Dear Editor,

Please find enclosed the revised version of our manuscript entitled "**Brief Communication "The use of UAV in rock fall emergency scenario**". We have found the criticism, comments, and suggestions received from the referees very constructive, and we have considered all of them in the revised version of our work. In order to comply with the referee's requirements, we have slightly exceeded the number of references allocated for Brief Communications. Would you decide to keep the 20 references limit, we will remove the exceeding references accordingly.

Please find here below for your reference the referee's comments, and in **Bold** our replies. Changes in the text of the revised manuscript are highlighted in ***Bold Italic.***

Looking forward to receiving the final acceptance of our manuscript,

Sincerely yours.

Daniele Giordan
(Corresponding author)

Interactive comment on "Brief Communication
"The use of UAV in rock fall emergency scenario"
by D. Giordan et al.
Anonymous Referee #1
Received and published: 25 June 2014

As somebody frustrated with media coverage of UAS relegated mainly to surveillance and package delivery, this manuscript was a refreshing read. For the most part, the paper reads well, and does a great job conveying how UAS can be a valid survey tool.

Our reply: We thank the Referee #1 for this comment. We are pleased to read that our work on UAS is appreciated.

I was dissapointed however, in the use of the word 'drone' as this is a term that advocates for UAS stay away from due to the negative image it connotes. I was also disappointed in the misuse of terms within the manuscription, along with some very import terms never even brought up. These I will cover in my specific comments below.

Our reply: We thank the Referee #1 for this comment on terminology. We have analyzed his criticism and updated the manuscript according to the suggestions received.

Despite needing to fix these issues, the overall message of the paper is very good, and should provide a great foundation for others to add upon as research related to the practical applications of UAS in the geomorphic realm continues to build. To build upon the specifics of the terminology, I must point out the geocoding involves matching something such as an address to a set of coordinates, not providing an image with a set of geographic coordinates. The term the authors are looking for here is 'geotagging'. Beyond that, I still am not sure if the authors performed a georeferencing operation, or an orthorectification of their image. From what I can tell, since you generated a point-cloud DSM with the imagery gathered, and then use both the GCPS and the

DSM, you performed an orthorectification. I can't tell because nowhere in the manuscript was point cloud generation described (only mentioned in passing), nor was the percent overlap of the imagery. The details behind this are very important to the methods section.

Our reply: We thank the Referee #1 for this comment. We agree with the terminology proposed and we updated the revised version of the manuscript accordingly. Moreover, we have better clarified the whole process from the point-cloud to the DSM generation and the subsequent orthorectification.

The reader will also want to know the speed/specs of the computer the processing was performed upon, as the authors likely know that crunching all the data requires a decent amount of processing power.

Our reply: In the revised version we added the specs of the computer used for processing and details on the computational power/time required.

Finally, for the GCPs, I want to know how the TS was tied into cordinates on the ground. Was a survey grade (dual frequency) GPS used to site the TS? The authors described in high detail the pixel resolution, but not much on the spatial resolution of the GCPs. To summarize, I think some tweaks need to be made for this paper to hold weight.

Our reply: We thank the Referee #1 for this comment. We have now specified that the TLS data was processed by considering positioning data acquired with a two L2 GPS installed in-place and acquiring in static mode during the whole scanning operations (about 2 Hours)

Here are some technicals I came across:
P 4012 L13 Generally, rock falls size ranges..... I would change to rock fall or reword sentence.

Our reply: Thanks, we have reworded the sentence.

P 4013 L19 This last sentence needs commas or rewording. Also, as I pointed out earlier, I don't think you georeferenced...you orthorectified. I say this because georeference does not use z values, which you did use with the point cloud you generated.

Our reply: Thanks, we have reworded the sentence.

Interactive comment on “Brief Communication “The use of UAV in rock fall emergency scenario”” by D. Giordan et al.

Anonymous Referee #2

Received and published: 7 September 2014

General comments The paper presents the description of a methodology for the quick monitoring of rock fall phenomena using micro-UAV. The presented methodology is of interest for many applications and well describe the suitability of UAV for this kind of applications. You propose a time-sheet for the delivery of different products (visual inspection, 3D model, etc.) that are completely in accordance to similar studies performed with UAVs. The paper is usually clear and most of the elements are well-written.

Our reply: We thank the Referee #1 for this comment.

Anyway, I have some comments that should be considered for the final version of the paper. Specific comments The introduction is quite complete. Anyway you should add more references for the different UAV applications. UAV are nowadays used for thousands of different applications, please list some of these.

Our reply: We thank the Referee #1 for this comment. In order to comply with this comment, we have included 2 additional references. However, NHESS Brief Communications have a limit on the citable references (up to 20), thus the final decision on the inclusion of these additional references in the final version of the manuscript stays on the Editor.

pp. 3. You mention the solid image, but most of the readers couldn’t know what you mean. In the test there are several references to this product, but there isn’t a clear explanation. Please, put all the references of the solid image together and briefly describe it. You must also provide evidence of the used algorithm/software to generate them.

Our reply: In the revised version, we have now included a clarification and a description of the solid image product. Also, the algorithm and the software used to produce it is now more extensively described.

