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Multitemporal UAV surveys for landslide mapping and characterization

Abstract This paper presents the preliminary results of the IPL project 196 "Development and applications of a multi-sensor drone for geohazards monitoring and mapping." The objective of the project is to test the applicability of a multi-sensor drone for the mapping and monitoring of different types of geohazards. The Department of Earth Sciences of the University of Florence has developed a new type of drone airframe. Several survey campaigns were performed in the village of Ricasoli, in the Upper Arno river Valley (Tuscany, Italy) with the drone equipped with an optical camera to understand the possibility of this rising technology to map and characterize landslides. The aerial images were combined and analyzed using Structure-from-Motion (SfM) software. The collected data allowed an accurate reconstruction and mapping of the detected landslides. Comparative analysis of the obtained DTMs also permitted the detection of some slope portions being prone to failure and to evaluate the area and volume of the involved mass.

Keywords Drone · Landslides · Mapping

Introduction

Mapping and displacement monitoring of unstable slopes is a crucial issue for the prevention and assessment of hazards.

Remote sensing techniques are effective tools to rapidly obtain spatially distributed information on landslide kinematics (Delacourt et al. 2007), and can be operational from spaceborne, airborne, and ground-based platforms. The main advantage of remote sensing data is the capability to acquire spatially continuous data, even with centimeter precision, that can be very useful when they have to be integrated with conventional ground-based techniques (Tofani et al. 2013).

Nevertheless, remote sensing analysis performed using aerial and satellite platforms highlights some drawbacks, mainly high associated costs and the logistical challenge of conducting repeat surveys within a short time.

During the last decade, a rapid and consistent development of small UAV (unmanned aerial vehicles) systems for civil use with high performances and low cost, along with a rapid development of new improved sensors in terms of effectiveness and miniaturization, is opening interesting scenarios in the use of conventional remote sensing techniques for surface modeling and monitoring (Colomina and Molina 2014; Travelletti et al. 2012; James and Robson 2012; Remondino et al. 2011; Eisenbeiss and Sauerbier 2011; Fabris and Pesci 2005). As an important mean of obtaining spatially distributed data, UAV-based remote sensing has the following advantages: real-time applicability, flexible survey planning, high resolution, low cost, and it can collect information in dangerous environments without risk (Chang-Chun et al. 2011). The increasing diffusion of UAVs has encouraged many companies to develop dedicated sensors for these platforms. Besides the conventional RGB cameras, other camera sensors are nowadays available on the market such as thermal sensors and multi- and hyper-spectral cameras (Giordan et al. 2017).

The recent development of innovative optical image processing techniques has further lowered the costs for the rapid execution of high-resolution topographic surveys, previously carried out by means of very expensive airborne or ground-based LiDAR sensors. Topographic surveys are now possible through the simple use of a set of RGB aerial images combined exploiting digital photogrammetric algorithms.

Digital photogrammetry is a technique that permits the reconstruction of topography as a 3D model using algorithms that can provide 3D spatial information from features and elements visible in two or more images acquired from different points of view (Westoby et al. 2012).

Once images are oriented and, possibly, calibrated with sensor and lens data, it is possible to obtain very high-definition point clouds (Colomina and Molina 2014), along with digital surface models (DSM), orthophotos, and accurate 3D representation of objects or surfaces. This process is generally carried out using one of the numerous Structure-from-Motion (SfM) software packages that can compute the 3D data from a series of overlapping, offset images (Westoby et al. 2012). SfM processing is based on specific algorithms for feature-matching and bundle adjustment, allowing also to estimate automatically the internal camera corrective parameters.

The time and cost-effectiveness of the technique make it possible to repeat measurement surveys at regular time intervals to monitor the changes occurred between different acquisitions, by comparing the resulting digital models.

In the last few years, UAVs, equipped with optical cameras to perform digital aerial photogrammetry, have been applied to study landslides (Balek and Blahut 2017; Marek et al. 2015; Turner et al. 2015; Mateos et al. 2017; Rossi et al. 2016; Peternel et al. 2017; Peppa et al. 2017). The contribution of UAVs to landslides can have various applications: recognition, mapping, monitoring, and hazard analysis (Giordan et al. 2017).

In this work, a multicopter drone named *Saturn*, developed by the research team of the Department of Earth Science at the University of Florence and equipped by a consumer-grade optical camera, is used to carry out photogrammetric data acquisition in an area close to the village of Ricasoli, in Tuscany (Italy), strongly affected by active landslides. Multiple photogrammetrical surveys were performed using the *Saturn* drone to provide multitemporal 3D models of the slope.

The aim of the work is to test the applicability and to validate the first preliminary results of the newly developed drone as well as to create high-resolution 3D surface models to better characterize and to monitor the landslides affecting the village.

Study site

Ricasoli is a small village in the Upper Arno river Valley (Tuscany, Italy), an area strongly affected by diffuse slope instability. The village is located in an intramontane basin with a NW-SE orientation, which has been formed during the extensional phase of the Neogene-Quaternary evolution of the Tyrrhenian side of the Northern Apennines (Abbate 1983).

