Investigating an active rockslide by long-range laser scanner: alignment strategy and displacements identification

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Key words: Laser scanning, Displacement measurement, Monitoring system, Engineering survey

SUMMARY

Landslides are considered one of the major natural hazards in mountain regions. Nowadays landslides monitoring has become a central issue for Authorities to be able to anticipate hazards. For this reason, several examples exist about landslides monitoring; they may be installed in different configurations depending on purposes and economic resources.

The heart of this research is to detect an efficient methodology for the reliable acquisition and interpretation of Terrestrial Laser Scanning (TLS) data: the final purpose is a proposal for a methodology which is based on TLS technology for identifying displacements and extracting geomorphological changes. The approach is clearly based on a multi-temporal analysis which is computed on several repetitions of TLS surveys performed on the area of interest. To achieve best results and optimize the processing strategy, different methods about point clouds alignment have been tested, together with algorithms both for filtering and post-processing. The final aim is also to provide a sort of guidelines about a suitable way for planning and properly carrying out TLS surveys.

The case study is the Col Piagneto landslide, located in the North Apennines (Reggio Emilia, Italy) on the right flank of Biola torrent. The large scale composite landslide area is made both by a wide rock slide sector and a more limited earth slide sector. An integrated monitoring system is installed since 2009 and comprises both point-based technologies (extensometers, total station and global positioning system), as well as area-based ones (airborne laser scanner, long-range TLS and ground-based radar). This choice combines the advantages of both approaches.

The research focuses on TLS surveys for trying to detect displacements which might be considered responsible for instability. By sequentially analyzing TLS surfaces, displacement maps have been obtained for the rockslide area. Confirmation can be achieved by comparing results with movements of reflectors located on the slope and continuously measured by total station. Such validation strengthens the idea that TLS may be successfully used for analyzing instability.

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1. INTRODUCTION

The current research deals with a large scale rockslide which is investigated by a traditional monitoring system. In addition to the need of monitoring the rockslide and its deformation behaviour, the main purpose of this research is to test the use of very long-range Terrestrial Laser Scanning (TLS) for trying to identify movements and displacements over time. The most challenging goal is the proposal of a methodology for multi-temporal surface analysis of the phenomenon, based on TLS with the validation of Automatic Total Station (ATS) measurements. Multi-temporal investigation, is an innovative use of TLS; particular attention is being paid to the difficulties encountered especially where long distances (more than 1 km) are involved.

In case of an active landslide, the main action to prevent the hazard consists in installing monitoring systems able to collect useful information about the slope stability. Unfortunately, due to limitation of budgets and roughness of the morphology, just few points, often not well distributed on the unstable area, can be measured. This is usually achieved by a traditional monitoring system based on the installation of topographic and geotechnical instrumentation. A spatially-continuous monitoring system is the key for increasing the assessment of the phenomenon. Nowadays, the well-established Airborne Laser Scanning (ALS) technique is the most appropriate approach for surveying a large area measuring millions of points in relatively short time, then creating the Digital Terrain Model (DTM). However, the ALS is not always suitable for providing reliable results; for example when dense vegetation covers the ground or when strong morphological discontinuities hide natural features from the laser scanner line of sight. This second aspect might be overcome by choosing TLS technology, which allows changing the point of view by positioning the instrument in the most suitable line of sight frontal instead of vertical, for instance). Several examples of this approach can be found in literature; though, the majority of them focuses on the use of TLS for improving the description of morphology (Abellan et al., 2006; Bitelli et al., 2004; Glenn et al., 2006; Oppikofer et al., 2009; Travelletti et al., 2008). To this date, however, few efforts have been dedicated to identify movements by multiple TLS surveys, mainly where short distances are involved (Abellàn et al., 2011; Monserrat and Crosetto., 2008; Oppikofer et al., 2009; Prokop and Panholzer, 2009; Scaioni et al., 2004; Teza et al., 2007).