You mention that you use the go-pro for the photogrammetric processing. This camera has 2 different problems: the first is the resolution (as you mentioned), the second is the big image distortion and the poor radiometric content. Please add this second aspect in the paper.

Our reply: We thank the reviewer for this comment. We agree that the go-pro for photogrammetric processing has different problems. On the other hand, in the specific case the acquisitions were made from 20-30 meters distance from the target, thus distortion is not as high as it would have been from 60-70 meters distance. This is now clarified in the revised version of the manuscript.

Due to the low image quality, your 3D model could be nice-looking, but I believe it would be so accurate as it seems. pp. 7: I agree that you way to georeference the data (using on board data) is just sufficient to provide a rough scale of your 3D model. Anyway, the use of GCP must be performed too. I think that a 3D model performed in such a way is not sufficient to take accurate measurements of you area.

Our reply: We agree with this general comment. As specified in the paper, the accuracy of the measurements you can take in these conditions is also function of the time you need for survey operations. In the manuscript we state "*Time-consuming processes have the advantage of providing highly accurate results, but they are not suitable in emergency contests, where the rapidity of the response is crucial.*" The proposed methodology allows to build-up in a straightforward manner and relatively short time a rough 3-D model, which is useful for different applications especially in emergency conditions. GCP are surely necessary to achieve a more accurate measurement, but in real case scenarios often GCP cannot be acquired safely. The revised manuscript outlines also that by using UAS acquisitions to perform such measurements, one has to be aware of the limitations.

pp. 8: If you use these GCP for multi-temporal analysis, some of them could be displaced between epochs due to the landslide. Probably in this case, a photogrammetric registration of the images would be of help to match the data at different epochs.

Our reply: GCP have been taken on a stable area. However, we agree that in case of displacements due to landslide photogrammetric registration can be a solution to match data at different epochs

Brief Communication: the use of UAV in rock fall emergency scenario

Daniele Giordan*[1], Andrea Manconi[1], Anna Facello[1], Marco Baldo[1], Federico dell'Anese[1], Paolo Allasia[1], Furio Dutto[2]

1 National Research Council, Research Institute for Geo-hydrological Protection, Geohazard Monitoring Group, Strada delle Cacce 73, 10135 Torino (Italy)

2 Torino Province, Civil Protection Service, Via Alberto Sordi 13, 10095 Grugliasco (Italy)

*Corresponding author: daniele.giordan@irpi.cnr.it

Abstract

In recent years, the use of Unmanned Aerial Vehicles (UAVs) in civilian/commercial contexts is becoming increasingly common, also for the applications concerning the anthropic and natural disasters. In this paper, we present the first results of a research project aimed at defining a possible methodology for the use of micro-UAVs in emergency scenarios relevant to rock fall phenomena. To develop and support the herein presented method, the results relevant to a rock fall emergency occurred on March 7, 2014 in the San Germano municipality (north-western Italy) are presented and discussed.

Key worlds: rock fall, UAV, emergency management

1. Introduction

In mountainous regions, transportation corridors are often susceptible to landslides (Michoud et al., 2012). In particular, rock falls constitute a major hazard in numerous rock cuts. Generally, rock falls size ranges from small (less than a cubic meter) to large boulders hundreds of cubic metres, and travel at speeds ranging from few to tens of metres per second (Cruden and Varnes, 1996). Emergencies related to rock falls occurring on settlements or roads require an a-priori detailed characterization of the instable areas, as well as of their potential evolution over time. The latter areas, however, are often difficult to access due to their typical morphology. Moreover, during emergency scenarios field operations are prevented due to the potential risk associated to further gravitational phenomena. Therefore, there is a real need of straightforward procedures allowing to obtain robust and reliable datasets in a rapid and safe manner, aiming at a achieving a more quantitative analysis of the rock mass.

In recent years, the use of Unmanned Aerial Vehicles (UAVs) in operations relevant to civilian/commercial contexts is becoming increasingly common (Chiabrando et al., 2013). For example, an important application domain is in the area of emergency assistance and management, with scenarios including anthropic and/or natural disasters such as floods, earthquakes, and landslides (Tien-Hin et al., 2010). Micro-UAVs are used to carry lightweight instruments, such as consumer digital cameras, to acquire photographs of the area of interest and eventually allow for photogrammetric processing (Neitzel et al., 2011). Moreover, micro-UAVs are also used as a test bed for the integration of multiple instruments, as well as for the development of new sensors (Colomina, 2007).

As an example of application in a real-case scenario, after the Hurricane Katrina micro-UAVs equipped with three different sensors (pan-tilt thermal and visual sensor, and a fixed visual sensor for pilot view) were used to inspect collapsed buildings (Pratt et al., 2009). In addition, images from a micro-UAVs and unmanned sea surface vehicle were used for inspection of bridges and seawalls for structural damages (Murphy et al., 2008). Also, after the earthquake in L'Aquila, April 2009, UAVs equipped with cameras were used for building inspection and situation assessment (Nardi, 2009).