The substrate of the basin consists flysh-type formations constituted by sandstones interlayered with siltstones. This substrate is overlain with fluvial-lacustrine sediments that were deposited in this area in three phases between Lower Pliocene and Upper Pleistocene (Fidolini et al. 2013).

From a geomorphological point of view, Ricasoli is located on topographic high made of fluvial-lacustrine sediments overlaid with fluvial sediments (Fig. 1). Fluvial-lacustrine sediments are mainly made of silts, clays, and peaty clays (*Terranova Silt TER and Ascione Stream Clay*, *ASC*), while fluvial sediments are constituted by silts, sands, and gravels (namely *Silt and Sand of Oreno Stream LSO*, *Casa La Loccaia Sands LOC*, *Latereto silt LAT*) (Rosi et al. 2013).

The slopes surrounding the hill of Ricasoli are affected by numerous landslides, which cause the retreat of escarpments near the village, affecting community infrastructure and buildings.

Different types of landslides affect the village of Ricasoli. Falls with topples, and shallow landslides, affect the slopes surrounding the village. These landslides consist of sands and sandy silts with high slope angles. Moving downslope, the cohesive soils substitute granular materials, slope angle decreases, and compound rotational slides develop (Fig. 1). The diffuse sliding phenomena, generally triggered by heavy and continuous rainfall, are causing a progressive retreat of the escarpments. Particularly in the northern slope, many evidences of landslide activity, consisting in cracks, small escarpments, and counterslopes, can be recognized (Rosi et al. 2013).

Since 2004, several monitoring instruments have been installed: inclinometers, extonsometers, and crackmeters.

In 2014, consolidation works have been realized in the northern flank of the village that according to the monitoring results is the more active in terms of displacements measured. In particular, slope reshaping and consolidation using wooden poles have been used.

The study is particularly focused on the eastern part of northern slope, where two new shallow landslides occurred respectively on March 1st (Landslide 1, LS1) and March 30th 2016 (Landslide 2, LS2) after a period of heavy rainfall (Fig. 2) involving a portion of the superficial recent landfill and underlying in situ soil formations.

Materials and methods

The multicopter drone

The more commonly used multicopter drones have a radial airframe where, from a central chassis, a variable number of arms support the engines and the propellers.

Aimed at improving the structure of the existing multicopters, the Department of Earth Sciences of University of Florence (DST) has developed a new type of airframe that overcomes some critical issues in carrying scientific and heavy payload or in applications requiring long flight autonomy (Fig. 3a). It is an innovative circular-shaped airframe that fully supports flight dynamics (Fig. 3a), currently patented in Italy, protected by PCT (Patent Cooperation Treaty) valid in 117 countries and patent pending in the USA and all Europe countries.

The drone, named *Saturn*, has several key features including:

- Increased space without constraints to positioning electronics, flight system, and instruments.
- The central payload area can be connected in a rigid manner or with a flexible mount to dramatically dampen mechanical vibrations from the propulsion system without compromising flight dynamics and performance.