2. CASE STUDY

The studied rock slide affects a large area of the Col Piagneto slope, located in the northern Apennines (Emilia Romagna Region - Italy). It often endangers part of the National Road 63, near the Cerreto Pass, and it also might dam the Biola Torrent below. The rockslide analysed (subunit G1 in Fig. 1) is part of a larger composite landslide complex that includes another rockslide (subunit G2 in Fig. 1) as well as a more limited earth slide (subunit G3 in Fig. 1) which disrupted the National Road 63 in proximity of Piagneto, Collagna (Reggio Emilia, Italy), after heavy rains. In more than two years of monitoring, the whole landslide has showed active movements cycles related to the seasonal distribution of the groundwater replenishment into the slope. The displacement data show acceleration phases in autumn, mainly due to intense rainfalls, and in spring, due to the melting of snow-pack cover.

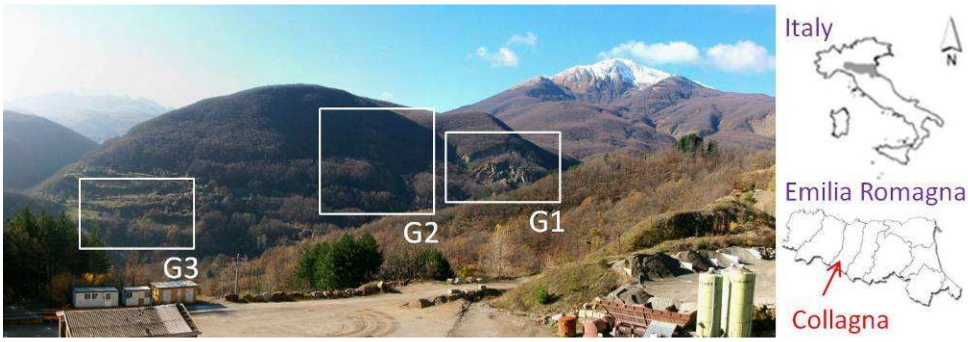

Figure 1: Photograph and geographical location of the Col Piagneto landslide. White rectangles evidence the three sectors of the landslide.

Since summer 2009 the Col Piagneto landslide is monitored continuously by using spatially discrete and points-based techniques. The topographic monitoring system is based on a master station which is installed in a geologically stable area with respect to the landslide. The master station was installed, in fact, on the opposite front side of the mountain at an average distance of 1÷1.5 km. It includes a meteorological station, a stable pillar for periodical checking of the stability of the area, by means of a dual-frequency Global Positioning System (GPS) tracking in static mode for long sessions, and an Automatic Total Station (ATS), whose equipment is also based on a computer unit, electrical power with a battery power supply and internet connection for real-time data stream and remote control. The master station location faces the landslide and is surrounded by a cave in the back and on one side, while the opposite side consists of a slope full of vegetation. Reflectors for ATS measurements were located within the investigated phenomenon and a few of them were installed in stable positions with the most homogeneous and symmetric configuration possible. Due to the presence of the cave, nothing was installed in the back nor on the side except for reference reflectors in few visible positions at the border of the caved area.

In spite of the high accuracy and precision of points-based technique, these types of systems are not able to fully describe large slope instability. In order to fill this gap, a near spatially continuous approach is required. An ALS survey was performed on the Piagneto slope in 2010 in order to obtain the overview of the whole area. After installation and verification of the proper functioning of the ATS, TLS surveys were also considered for spatially improving the description of the rockslide G1 sector. Before performing such TLS surveys, some reflectors were installed to improve the probability of a proper and successful point clouds alignment. These specific TLS targets are white, square and high reflective panels of about 50 cm per side. Due to logistic difficulties, these special reflectors could not be installed within the rockslide as control points; thus, they were placed in stable areas, often in the same locations of the ATS reference prisms, in order to be used for the registration process.

3. METHODOLOGY

The most challenging aim of this paper is to define a methodological procedure for the use of long range TLS technique for the multi-temporal analysis of rockslides, aimed at identifying displacement and extract geomorphological changes. Any significant detail about alignment strategies and processing procedures is being given, together with the appropriate validation methods.