In this paper, we present the first results of a research project aimed at defining straightforward methodologies to use micro-UAVs in emergency scenarios relevant to rock fall phenomena. The project is carried out by the Geohazard Monitoring Group (GMG) of CNR IRPI and the Civil Protection of the Torino Province. The main purpose of the project is the use of micro-UAVs equipped with high-resolution digital video- and photo-cameras to build up in a rapid and straightforward manner orthorectified 3-dimensional terrain models in areas potentially affected by rock fall. In general, the expected output of the survey a 3-D solid image of the area of investigation to measure 3D coordinates from a simplified 2D image. The concept of solid images was firstly introduced in 2003 as a geomatic product to describe 3D objects in a straightforward and complete manner (Bornaz and Dequal, 2004; Gonzales, 2009). In rock fall scenarios solid images can be used for the recognition and the characterization the most instable sectors, and to support the management of emergencies. In the following, we present the first results obtained on a recent rock fall event occurred in the San Germano municipality, northwestern Italy. There, we applied the herein presented methodology to retrieve solid images from pictures acquired by a micro-UAV during the emergency phases.

2. The San Germano rock fall event

At the beginning of March 2014, a critical instability involving a large portion of a rock wall was detected along the Provincial road SP 168 (Torino province, NW of Italy, see Figure 1). The SP 168 is the sole route connecting the Pramollo municipality with the bottom of the valley, and allowing the population to reach services, schools, and workplaces. The instability involved an outcrop mainly composed of Dora Maira micashist (Borghi et al., 1985) about 100 m long and 40 m high. Despite stabilization works were performed about 20 years before, a large fracture progressively developed along the entire rock wall. On March 06, 2014, this fracture started opening with a rate estimated in several centimeters per day, and minor falls started to affect the rock wall. In order to comply with these clear signs of criticality, the pathway adjacent to the rock wall has been closed to the traffic by the authorities responsible of the viability (Viability Service of the Torino Province, VSTP). In addition, VSTP informed the Torino Province Civil Protection Service (CPS) about the hazard potential related to the San Germano rock mass.

In this scenario, GMG and CPS operated the first survey during the afternoon of March 7, 2014. GMG performed a preliminary field observation aimed at identifying the instable area and recognize the main evidences of activity. The principal indication of the instability was the presence of a large fracture on the frontal side of the rock wall, and the presence of trenches in the upper part of the slope over the steeper sector. The lateral side of the rock wall was suffering an increasing number of minor rock falls, and the evolution of the opening of the main fracture started to be extremely evident. The frequency of minor falls increased during the afternoon, and at 17:00 CET the road was totally closed to the traffic. At 17:15 CET the rock cliff collapsed, and more than 1x10^3 cubic meters of rock deposits covered the entire road path. After the collapse, the communication with the upper part of the valley and the Pramollo municipality was interrupted, and an emergency procedure to restore the street and to assure an emergency communication and support to the population was immediately settled on. The SP168 remained closed until March 15, 2014, to allow the removal of the rock fall deposits, as well as to stabilize the new profile of the rock wall modified by the event.

2.1 Use of micro-UAV during the San Germano emergency

During the MASSA Project (Lanteri et al., 2015), the GMG and CPS have developed a protocol to support survey activities relevant to rock fall events in order to provide decision makers with quantitative data useful to deal with emergencies scenarios. In this context, GMG and CPS have postulated also to use of micro-UAVs equipped with digital video- and photo-cameras to obtain a complete survey of the instable rock mass.

According to the MASSA Project indications, a first survey with a micro-UAV has been performed on Friday March 7, 2014, shortly before the San Germano rock fall event. Moreover, a second survey has been repeated also on Saturday March 8, 2014. In the event's aftermath, several complementary investigations have been performed, including terrestrial photographic surveys (©Nikon AW 100) as well as a Terrestrial Laser Scanner (TLS) acquisition. The micro-UAV available was a 6-rotors multicopter Carnboncore 950 equipped with a ©GoPro Hero 3 digital video-camera (hereafter referred to as ©GoPro). The remote control ensured the management of the flight of the micro-UAV and of the gimbal orientation. The ground control station was equipped with a monitor displaying in streaming the data flow acquired by the ©GoPro. In this modality, the survey operation was performed by a team composed of the pilot, taking care of the UAVs stability only, and a geologist, monitoring in real-time the position and the point of view, and eventually indicating changes of trajectory. In these scenarios, due to the complexity of the operations and the morphological characteristics of the area investigated, the autopilot solution is not envisaged. Table 1 summarizes the dataset collected during several surveys and considering different settings and instruments.

The data acquired during the micro-UAV surveys have been processed with the ©Agisoft Photoscan software (hereafter referred to as Photoscan). Photoscan is based on the "Structure from Motion" technique , and is capable to process the digital images and extract point clouds relevant to the common areas of the scenes acquired (Westoby et al., 2012). To automatically obtain the image sequence of interest also from the ©GoPro videos, the MPEG2 original video was processed by means of an OpenSource video editing application, ©VirtualDub (v1.10.4 stable, http://www.virtualdub.org). After the selection of the suitable content, the video frame rate was downgraded to 0.20 fps and finally exported as image sequence (JPEG, full quality).