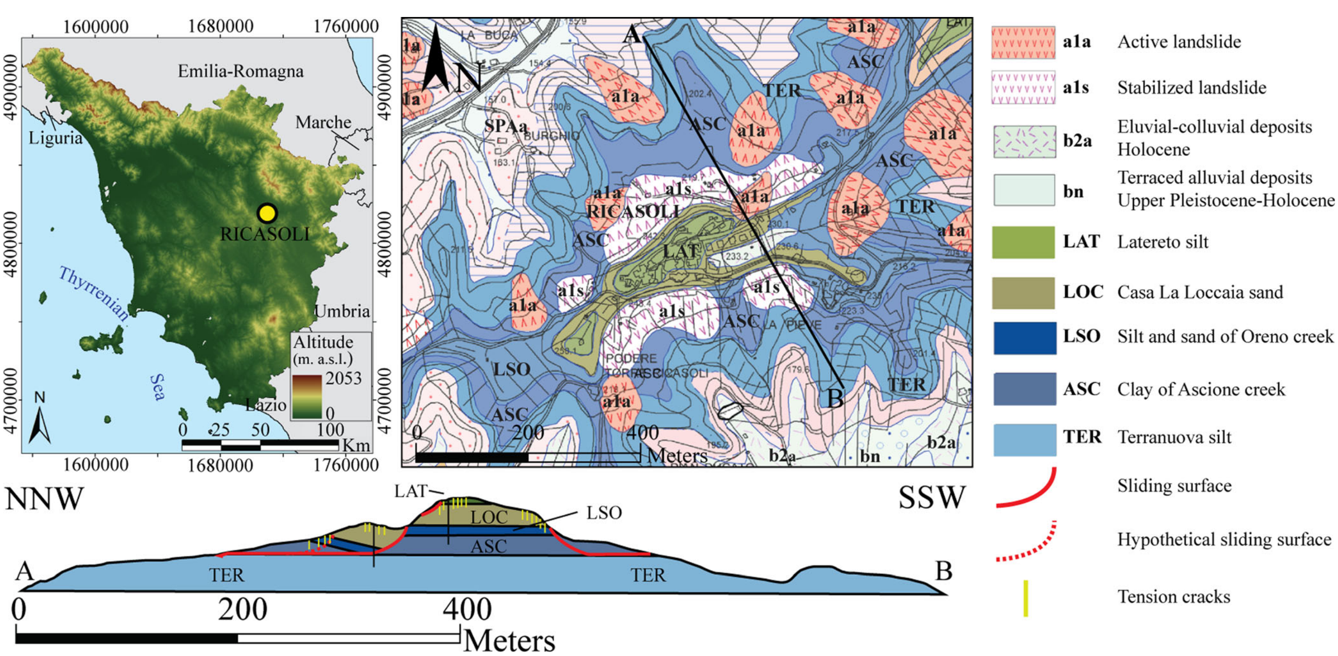

Fig. 1 Location, geological map, and geological cross section of Ricasoli village (modified after Rosi et al. 2013)

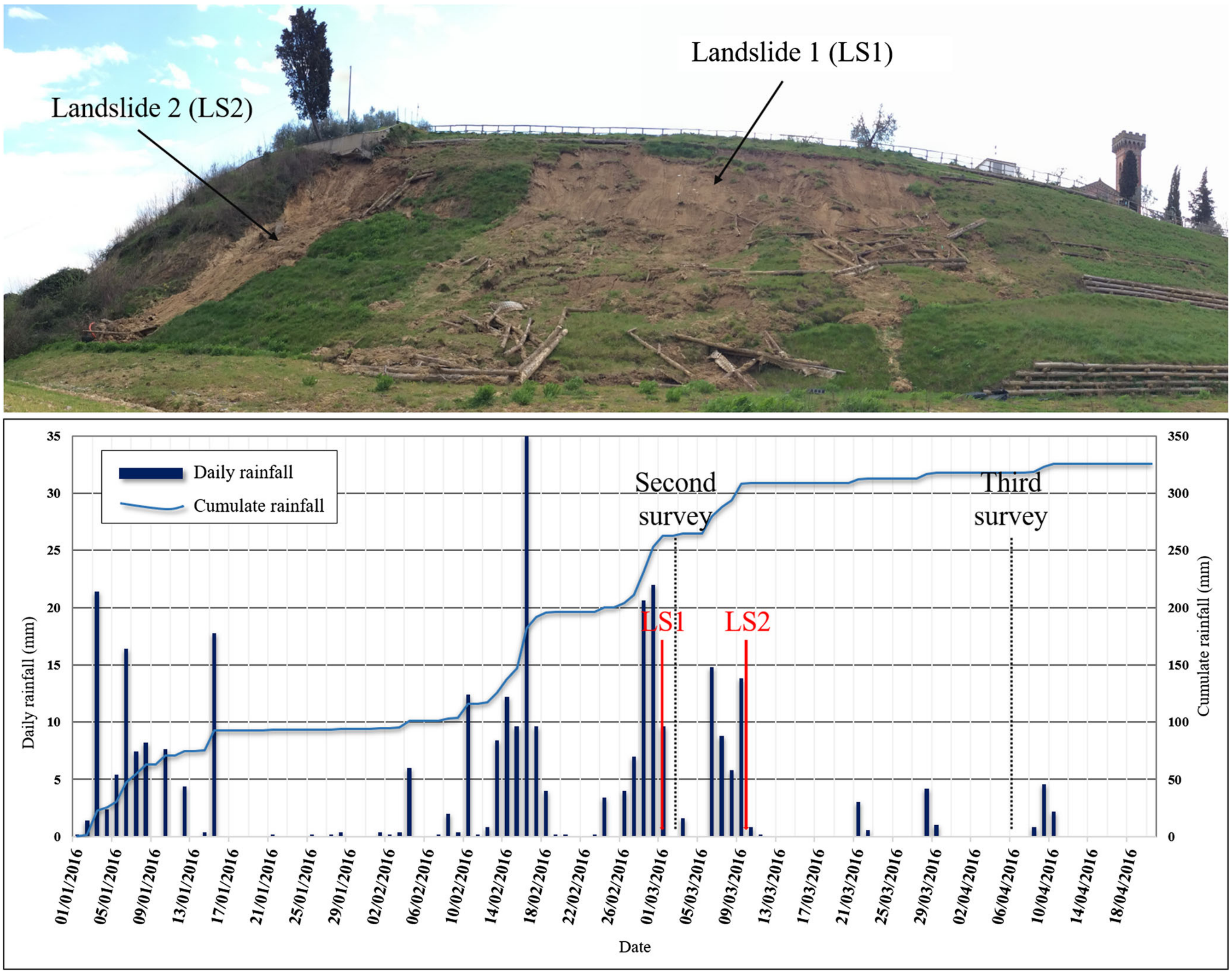

Fig. 2 Panoramic view of the portion of the northern slope of Ricasoli affected by the landslides. The plot below shows the cumulated rainfall registered by a nearby rain gauge, from January 1st 2016 to April 21st 2016, along with the occurrence of the two landslides. UAV survey dates are marked as dashed black lines