The ALS survey was performed in 2010 while the multi-temporal TLS surveys were carried out in 2010 and 2011. Most interesting and useful results concerning geomorphology investigations were obtained by TLS, while ALS was mainly used for an overview of the whole area. The ALS and TLS surveys performed in 2010 have been integrated to generate an high resolution DTM of the whole landslide.

The following analysis will concentrate on the rockslide G1 sector because it highlights the most interesting geological characteristics. Since the ALS survey was not able to provide a reliable description of vertical walls because the line of sight is itself vertical, the long range TLS surveys were performed specifically with the aim of collecting data on the G1 vertical walls. In the following paragraphs details on surveys and alignment strategies are provided; also with attention to encountered problems.

3.1 Long range TLS surveys

The instrumentation was always positioned close to the master station of the continuous monitoring system, in a frontal point of view with respect to the G1 sector at a distance of about 1.3 km. It is worth to underline that, the first campaigns (2010) have been performed from a tripod, whereas from 2011 the instrument was installed on a stable pillar by means of a forced centring. An hollow aluminium pole was planted in the ground for almost half of its length and then it was filled with a mixture of terrain and concrete in order to make it more stable.

Figure 2: Photograph of the master station of the monitoring system. It shows the RTS, GNSS, meteorological station and long range TLS on the forced centring aluminium pillar.

Surveys were performed using two different types of long range laser scanners by Riegl with maximum ranges of 6 and 2 km respectively. The technical characteristics of the adopted instruments are summarized in Table 1. All acquisitions of data were performed at the maximum scan resolution; this parameter, as well as the value of the footprint of the laser beam, depends on the laser scanner capabilities and the operating distance. Considering the technical characteristics of the less accurate TLS, the significance of measurements is about 10 cm at 95% confidence level at a distance of 1.3 km.

Table 1: Technical data of the long range Terrestrial Laser Scanners used.

Laser scanner model	Riegl LPM-321	Riegl LMS-Z620
Laser class	1M (IEC60825-1: 2007)	1 (IEC60825-1: 2007)
Laser wavelenght	Near infrared	Near infrared
Multi-target	3 target distances per measurement	Absent
Max measurement range	ρ≥80%: 6000 m ρ≥10%: ≥ 1500 m	ρ≥80%: ≥ 2000 m ρ≥10%: ≥ 750 m
Measurement accuracy	25 mm*	10 mm**
Precision	15 mm	10 mm
Laser beam divergence	typ. 0.80 mrad	0.15 mrad
Angular step width	≥ 0.018° (horizontal & vertical)	≥ 0.004° (horizontal & vertical)
Angle measurement resolution	0.0090° (vertical) 0.0090° (horizontal)	0.0020° (vertical) 0.0025° (horizontal)
Inclination sensor	Absent	Integrated

* one sigma std. dev. @ 50 m range under Riegl test conditions, plus distance-dependant error ≤ ± 20 ppm

** one sigma std. dev. @ 100 m range under Riegl test conditions

3.2 Alignment strategy

Each field campaign provided a point cloud which was measured against its own reference system. The first step of the data processing is the need to perform the well-established procedure for obtaining a point cloud which is as more representative as possible of the slope features. In order to accomplish this goal, the sequence of noise removal and semi-automatic or manual filtering is required. In addition, the registration of different point clouds in a unique reference system needs to be performed, by computing roto-translation parameters of the Helmert transformation (Watson, 2006). This is a basic step for the following multi-temporal analysis. Three main approaches are commonly chosen (Alba and Scaioni, 2007) for performing the registration: the first one based on the identification of common points, the second one based on direct orientation of the laser scanning sensor and the third one based on surface matching. However, it is worth to underline that the direct approach can be performed only for the campaigns of 2011, after the stable pillar had been installed. Thus, for the scans of 2010, the registration methods are actually only two.
The first approach is based on the need to find out at least three homologues points for each scans pairs without any ambiguity. This is the basis for a successful registration, both whether their coordinates have been measured by a total station (unstable points) or not. This is the reason why specific square reflectors were installed in stable zones around the area of interest with the aim of obtaining an accurate identification of the panels centre. ATS measurements