We generated two solid images by considering the data acquired with ©GoPro. Further, an additional solid imaged was created by using the data collected via a Nikon AW 100 dataset, in order to compare the results obtained by using the micro-UAVs to terrestrial acquisitions. In total, a dataset of about 200 pictures has been processed for the generation of pre- and post-event solid images. In table 2, we present a synthetic comparison of results obtained.

The 3-dimensional solid images obtained have been used to generate a rough scale digital surface model (DSM), which can supply information about the relative dimensions of different elements inside the scene (e.g., height of the instable area, length of the fractures). By using ground control points (GCP), it is also possible to improve the accuracy of the geographic positioning of the solid image, which can supply thus the orientations of the main discontinuities identified in the rock mass. Figure 2 shows an example of the shaded relief derived from the DSM obtained from the survey of pre rock fall survey. This class of results can be used to perform first order quantitative analyses of the instable volume, as well as detection of joints and their classification.

3. Progressive results obtained by micro-UAVs in rock fall scenarios

The San Germano case study can be considered as test bed for the use of micro-UAVs useful to set up standards for rock fall emergency conditions. During emergencies, the processing time required to obtain the results is a very important element that has to be carefully considered. Time-consuming processes have the advantage of providing highly accurate results, but they are not suitable in emergency contests, where the rapidity of the response is crucial. Accordingly, we propose a procedure for the employment of micro-UAVs in rock fall scenarios consisting in several steps, which mainly depend on the processing time required to obtain the results and on their accuracy in terms of geo-positioning. The procedure considers the mission planning of a micro-UAV and, in particular, the sequence of obtainable products that can be used to study the bedrock structures and instabilities.

After the micro-UAV landing and the download of the acquired digital images, three different levels of results can be obtained in a timely progressive fashion: (i) video and photos of the instable area. These results are immediately available on site without any post processing activity. The immediate availability of videos of the area can be a very useful support in the field, mainly because the analysis of this data allows to image the instable area from different points of view, unlikely obtainable with field surveys. In addition, aerial photos taken from the micro-UAV can be very useful; however, the pictures sequence are usually not exploitable on site in a user-friendly manner. To cope with these problems, procedures of photo mosaicking can be considered to obtain a better overview of the surveyed area. At this stage, the information obtained from videos and photos is not orthorectified, thus allow only qualitative and semi-quantitative evaluations on the instable rock mass. (ii) 3-dimensional solid images. By using dedicated software, as for example ©Photoscan, it is possible to extract first a point cloud relevant to the common areas acquired in the scene. Subsequently, a Digital Surface Model (DSM) can be retrieved by calculating a best fitting surface with Delaunay triangulation or other interpolation algorithms (nearest neighbor, kriging, etc.) .The combination of the DSM and the photos allows to compose a 3-dimensional solid image of the investigated area (Hugenholtz et al., 2013). By considering the geographic coordinates acquired by the onboard GPS, the solid image can be roughly orthorectified. This second-stage result allows operators involved in the emergency scenario to have an additional tool, which can be now used for first quantitative evaluations. The resolution of the 3-dimesional solid image can be very high (in the order of 2 to 10 centimeters pixel resolution), and may allow for very detailed analyses of the structural settings of the rock mass, even in the zones with limited access. However, it is worth to mention that most of the micro-UAVs available in the market are equipped only with L1 GPS, thus their attainable accuracy on positioning is limited (in the order of 5 to 10 m). The time required to get this second-stage result depends mainly on the computing capabilities and on the size of the investigated area. In general, with off-the-shelf computers, we can consider a range of 2-3 hours for small areas, to 10-15 hours for larger instable sectors. (iii) The third-stage result differs from the previous one mainly because of the level of accuracy of the 3-dimensional solid image achieved through a straightforward orthorectification strategy. To increase accuracy in the geocoding, a set of ground control points (GCPs) is required. The coordinates of GCPs have to be measured by considering high accuracy geodetic instruments, such as terrestrial laser scanners, theodolites, and/or GPS receivers (Paar et al., 2012; Torrero et al., 2015). The key point is to identify a network of GCPs that have to be first recognized in the solid image, and then measure in the field their position. This kind of topographic survey can be time consuming, and increases the complexity of both the field activities and the number of people and instruments involved in the operations. In this latter case, the results are characterized by a higher accuracy in terms of orthorectification and geographic positioning, allowing for the definition the absolute orientations of joints families (e.g. Ferrero et al., 2011), as well as permitting for a more accurate estimation of the instable volumes. The accuracy level of these products may permit to use the dataset for monitoring purposes using a multi-temporal approach, if GCPs are stable during the investigation period. Figure 3 describes these three different levels of output, and considers also an indication of the time necessary for the restitution of different results. We remark that the indication of necessary time depends on the dimension of the studied area and/or on the available computational capacity.