- Maximized flexibility of propulsion configuration: without any modifications to the airframe, it is possible to vary the number of propulsion systems (three, four, six etc.) even during the flight. The flexible propulsion configuration allows us to fit the need of every single mission: less engine to increase autonomy, more engine to allow for heavy payload.
- Variable propulsion geometry to keep the perfect balance with all types of payloads and to manage an emergency landing in case of a propulsion unit failure.
- Completely water-resistant electrical and electronic systems to fly during any weather condition.

The *Saturn* drone is capable of autonomous flight, from take-off to landing, and emergency management. The autopilot software is completely programmable and configurable.

The *Saturn* drone has onboard a complete and fully configurable acquisition system with frame grabber for scientific instruments. The drone is a "light" UAV class (< 25 kg take-off weight), can hover until 30 min, and has a useful load of 10 kg.

Digital photogrammetric surveys

Three aerial photogrammetric surveys were performed (see Table 1), respectively on July 30th 2015, March 2nd 2016, and April 6th 2016 using the DST drone Saturn, equipped with a Sony digital RGB camera with 8-MP resolution, mounted on a gimbal fully designed and assembled ad hoc by the research team of the Department of Earth Science.

The photogrammetric surveys were performed in five different stages: (1) mission planning, (2) acquisition of ground control points with GPS, (3) flight and image acquisition, (4) point-cloud processing and refinement, and (5) implementation in GIS environment (Fig. 3).

The first stage consists in the flight planning, which must ensure the best coverage of the target area with an optimal photo overlap in frontal (overlap) and lateral direction (sidelap), considering the camera footprint at the desired flight altitude (Fig. 3b). To optimize flight time, spatial coverage, and ground resolution

