009) are
presented to illustrate the performance of the approach and the behaviour of the landslide (Fig. 7). For the period July–October 2008, displacements between 0.5 and 1.5 m are observed, corresponding to an average displacement rate of 0.6 to 1.7 cm day\(^{-1}\). The displacement field displays significant spatial heterogeneities. The largest displacements are detected in the front of the toe where the slope gradient increases. The detachment of a toe compartment is also highlighted in the front.

During the period July–October 2009, the landslide displays a very different kinematics both in terms of magnitude and spatial distribution. Displacements are shorter and range from 0.1 m at the front to 0.6 m in the upper part, corresponding to an average displacement rate of 0.1–0.8 cm day\(^{-1}\).

The computed displacements are validated by comparing the displacement values to dGPS observations of a series of blocks easily recognizable in the TLS point clouds. This comparison allows evaluating the accuracy of the approach by taking into account the noise in the data with the co-registering errors between two acquisitions. The displacements perfectly correlate \((r^2 = 0.99)\), and a mean error and a standard deviation of 0.04 m and 0.03 m are determined (Fig. 8). This results show that the error due to the co-registering is about 3 cm.

**Application 3: Image Correlation of Airborne LiDAR Point Clouds (ALS)**

A similar approach can be used for the creation of displacements maps from repeated airborne LiDAR point clouds (ALS). In this case, the landslide of La Valette is taken as example to illustrate the potential of the technique. Two DEMs with 1 m mesh size are interpolated from airborne LiDAR data acquired in October 2007 and July 2009. The average point density at the ground surface varies from 0.7 to 7.2 pts m\(^{-2}\) with a standard deviation up to 12.1 pts m\(^{-2}\). Two complementary pieces of information are directly derived from the DEMs (Fig. 9):

+ the elevation differences (Z component) indicating an accumulation of mass in the transit zone;
+ the horizontal displacement field (E-N components) obtained by correlating the 2D gradient of the topography with a size of the correlation window of 20 m; the results indicate a decrease of the displacement magnitudes from...
Fig. 6 Images derived from the gradient calculation on the TLS point clouds for the period October 2007–October 2008 at Super-Sauze. The morphology of the landslide toe is very well represented and the progression of the landslide toe is highlighted.

the transit zone to the accumulation zone where nearly null displacements are observed. The landslide behavior is controlled by a drainage system installed to stabilize the accumulation zone. Consequently, an increase of strain and an accumulation of mass occur near the Serre road demonstrating that the drainage system might not be the best solution to control the long term behavior of the slope.
Fig. 7 3D displacements field obtained by TLS measurements related to the acquisition periods of July–October of the years 2008 and 2009. The dashed circle indicates the detachment of compartment at the front of the toe.
Fig. 8  Comparison and validation of the displacements obtained by correlation with dDGPS observations on a series of blocks
Fig. 9 Displacement field calculated at the La Valette landslide from two airborne LiDAR acquisitions in October 2007 and July 2009. Left: Displacement field in the Z direction indicating changes in elevation, and possible zones of material accumulation or erosion. Right: Displacement field in planimetry indicating changes in distribution of mass.

Conclusion

The potential of Image Correlation technique applied to multi-temporal terrestrial photographs or airborne or terrestrial LiDAR point clouds has been evaluated using datasets available on the Super-Sauze and La Valette landslides (South French Alps). Operational methodologies are available to compute displacement rates both in the image plane coordinate system and in local geographic coordinate systems. The technique allows one to clearly characterize heterogeneous displacement field of landslides in space and in time, with a high detection thresholds (cm day⁻¹). The displacements maps computed from the images are in good agreement with local information on the displacement rates observed with classical geodetic techniques such a dGPS.

Using terrestrial images, the effect of pixel size at the ground (according to the distance to the target), the incidence of the line of sight to the ground and the resolution of the image are limiting factors to detect low displacement rates. Moreover, areas of low incidence angles (<5°) are very sensitive to small movements of the acquisition platform, that can partly be corrected.

Other limiting factors for optical images are related to the meteorological and illumination conditions and the ground surface changes inducing partial or complete loss of coherence between image pairs.

The results demonstrate that Image Correlation techniques implemented in permanent monitoring system are particularly interesting for monitoring landslides characterized by annual pluri-decimetric displacements.

This work offers very promising perspectives for operational applications which can be potentially integrated in early warning systems by considering additional efforts in direct data transmission. Finally, inversion of the displacement field could be developed to characterize the macroscopic rheological properties of the landslide material.

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