4. Concluding remarks

In this work, we have shown the results obtained by using micro-UAVs to survey areas affected by rock fall phenomena. In the San Germano case study, we use the micro-UAV to support the analysis of the instable area and the evaluation of the risk with photos, videos and 3-dimensional digital models. The products outlined have been considered to support the CPS to manage the emergency operations. The GMG with CPS acquired a large dataset using the UAV and other terrestrial instruments, mainly to cope with the emergency situation, but also to acquire know-how and possibly define a standard methodology to manage rock fall scenarios. The presented case study evidenced that the use of micro-UAVs is a suitable solution to support both qualitative and quantitative evaluations during emergency conditions, where the survey results have to be available in a rapid and straightforward manner. One of the common limitations in rock fall emergency scenarios is the availability of only limited point of views of the instable area, which hamper a complete analysis of the detachment zone. In this context, the use of UAVs can be considered as a rapid and low cost solution to reach the zone hit by the rock fall, which is often difficult (or even impossible) to investigate in safe conditions. Indeed, micro-UAVs can be used to obtain information on the instable area, by taking a large number of photos and videos from several points and different angles of view. According to the problems that often characterize and have to be faced in emergency conditions, we have analyzed the processing time needed to get a set of results from the surveys, and defined a standard workflow for the use of micro-UAVs in rock fall scenarios. A set of products characterized by an increasing accuracy over time has also been defined to support the activities connected to the management of the emergency condition, which is the principal aim of the herein presented work. According to the processing time (Figure 3), the qualitative results obtained are important to recognize the principal instabilities of the studied area. These are one of the most important elements for an appropriate evaluation of the residual risk after the first activation of a rock fall. In this way, photos and videos taken by the UAV can be used immediately on site to support the first decisions for the management of the emergency (close roads and/or evacuate houses, etc.). After the first phase, usually it is also important to have a more detailed evaluation of the instable area to define possible scenarios. This second task needs to be supported by a quantitative approach, which allows for a first hypothesis about the instable sectors, their position and geometry. Also in this phase, the products obtained from micro-UAVs can be considered for the analysis of the phenomenon, as well as for supporting actions of decision makers, which have the duty to manage the emergency condition defining the elements at risk and planning a mitigation project.

In the San Germano case study, the available dataset has been acquired by using a ©GoPro video-camera. The use of video-cameras has the main advantage of providing images of the rock mass in very different conditions. On the other hand, at the moment several limitations can be associated to the use of ©GoPro:

(i) videos are limited by a relatively low resolution of 2-4 Mpixel; (ii) unavailability of the geographical coordinates of the acquired images; (iii) image distortion and poor radiometric content. In our specific case, the acquisition were made from 20-30 meters distance from the target, thus the limitations have been mitigated. However, by considering larger distances (60-70 meters) the mentioned limitations may impede obtaining products suitable for rock fall analysis. Instead, photo cameras are characterized by a higher resolution (10 Mpixel and above) and radiometric content. However, the quality of the images acquired by UAVs can be hindered by problems of focusing, in particular in windy or in complex scenarios where the presence of close-up elements (like trees or others) can shadow the real target, i.e. the rock mass. In order to manage these limitations, a possible solution can be to set up a payload composed by both a video- and a photo-camera, which can acquire information concurrently.

The exclusive use of micro-UAVs can be efficient for the generation of the first two order of results of the proposed methodology, but may suffer several limitations if we want to consider monitoring applications. In particular, repeatability conditions between successive surveys have to be respected. For this reason, in the San Germano case study we have contextually used a TLS acquisition to obtain a high resolution DSM of the studied area, to validate and improve the result obtained via the micro-UAVs survey. The DSM obtained via the TLS survey is characterized by a high point cloud density, and also by a very accurate geographic positioning. Indeed, two L2 GPS acquiring in static mode during the whole TLS acquisition where used to position the point cloud. The TLS has another important positive advantage: the availability of a very detailed DSM can be used to validate the results obtained via the micro-UAV (Henry et al., 2002; Jabojedoff et al., 2012). Moreover, this can also be used for a multi-temporal comparison aimed to define the morphological changes of the studied area linked to the gravitational phenomenon's evolution (Niethammer et al., 2012; Giordan et al., 2013).

In the presented case study, we also tested pros and cons associated with the use of different geodetic instruments for the acquisition of GCP, performing surveys not only with a Terrestrial Laser Scanner (TLS) but also with a Total Station (TS). TS can be considered as a suitable solution to get GCP coordinates on a rapid fashion, because the post processing time is very short. Moreover, if the GCP can be well identified in the field, the measurement of their absolute position can be done using the reflectorless technique. In a time comparable to the micro-UAV survey, the TS can acquire several tens of points. The most important limitation of this approach is the a priori identification of GCP, which is usually critical because it is not always possible to clearly recognize these points also in the solid image generated by exploiting the micro-UAV survey. On the contrary, TLS is a more time consuming technique, needing more time in the field and for the data post processing. The most important added value of TLS is that it is possible to a posteriori compare the solid image and the TLS colored point cloud and find the best matching points.

Another important limitation for the use of micro-UAVs is the occurrence of extreme weather conditions. This can be very critical, in particular during emergency condition, which usually are related to extreme weather events. However, we consider this as a current technical limitation, which will be likely solved and/or provide better performances in the near future. The use of UAV for the management of geo-hydrological instabilities is a new research field that will probably have a progressive increase in the next years. The potential of these tools is very high, and their development for application is only at the beginning. At the moment, one of the most important issues is the definition of procedures for their appropriate use. Such procedures have to consider carefully both the limitations and characteristics of the UAV and the kinematics properties of the phenomenon under evaluation. In this way, the results obtained from UAVs can be well exploited in several contexts, and will improve our capability to investigate geohazards by considering this new category of remote sensing data.