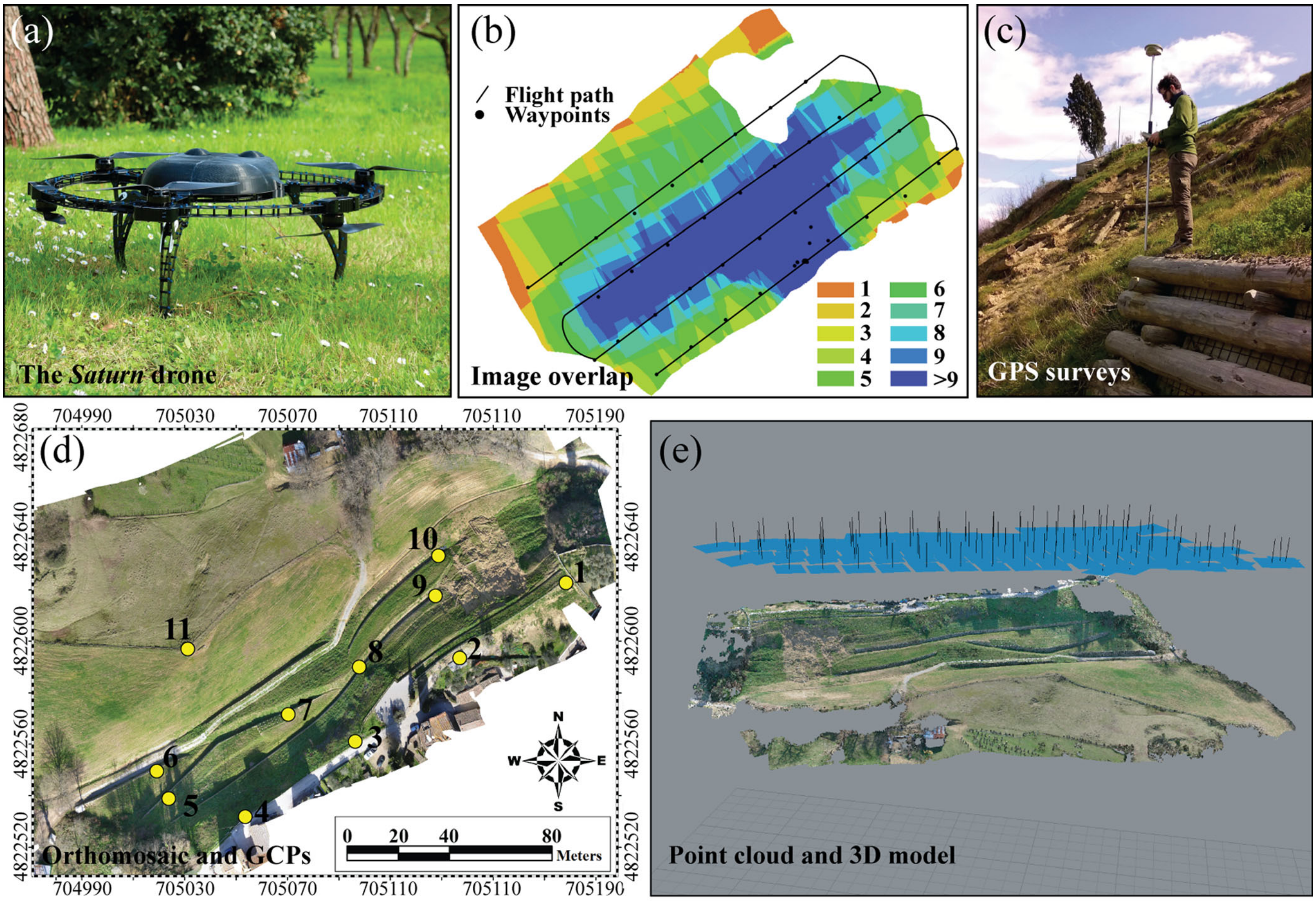

Fig. 3 The *Saturn* drone designed and built by the Department of Earth Science of the University of Florence (**a**) and stages of photogrammetrical surveying: flight planning (**b**), GPS acquisition (**c**, **d**), and point-cloud processing (**e**)

Table 1 Data related to the three different surveys

	Multicopter drone surveys July 2015	March 2016	April 2016
Number of images	58	106	45
Average flying altitude (m.a.g.l.)	70.6	70.3	69.7
Ground resolution (m/pix)	0.019	0.02	0.019
Number of GCPs	12	18	5
Coverage area (km^2)	0.0186	0.0186	0.0151
Number of tie-points	9328	14,690	31,910
Number of projections	52,527	96,102	160,217
Overall error in XY (m)	0.0741	0.0475	0.0595
Overall error in Z (m)	0.0791	0.0115	0.0221
Overall error (m)	0.1085	0.0489	0.0635
Overall error (pix)	0.91	0.07	0.77
Processed points	10^8	9.96×10^7	4.11×10^7
Orthomosaic resolution (m/pix)	0.02	0.02	0.02
DEM resolution (m/pix)	0.02	0.02	0.02

the multicoper was programmed to fly at a constant altitude of approximately 70 m a.g.l. from the top of the slope, with side overlap and front overlap respectively set to 50 and 60% to guarantee optimal conditions for the tie-points detection algorithm and camera alignment (bundle adjustment).

The position of objects on the ground that can be easily recognized in the aerial photos were measured with a GPS (Leica 1200 series) and used as ground control points (GCPs) (Fig. 3c): a special care was taken to have a homogeneous spatial distribution of GCPs on the scene. The images were processed using Agisoft Photoscan Professional (Agisoft LLC 2016) software, and the resulting data were implemented in GIS environment using the ESRI ArcGIS package (Fig. 3d and Fig. 3e).

Nevertheless, the scene was mainly characterized by low vegetation and grass, and it was decided to integrate natural GCPs with some artificial markers, placed on the ground prior to each flight and georeferenced with centimeter accuracy (generally an average value of 0.03 m RMSE in XYZ).

The original point clouds were opportunely filtered using Photoscan tools in order to detect and to remove points that corresponded with vegetation and needed to be removed to compare with the other survey dates. This step was necessary since the grass growth generated an irregular positive offset of 20–40 cm, along the whole scene, between the first and the third survey.

The ground image coverage obtained by the aerial survey is shown in Fig. 3b; the maximum coverage is in correspondence of the lower part of the escarpment where every point of the scene is visible in more than nine images.

Further details on the aerial survey are reported in Table 1.

The resulting 3D point clouds were composed by up to 100 million points (Fig. 3d) and high-resolution DTMs (0.05 m/pix) were obtained by using the point clouds, appropriately filtered to remove all the points processed on buildings, unwanted elements on the scene, and high vegetation. Furthermore, for the three surveys, digital orthomosaics were processed in Agisoft Photoscan, with a ground resolution of 0.05 m/pix, using the DTMs as a base for the orthorectification process.

Results

The data collected in the three photogrammetric surveys were analyzed and compared each other to assess the precision of the resulting digital models and to detect areas affected by instability processes.

The comparison was performed using both the orthomosaics resulting by the photogrammetric processing and DTMs derived by the point clouds.

The DTMs were compared to detect any morphological change between the three acquisitions, permitting to characterize the landslide and, in addition, to precisely point out geomorphological features of landslide-prone areas on the slope.

The result of the first aerial survey carried out on July 30th 2015 shows an incipient deformation on the ground surface (yellow dashed circle in Fig. 4a) on the eastern part of the slope. During a preliminary survey, we assessed that such part of the slope was stabilized only using wooden poles, anchored at a low depth, that appeared bended downslope, with tension cracks and a little sink uphill. This incipient movement phenomenon is indicated as pre-existing LS1 in Fig. 4a. No other indicators of ongoing movement were detected on the remaining part of the northern slope during the first flight.