can be helpful for checking the stability of these points over time. The second strategy to perform the registration is based on the direct approach. TLS can be directly registered, that means the sensor can be centred over a known position and levelled, while the last remaining degree-of-freedom can be fixed by orienting the intrinsic reference system towards a known point. This last task is performed by scanning a backsighting target (Lichti and Gordon, 2004; Scaioni, 2005). The third approach is based on the well known Iterative Closest Point (ICP) algorithm (Besl and McKay, 1992; Chen and Medioni,1992; Zhang, 1994), which needs the identification of surfaces that are considered stable in subsequent TLS campaigns. The algorithm relies on the iterative search of pairs of closest points in two datasets in order to estimate the rigid transformation which aligns the scans by minimizing the residual errors.

3.2.1 Encountered problems

Main difficulties have been encountered in the alignment process. Because of the long distances involved, about 1.3 km, and considering the TLS angular resolution and laser beam divergence, the ambiguity in identifying pairs of points did not permit to achieve the proper accuracy for registration, even by using the specific reflective panels. Major efforts and many tests were required on the strategy for a suitable identification of homologous points but were not successful enough for reliable comparison. Indeed, the half-meter side of targets, scanned from a distance of more than 1 km, is lower than the laser beam footprint and about equal to the point cloud resolution of scans acquired by the less accurate TLS. This means no possibility to identify the target shape, nor its centre, without any ambiguity because few points belonging to the panel are available.
Taking into account the presence of ATS reflectors, which were installed within the rockslide, a second attempt has been done trying to use them for the alignment process. Obviously, this effort is not based on their very small diameter but on their very high reflectivity. Due to the laser beam divergence, the high reflectivity of the prism is spread around it and creates a rim of highly reflective points in the neighbourhood that make it impossible to distinguish the actual position of the prism.

3.2.2 Adopted solutions

The approach chosen for the alignment process is based on the surface matching by means of the ICP algorithm. This method, normally used to register scans acquired in different epochs, requires the identification of surfaces that are not affected by any movements and may be considered quite stable in each TLS campaigns. Unfortunately it has not been possible to identify *a-priori* stable areas for performing the alignment by the ICP algorithm. It is however possible to analyse the ATS data in relationship to the geomorphological characteristics of this sector to determine whether there was a stable portion within the rockslide. The ATS monitoring system provides very useful time series about prisms and, focusing the attention to prisms installed on rock walls of the G1 sector, it is possible to find out that the upper scarp is quite stable because no significant displacements have been detected since the epoch of the first TLS campaign. To this date the prism installed on the main scarp can be considered stable: the linear regression of time series shows a mean displacement of about 1.5 cm over two years, which is a lower value than the ATS accuracy and atmospheric influence as well.

All other prisms installed on G1 sector moved about 10 cm to more than 25 cm, with the higher rate of displacement noticed on those located in the lower part of the rockslide. As a consequence, points belonging to the upper block and acquired in the first campaign have been used for the surface matching process. This simply means that the final reference system of each point cloud coincides with the reference frame of first TLS survey.
Although reflecting panels did not provide sufficient precision for the alignment process, the approximate identification of their centre could still be used for the pre-registration step.
This strategy has been used for first TLS campaigns, while the last ones have been aligned on the reference system by means of the direct approach. This was possible because the instrument was set up in the same configuration thanks to forced centring on the aluminium pillar fixed in the ground. In this way, the same reference system is guaranteed; no translation is required for comparing point clouds. The second and third degrees of freedom to be determined are the vertical setting of laser scanner principal axis and the rotation around it. The vertical positioning is achieved by levelling the instrument and by adjusting the inclination sensor, if available; the azimuth orientation is assessed by a reflecting panel which is installed at a distance of about 280 m away from the laser scanner position and is measured in order to allow the easy recognition of its centre.
For the first campaigns, the quality of the resulting alignment process is obtained by the mean error of surface matching which results to be about 3÷4 cm. Even if the last surveys have been registered in a different reference system by means of the direct approach, it is easy to compute the roto-translation matrix as it permits the alignment of all point clouds in the first reference system. The final alignment accuracy occurs through the backsighting orientation procedure and it is about 2 cm.