Acknowledgements

We thank Andrea Bernini and Mario Truffa from the Civil Protection Service of the Torino Province for technical support during the micro-UAVs survey. The comments of two anonymous referees have improved an early version of the manuscript. Disclaimer: in this work, the use of copyright, brand, trade names and logos is for descriptive and identification purposes only, and does not imply endorsement from the authors, or their institutions.

References

Borghi, A., Cadoppi, P., Porro, A., and Sacchi, R: Metamorphism in the northern part of the Dora Maira massif (Cottian Alps), Boll. Mus. Reg. Sci. Nat. Torino 3:369–380, 1985.

Bornaz, L., and Dequal, S.: The solid image: An easy and complete way to describe 3D objects. XXth ISPRS congress, Volume XXXV part B5: Istanbul, 183–188, 2004.

Colomina, I., Aigner, E., Agea, A., Pereira, M., Vitoria, T., Jarauta, R., Pascual, J., Ventura, J., Sastre, J., Brechbühler de Pinho, G., Derani, A., Hasegawa, J.: The Uvision project for helicopter-UAV photogrammetry and remote-sensing, Proceedings of the 7th International Geomatic Week, Barcelona, Spain, 2007.

Cruden, D. M. and Varnes, D. J: Landslide types and processes, in: Landslides, Investigation and Mitigation, Special Report 247, Transportation Research Board, Washington, 36–75, 1996.

Eisenbeiss, H.: The autonomous mini helicopter: a powerful platform for mobile mapping, The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences Vol. XXXVII Part B1: Beijing, 2008.

Chiabrando, F., Lingua, A., Piras, M.,: Direct Photogrammetry Using Uav: Tests and First Results, Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XL-1/W2, 81-86, 2013.

Ferrero, A.M., Migliazza, M., Roncella, R., Rabbi, E.: Rock slopes risk assessment based on advanced geostructural survey techniques, Landslides Vol 8, Issue 2, 221-231, 2011. DOI 10.1007/s10346-010-0246-4

Giordan, D., Allasia, P., Manconi, A., Baldo, M., Santangelo, M., Cardinali, M., Corazza, A., Albanese, V., Lollino, G., Guzzetti, F.: Morphological and kinematic evolution of a large earthflow: The Montaguto landslide, southern Italy, Geomorphology, 187, 61-79, 2013. DOI: 10.1016/j.geomorph.2012.12.035

González-Aguilera, D., Muñoz-Nieto, A., Gómez-Lahoz, J., Herrero-Pascual, J., Gutierrez-Alonso, G.: 3D Digital Surveying and Modelling of Cave Geometry, Application to Paleolithic Rock Art: Sensors, 9, 1108-1127, 2009.

Henry, J-B., Malet, J.P., Maquaire, O., Grussenmeyer, P.:The use of small-format and low-altitude aerial photos for the realization of high-resolution DEMS in mountainous areas: application to the Super-Sauze earthflow (Alpes-de-Haute-Provence, France), Earth Surf. Process. Landforms 27, 1339–1350, 2002.

Hugenholtz, C.H., Whitehead, K., Brown, O.W., Barchyn, T.E., Moorman, B.J., LeClair, A., Riddell, K., Hamilton, T.: Geomorphological mapping with a small unmanned aircraft system (sUAS): Feature detection and accuracy assessment of a photogrammetrically-derived digital terrain model, Geomorphology 194, 16–24, 2013.

Jaboyedoff, M., Oppikofer, T., Abellan, A., Derron, M.H., Loye, A., Metzger, R., Pedrazzini, A.: Use of LIDAR in landslide investigations: a review, Nat Hazards, 61, 5–28. 2012. DOI 10.1007/s11069-010-9634-2

James, M., Ronson R., Straihtforward, S.: Reconstruction of 3D surface and topography with a camera: Accuracy and geoscience application, Journal of Geophysical Letters. 117, F03017. 2012.

Pratt, K., Murphy, R., Stover, S., Griffin, C.: CONOPS and autonomy recommendations for VTOL small unmanned aerial system based on Hurricane Katrina operations, Journal of Field Robotics, 26 (8), 636–650, 2009. DOI: 10.1002/rob.20304.

Lanteri, L., Bormioli, D., Morelli, M., Dutto, F., Giordan, D., Manconi, A.: Rockfall Analysis during Emergency Scenarios, Lollino, G. et al. (Eds.): Engineering Geology for Society and Territory, Springer International Publishing, Vol. 5, 711-714. 2015.

Michoud, C., Derron, M.-H., Horton, P., Jaboyedoff, M., Baillifard, F.-J., Loye, A., Nicolet, P., Pedrazzini, A., Queyrel, A.: Rockfall hazard and risk assessments along roads at a regional scale: example in Swiss Alps, Nat. Hazards Earth Syst. Sci., 12, 615-629, 2012.