As a consequence of intense rainfall occurring during February 2016, the area that was recognized as potentially unstable by the first survey was involved in a shallow landslide, affecting a portion of the slope with an overall extent of 1250 m^2 (LS1 in Fig. 4b).

The comparison between the first and second survey DTMs carried out on March 1st 2016 (Fig. 4d) highlights respectively the detachment, the transport and the deposition areas of LS1, and an appreciable displacement with the development of two new scarps on the eastern part of the slope (2a and 2b in Fig. 4d). The two scarps indicate a new landslide that involved a portion of a private property nearby. This landslide (LS2) eventually occurred in March 9th, 2016 after a few days of intense rainfall and appears visible when comparing the DTMs of the second and third survey that was carried out on April 6th, 2016.

The evolution of the superficial topography was also studied by extracting surface profiles along two selected sections (AA' and BB' as shown in Fig. 5).

The longitudinal profiles (Fig. 5) show the general geometry of the landslides. In the detachment area, LS1 is characterized by a nearly planar slip-surface with an average depth of 60–70 cm from the original topography. LS1 is also visible in the detachment area, has an extent of 480 m^2, and involves moistly a superficial level of artificial landfill that was put in place during previous slope stabilization works.

Furthermore, within LS1, a new scarp was detected by comparing the DTMs of the second and third surveys (scarp 1d in Fig. 4). This scarp was also verified during a field survey, and it partially delimits a secondary slope movement that involves the lower part of the landslide LS1. The movement of this portion was observed through a comparison between the DTMs and the orthophotos, with average superficial displacement of 0.6 m along the slope and resulted in an advancement of the landslide toe of around 50 cm, as measured during a field inspection.

Substantial changes in elevation of up to 0.6 m are visible only in the part immediately downslope of the scarp 1d (Fig. 4f). The rest of the moving portion do not show appreciable elevation differences.

The extent of such a secondary landslide is ~ 430 m^2, and it is characterized by a planar translational type of movement (Varnes 1978) with an average thickness of ~ 0.5–0.6 m, also involving part of the antecedent LS1 deposits.

The LS2, as visible from the BB' profile in Fig. 5, has a different geometry. In fact, it was composed of two roto-translational landslides that evolved into flow type landslides, creating a deposition area at the slope toe.

Thanks to the DEMs comparison it has been possible to estimate the total extent and volume, both including detachment and depositions zones, of LS1 and LS2. Extents for LS1 and LS2 are, respectively, 1250 and 320 m^2 while, considering our measurements errors in this area, volumes are 480 ± 150 m^3 and 70 ± 8 m^3 respectively.

Discussions

The aim of the work was to test the applicability and evaluate the potential use of drones, in this case, equipped with a commercial RGB camera to detect and possibly monitor mass movement on slopes. The comparison between the obtained DTMs provided the means for the mass movements on the northern slope of Ricasoli to be characterized in detail.