4. MULTI-TEMPORAL ANALYSIS

Once the alignment process has been computed with sufficient and satisfying accuracy, point clouds were transformed into surfaces in order to provide a continuous description of the morphology and with the aim to prepare conditions for the multi-temporal analysis.
Surfaces have been generated by the Delaunay 2.5D triangulation approach. This algorithm requires choosing a specific point of view to create surfaces from the same perspective. The process creates a plane behind the point cloud and perpendicular to the line of sight onto which the points will be projected. A bi-dimensional mesh is then created on that plane using the Delaunay 2D algorithm (Delaunay, 1934) and the mesh vertices are projected back to their original 3D coordinates. Thus, this triangulation process is based on all acquired points and it is particularly useful for hole-filling in meshes and for inspection and volume comparison of distinct models. This is especially evident in this specific case where the object of interest has been acquired from one position only. It also proved to be helpful for the subsequent multi-temporal analysis, as described below.
In order to carry out a multi-temporal TLS analysis with the purpose of providing semi-continuous displacement maps, the comparison between a reference mesh and a point cloud is achieved by means of an inspection tool. The algorithm performs an automatic distance computation from each point of the cloud to the mesh. The distance is computed along the normal direction to the infinitesimal plane generated around the point itself. The resulting product is a very useful and evident map where displacements are represented by a colour

scale. The two-dimensional colour representation of displacements permits to immediately detect the location of unstable areas. Displacement maps illustrating actual movements have been computed with the above tool. As mentioned before, the measurements significance, according to the technical characteristics of the less accurate TLS, is about 10 cm. Due to such broad accuracy and to the slow movements involved, only comparisons over a time span of at least one year allow detecting significant movements. An example of raw resulting map is shown in Figure 3.