Murphy, R.R., Steimle, E., Griffin, C., Cullins, C., Hall, M., Pratt, K.: Cooperative use of unmanned sea surface and micro aerial vehicles at Hurricane Wilma, Journal of Field Robotics, 25 (3), 164–180, 2008.

Nardi, D.: Intelligent systems for emergency response, Invited talk in Fourth International Workshop on Synthetic Simulation and Robotics to Mitigate Earthquake Disaster (SRMED 2009).

Neitzel, F. and Klonowski, J.: Mobile 3D mapping with a low-cost UAV system, International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol. XXXVIII-1/C22, 1-6, 2011.

Niethammer, U., James, M.R., Rothmund, S., Travelletti, J., Joswig, M.: UAV-based remote sensing of the Super-Sauze landslide: Evaluation and results, Engineering Geology, 128, 2–11, 2012.

Paar, G., Huber, N.B., Bauer, A., Avian, M., Reiterer, A.: Vision-based terrestrial surface monitoring, Pradhan B., Buchroithner M. (eds). Terrigenous Mass Movements. Springer Heidelberg New York Dordrecht London. 283-348, 2012. DOI 10.1007/978-3-642-25495-6_10

Tien-Yin, C., Mei-Ling, Y., Ying-Chih, C., Yen-Hung, C.: Disaster monitoring and management by the unmanned aerial vehicle technology, Wagner W., Székely, B. (eds.): ISPRS TC VII Symposium – 100 Years ISPRS, Vienna, Austria, July 5–7, 2010, IAPRS, Vol. XXXVIII, Part 7B, 137-142, 2010.

Torrero, L., Seoli, L., Molino, A., Giordan, D., Manconi, A., Allasia, P., Baldo, M.: The Use of Micro-UAV to Monitor Active Landslide Scenarios, Lollino, G. et al. (Eds.): Engineering Geology for Society and Territory, Springer International Publishing, Vol. 5, 701-704, 2015.

Westoby, M.J., Brasington, J., Glasser, N.F., Hambrey, M.J., Reynolds, M.J.: Structure-from-Motion photogrammetry: A low-cost, effective tool for geoscience applications, Geomorphology 179, 300–314, 2012.

Tables

	Date of acquisition	Type of survey	Raw data	Georeferenced data	Dataset employment	Average Ground Resolution
©GoPro video	7 and 8 March 2014	D	204 2 Mpix	No	Generation of solid image and DSM	3.5 cm/pix
©GoPro photo	7 and 8 March 2014	D	70 10 Mpix	No	Generation of solid image and DSM	1 cm/pix
©Nikon AW 100	7 March 2014	T	40 16 Mpix	Yes	Generation of solid image and DSM	2.5 cm/pix
TLS survey	11 March 2014	T	24 Million points	Yes	DTM Generation	-
Reflectorless Total Station survey	11 March 2014	T	10 points	Yes	GCPs for georeferencing	-

Table 1: Summary of the data and results obtained for the San Germano case study.

Dataset	Advantages	Disadvantages
©GoPro (video)	The number of available images taken from the video is very high and allows the restitution of a complete solid image of the area. The use of micro-UAVs allows the acquisition of images from different points of view	The resolution of the images is low and this limitation can be a problem for the representation of solid image details. The lack of GPS positions does not allow to generate a georeferenced solid image without the use of ground control points
©GoPro (photos)	The number of available images taken form ©GoPro is very high and allows the creation of a complete solid image of the area. Compared with the frames extracted from videos, the resolution allows the restitution of a more detailed solid image	The lack of GPS positions does not allow to generate a georeferenced solid image without the use of ground control points
©Nikon AW 100	The high resolution of the photos and the GPS positions allow for the restitution of a georeferenced high resolution solid image	Several sectors are not covered by the solid image because of shadowing

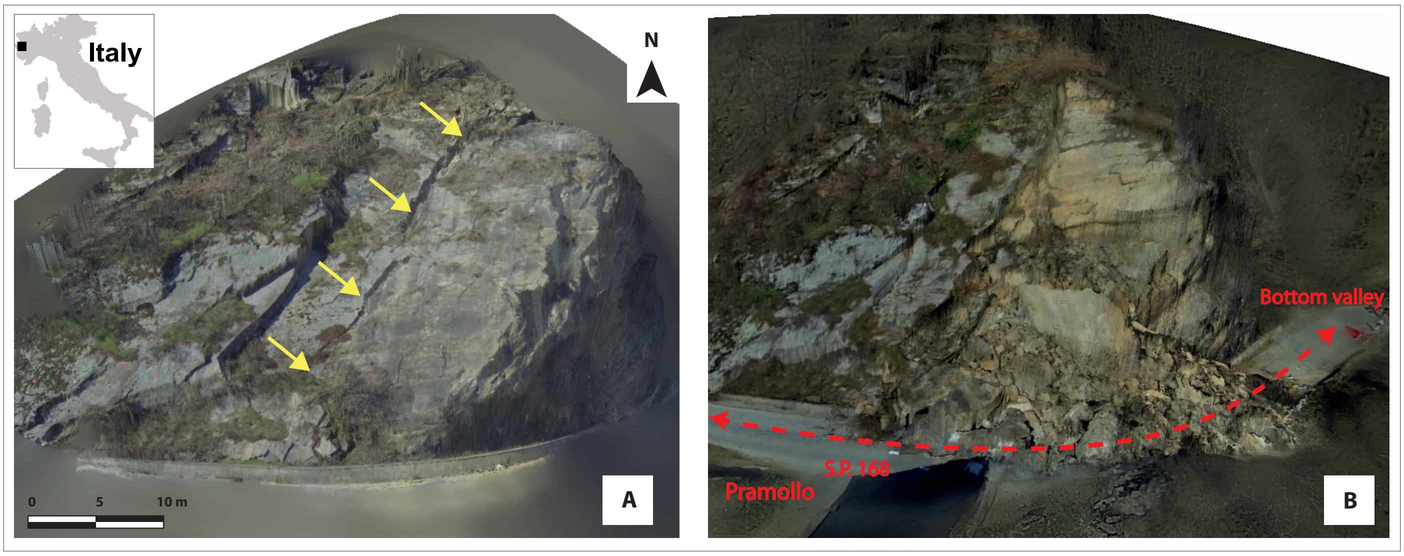
Table 2: Comparison between the results obtained for the San Germano case study.