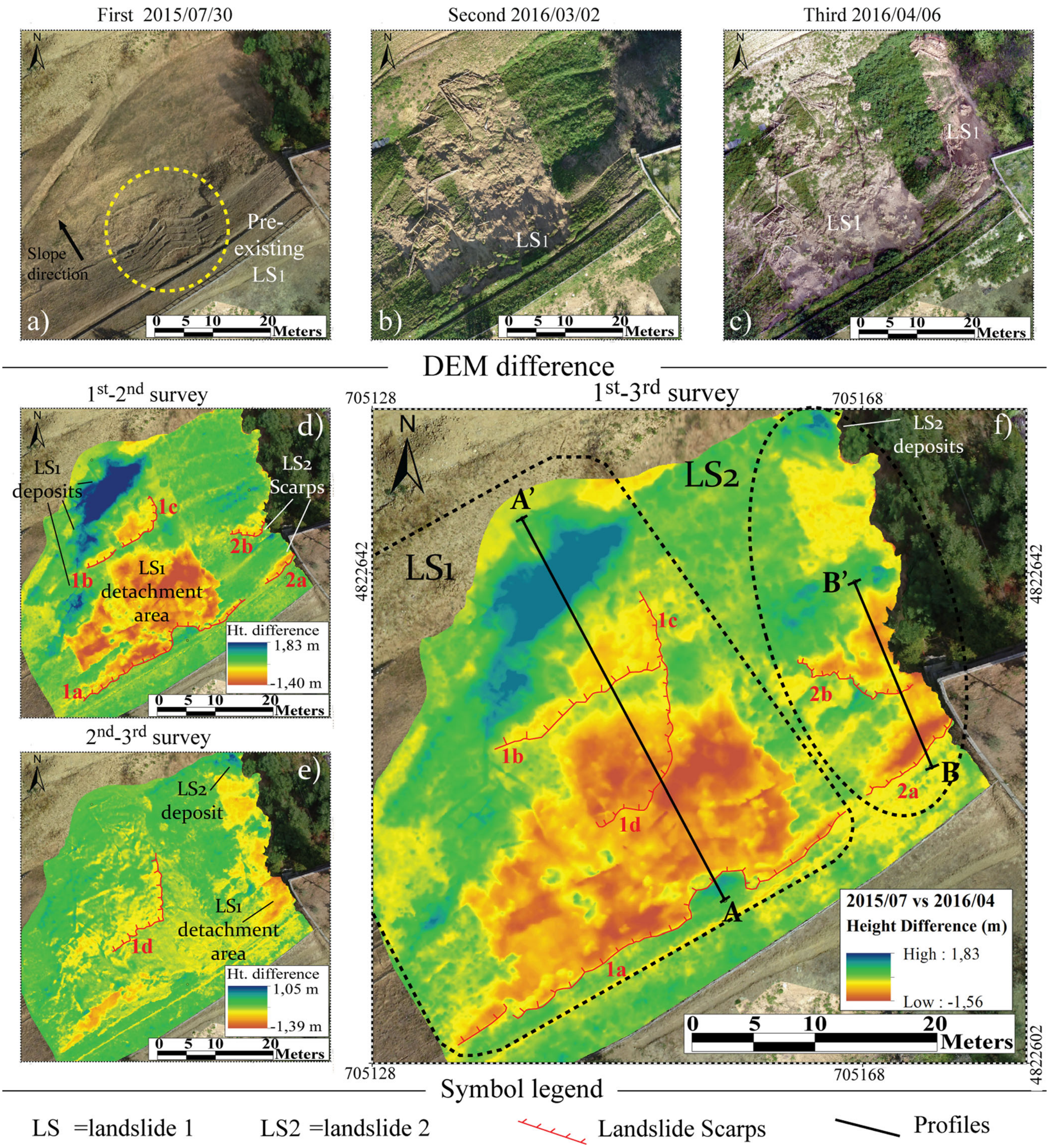

Fig. 4 Orthophotos of the area affected by the landslides (**a**, **b**, **c**) and DEM differences among different acquisitions (**d**, **e**, **f**)

Although this is a preliminary work, focused on a small area, it was sufficient to point out some advantages and drawbacks of the technique.

One advantage is the potential repeatability of the surveys in a relatively short time and with high resolution, especially when compared to other techniques such as terrestrial laser scanning, as well as the low cost. Indeed, in most of cases, in situ visually distinguishable ground features found in the imagery can be easily used as GCPs while at least a few artificial reflectors must be installed for a TLS survey, a time-consuming procedure that must be repeated every time. Furthermore, performing nadiral surveys using a drone instead of using photographs taken at ground level (nearly horizontal shooting direction) on a landslide allows an easy and uniform acquisition of high-resolution imagery in over a wide area in a short time and reducing the "shaded areas" that can lead to holes in the model. The overall time for the survey in the area covered (around 0.02 km^2) is about 40 min (10–12 min of

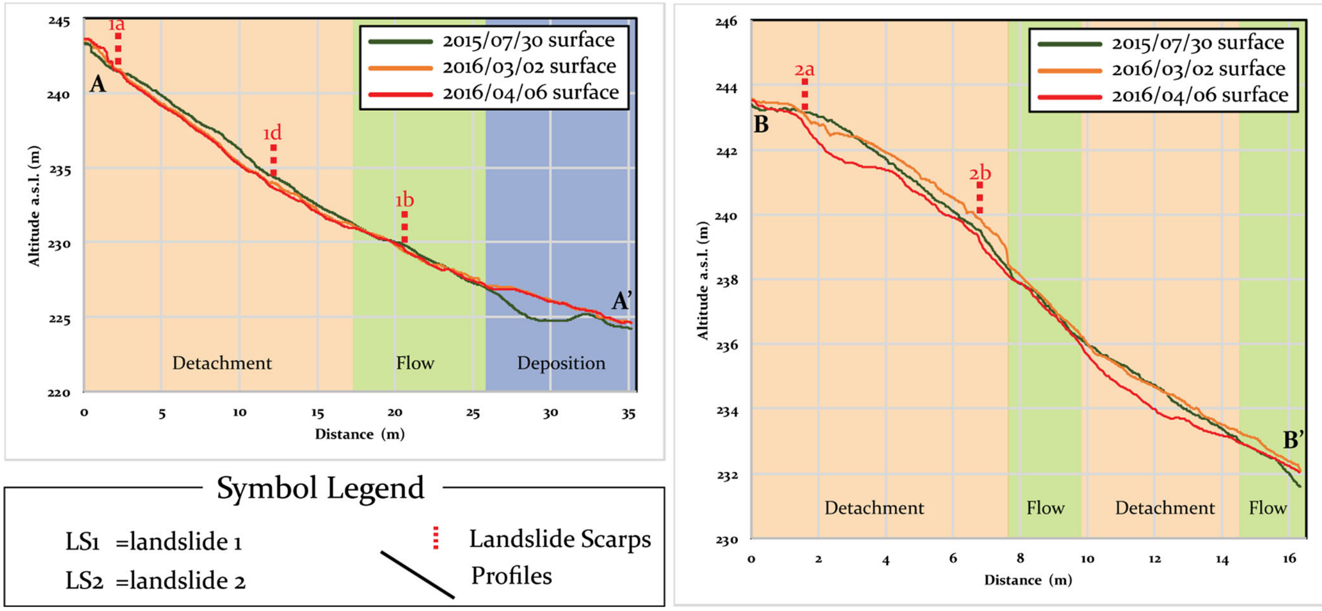

Fig. 5 Topographical profiles obtained from the three raster surfaces with location of the main scarps. The colors indicate the different zones of the landslides: detachment, flow, and deposition