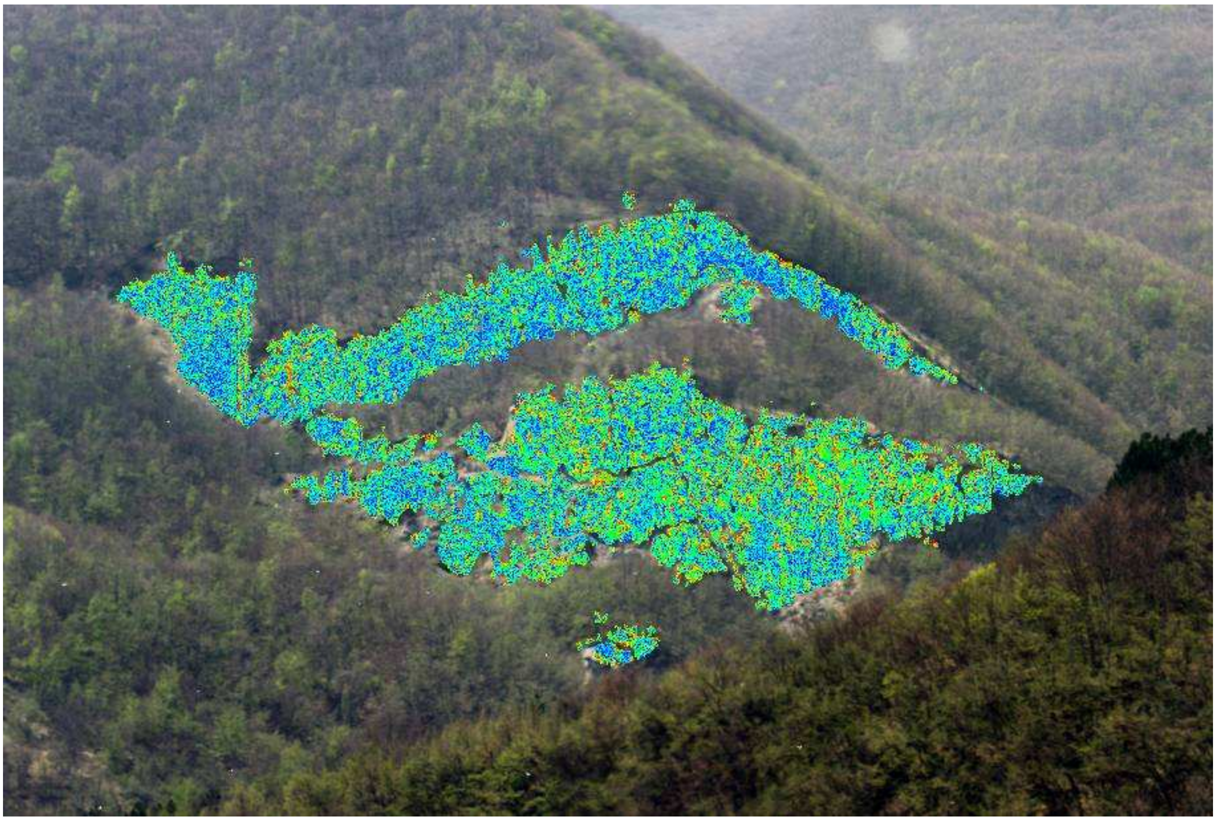

Figure 3: Example of raw map resulting from the multi-temporal analysis. The inspection colour scale has been omitted.

4.1 Data processing

Maps obtained by multi-temporal analysis show a high variability of computed displacement values over small areas. Thus, raw maps have been filtered in order to better highlight areas characterized by movements and improve their readability. A specific algorithm has been created by authors in Matlab language for smoothing results in order to make them coherent with geomorphological features and discontinuities.
The algorithm consists of a filtering based on moving average: it selects for each point all the points included in a neighbourhood whose diameter is adequate to the footprint of laser beam at that particular distance. A simple moving average filter is found to be unsatisfactory after the first attempt. Therefor a new approach has been tested by which selected points are first grouped in classes (*i. e.* 5), depending on the value of displacement that characterizes them.

After that, the algorithm is used to count the number of points falling in each class and, according to that frequency, the main class is identified for the considered the neighbourhood under considerarion. The average of displacement values associated with points falling within the main class is computed as well as values of points falling within classes located before and after the main one in the numerical classification. By this method, the algorithm takes and associates a displacement value which is much more representative of each point neighbourhood than what results by the use of the simple moving average. In this last approach, in fact, the presence of some outliers influences and distorts the final displacement value. Subjecting the raw displacement map that is shown in Figure 3 to this filtering algorithm, the result is the new map shown in Figure 4. The result is now clearly more consistent with actual movements of rock blocks. This map is the result of a long procedure of TLS data processing and products extraction but it is also the starting point against which geologists can make their analysis and interpretation of earth surface processes. Before allowing such interpretation, results need to be verified and validated by means of an independent technique. Details about that are given in the following paragraph.