actual flight) including flight planning and GCPs acquisition with GPS. Moreover, it allows immediate processing to create an aerial orthomosaic, useful for visual inspections, characterization and mapping of the detected phenomena even in emergency contexts.

The data were processed using a workstation (CPU 2x Xeon 2.93 GHz, 32 GB RAM, GPU Radeon HD 5870) with an average processing time for the point-cloud calculation of about 30 min for the first and the second dataset (less for the third one, due to the smaller size of the area, see Table 1), including the image matching, alignment, and point-cloud densification. The post-processing stage, consisting of the vegetation removal, meshes generation, mesh refinement, and DTM generation, required approximately few hours of work when the workflow is standardized.

This work pointed out one of the most important drawbacks of this kind of aerial photogrammetric applications with challenge of filtering (removal of) vegetation points to obtain an accurate representation of the "bare earth" when creating SfM 3D models.

The vegetation is generally removed from the resulting point clouds using automatic filtering algorithms (Brodu and Lague 2012) that could be based on the relative position between the points within a certain distance at a certain scale, on the RGB values or, at least, manually. The application of such techniques and automatic algorithms is often effective when using laser scanning data, thanks to the capability of the laser beams to penetrate the vegetation foliage, but less effective on photogrammetric point clouds, especially in presence of dense and uniform coverage. As seen in this work, the result of this effect is the inability to accurately reconstruct the terrain features below a dense grass coverage on the slope, increased from the first survey (July 2015) to the last one. Figure 4b, c shows how there was a significant growth of grass between the first and the second and third surveys. In the second and third surveys, a dense grass blanket that prevented the triangulation of points corresponding to the surface below covered the slope. This change in grass growth resulted in a diffuse increase in altitude in all the grassy areas (from 20 to 30 cm) and is visible from the DEM comparison. Removing these points would have led to widespread holes in the 3D model. On the other hand, isolated trees and sparser vegetation are generally easily removed by applying automatic filters and manual refinement. In this case, as well as leading to an uncertain volume calculation, such vegetation effect did not allow the detection of fissures and other features of the ground, useful for precise landslide delimitation and characterization.

However, the negative effects of vegetation on the precision of the model could be reduced with the use of a high-quality camera with higher resolution equipped with low distortion lens, avoiding fish-eye effects.

Generally, although pointing out the good potential of drone applications for mapping and characterization of rapid kinematic landslides, this work highlighted a strong need for a higher frequency of surveys and for the integration with other monitoring techniques, due to the temporal discontinuity of measurements.

A future development will regard the execution of further drone surveys, also testing the use of different types of sensors and the application of software to reconstruct the displacement vectors, based on the acquired point clouds, DTMs, or on the RGB imagery. In particular, the use of images acquired with multispectral sensors can provide important information to precisely distinguish areas with vegetal cover from the bare ones and it is of common use to produce landslide inventories at basin scale from satellite sensors (Martha et al. 2010; Lin and Zhou 2013) and due to the recent development of devoted sensors, it can become a valid approach also in the field of drone remote sensing for landslide recognition and mapping (as described in Shi and Liu 2015).

Conclusions

In the last decade, the combination of rapid development of low-cost small unmanned aerial vehicles (UAVs), improved battery technology, and conventional sensors (Optical and LiDAR) in terms of cost and dimensions, has led to new opportunities in environmental remote sensing and 3D surface modeling. The Department of Earth Sciences at the University of Florence has developed a new drone airframe that overcomes some critical issues for scientific and heavy payload or long flight applications. This drone has been equipped with an optical camera and it has been used to perform photogrammetric data acquisition in an area close to the village of Ricasoli, in Tuscany (Italy). The aim of this work was to test the use of aerial images taken from a multicopter for landslide detection and characterization. The images acquired during the aerial surveys allowed us to obtain a continuous 3D surface model of the studied area using a photogrammetric approach.

The detection of possible displacements occurred in the covered area between three aerial surveys was performed by comparing the different Digital Terrain Models and point clouds. As a result, two mass movements were detected and characterized, namely LS1 and LS2, affecting the northern slope of Ricasoli village, and a new incipient phenomenon in the lower part of LS1.

The drone survey has proven to be an easy and effective approach for landslide monitoring and surveying and thanks to these potentialities and to its repeatability, it has become an integral part of the monitoring system in Ricasoli village.

Acknowledgements

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