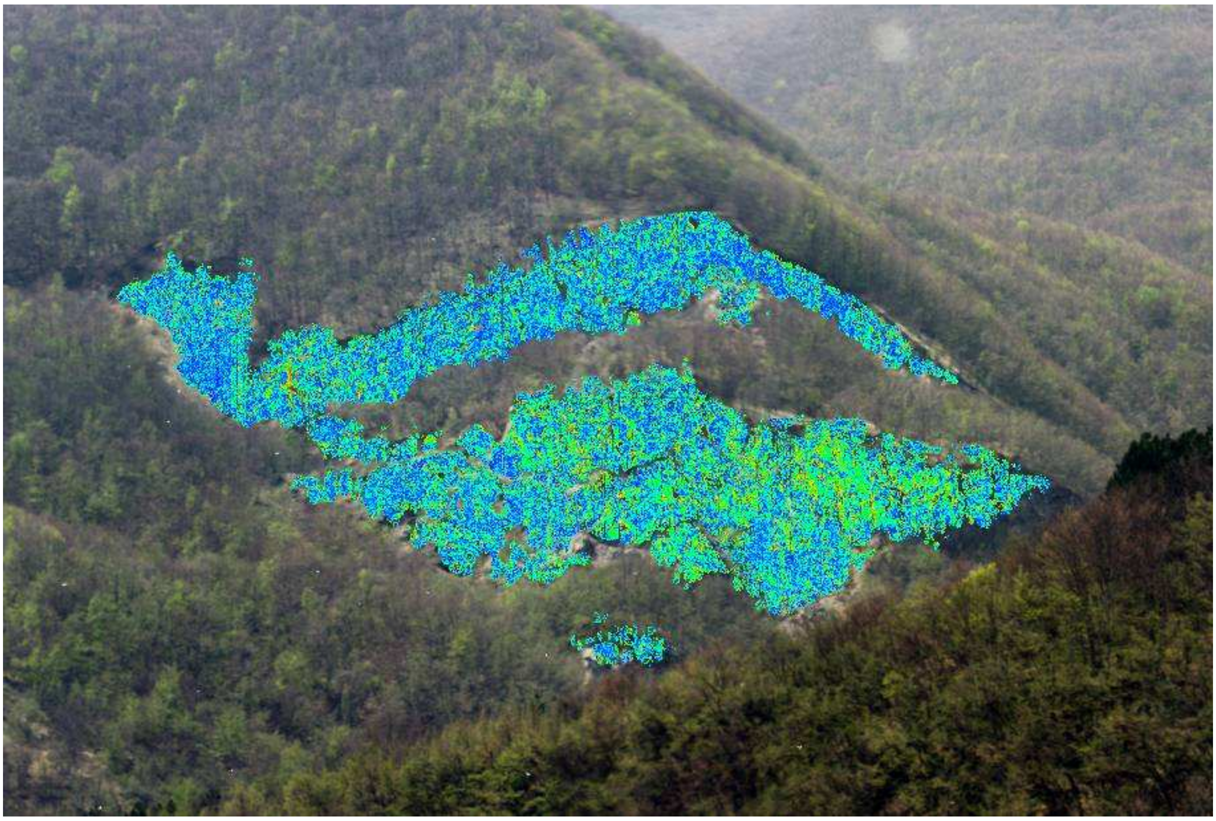

Figure 4: Example of processed map resulting from filtering based on moving average. The inspection colour scale has been omitted.

4.2 Validation

In order to validate the obtained results, an independent techniques is required. The only one information which is simultaneously available with TLS surveys is provided by ATS

measurements. Due to the importance given to the monitoring system, it is worth underlining that such system is often controlled. The stability of the master area is checked by periodic survey carried out by means of GNSS static sessions (dual frequencies equipment along with post-processing with respect to a close permanent station). Moreover, the stability of reference reflectors is also monitored by periodically surveying them by means of both GNSS and ATS network adjustment. This is essential because the real-time monitoring system provides geometric corrections of slope distance measurements on the basis of known coordinates of reference prisms. In addition, in order to improve the accuracy of ATS measurements, atmospheric corrections of the slope distances are computed in post-processing mode by applying the rigorous Barrel-Sears model (Bertacchini et al., 2011; Marini and Murray, 1973; Rüeger, 1990).
The validation process is performed on the lower scarp of the G1 sector, which is the area of major movements. The basic idea is to analyse the consistency of movements identifiable with respect to ATS and displacements obtained by inspection on TLS data. It is essential to take into account the specific accuracy of each technique. The described approach for the validation of the methodology is possible because the investigated phenomenon is characterized by blocks of rock: the basic hypothesis is that each prism is supposed to move approximately along the ATS (and TLS) line of sight and is representative of the whole rock block on which it is installed. Although, as already mentioned, due to laser beam divergence, the reflectance of the prism creates a rim of highly reflective points in the neighbourhood; such points are supposed to move with the prism because the rock just allows homogeneous and rigid displacements. Therefor, points characterized by the high reflectance have been selected and the average has been computed in order to associate a coherent displacement value to the prism. This is considered representative of the prism movement detected by TLS and compared with the value that emerges from ATS.
The comparison has confirmed the quality of the proposed methodology for multi-temporal analysis based on TLS data. Indeed, given the uncertainties of each method, TLS displacements can be considered coherent, consistent and comparable to results obtained by ATS. Confirmation comes by the difference between displacement results of the two techniques, which is lower than the accuracy of TLS. It must be emphasized that the comparison is possible on few points (ATS prisms), but these results are quite encouraging and motivate to continue in this direction.

5. CONCLUSIONS

TLS technique is potentially a very useful tool to identify movements of unstable slopes. Nonetheless it does not yet constitute a monitoring system because it is not possible to quantify the exact displacement associated with each point, especially when long distances are involved. The methodology developed for investigating the specific case of a rockslide yields excellent results; the validation based on a completely independent technique encourages to continue the study in order to develop and propose guidelines for planning and executing suitable TLS surveys aimed at this purpose.
TLS may be used not only for a successful integration with ALS in order to provide a correct description of the morphology but also as a useful technique capable of giving indication about movements. It is able to add a lot of information by means of its spatially continuous

approach; particularly when no further techniques can be planned such as ATS and in situ sensors (due to inability, inaccessibility or danger). It must be emphasized that validation is based on few points but these early results are quite encouraging to continue in this direction. New campaigns will be carried out in 2012 and more data will be collected in order to perform more significant tests.
Attention and further efforts should be addressed to assess the alignment process, which has proven to be the key to correctly quantify displacements, especially when long distances are involved. In this regard, specific studies will need to focus on the backsighting orientation with the help of the installation of the forced centring pillar.

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BIOGRAPHICAL NOTES

Eleonora Bertacchini was born in Reggio Emilia (Italy) the 18th January 1982. She graduated in 2007 at University of Modena and Reggio Emilia in Environmental Engineering with a thesis about the orthorettification of very high resolution satellite images. Now she is going to discuss her PhD dissertation about GB-InSAR for identifying landslide displacements. She is involved in surveying, mapping, remote sensing and topographical monitoring systems.

Alessandro Capra took his degree in Mining Engineering at the University of Bologna (Italy). He is Full Professor of Geodetic Sciences, Surveying and Mapping at the Engineering Faculty of University of Modena and Reggio Emilia. He also is Chief officer of Geosciences group of SCAR (Scientific Committee on Antarctic Research), President of SIFET (Italian Society of Photogrammetry and Surveying) and Editor-in-chief of *Applied Geomatics* journal.

Cristina Castagnetti successfully completed her PhD in March 2010 at the University of Modena and Reggio Emilia. She took her degree in Environmental Engineering studying kinematic positioning by means of GNSS. Her PhD dissertation focused on land-based navigation with particular attention to the design of a low-cost integrated system for precision farming application. Since few years she is also involved in archeaology and cultural heritage applications with the purpose of surveying and monitoring ancient structures.

Riccardo Rivola was born in Modena (Italy) on the January 25th, 1987. In November 2010 he received the second level degree in Environmental Engineering with honors at the University of Modena and Reggio Emilia. At the moment he is a Ph.D. student at the "High Mechanics and Automotive Design & Technology" School of Mechanical and Civil Engineering Department of the same University. His research area is mainly the monitoring of engineering structures and environmental processes, terrestrial laser scanning and integrated sensors measurements.

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