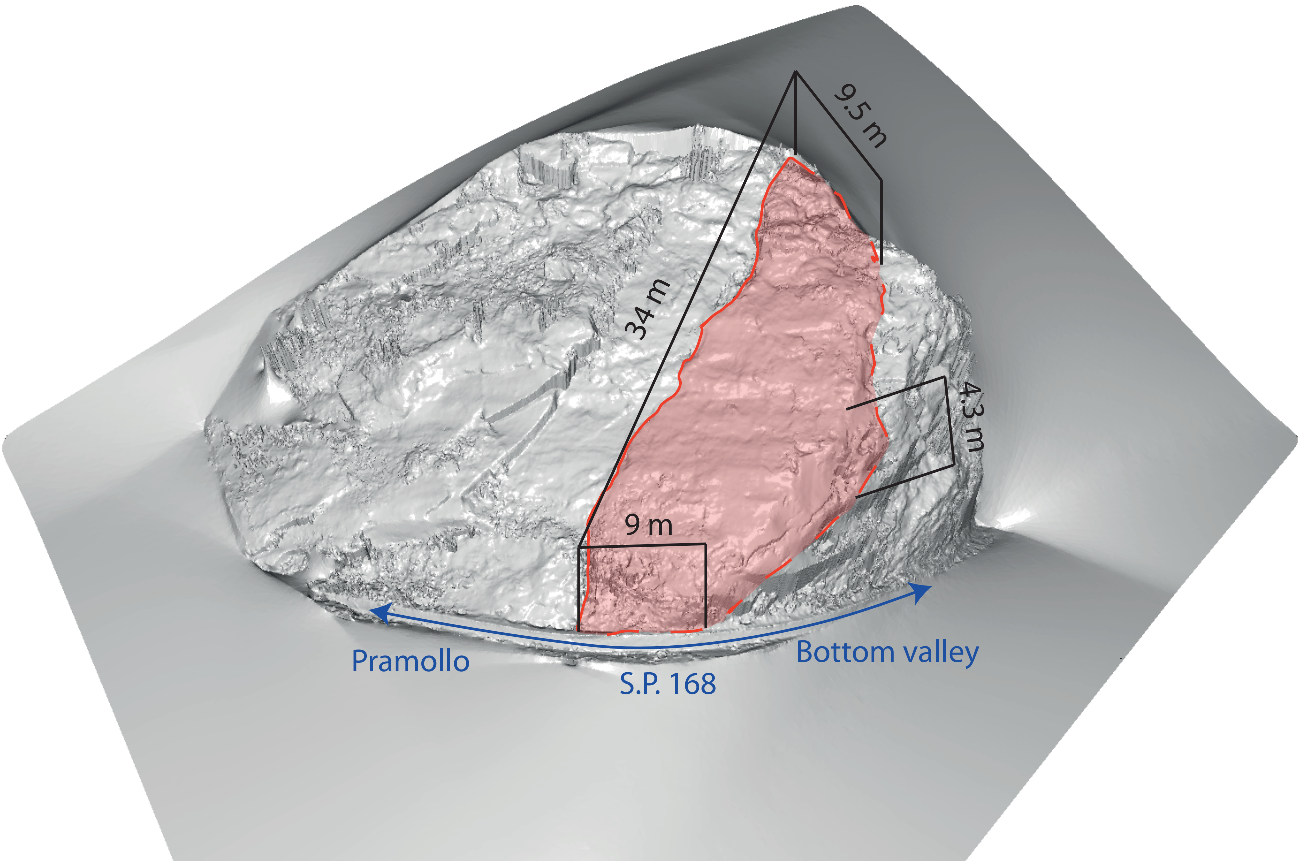
Figure captions

Figure 1: Comparison between 3-dimensional solid images of the study area before (A) and after (B) the San Germano rock fall event. Yellow arrows indicate the main lateral fracture. Red dashed line indicates the road path.

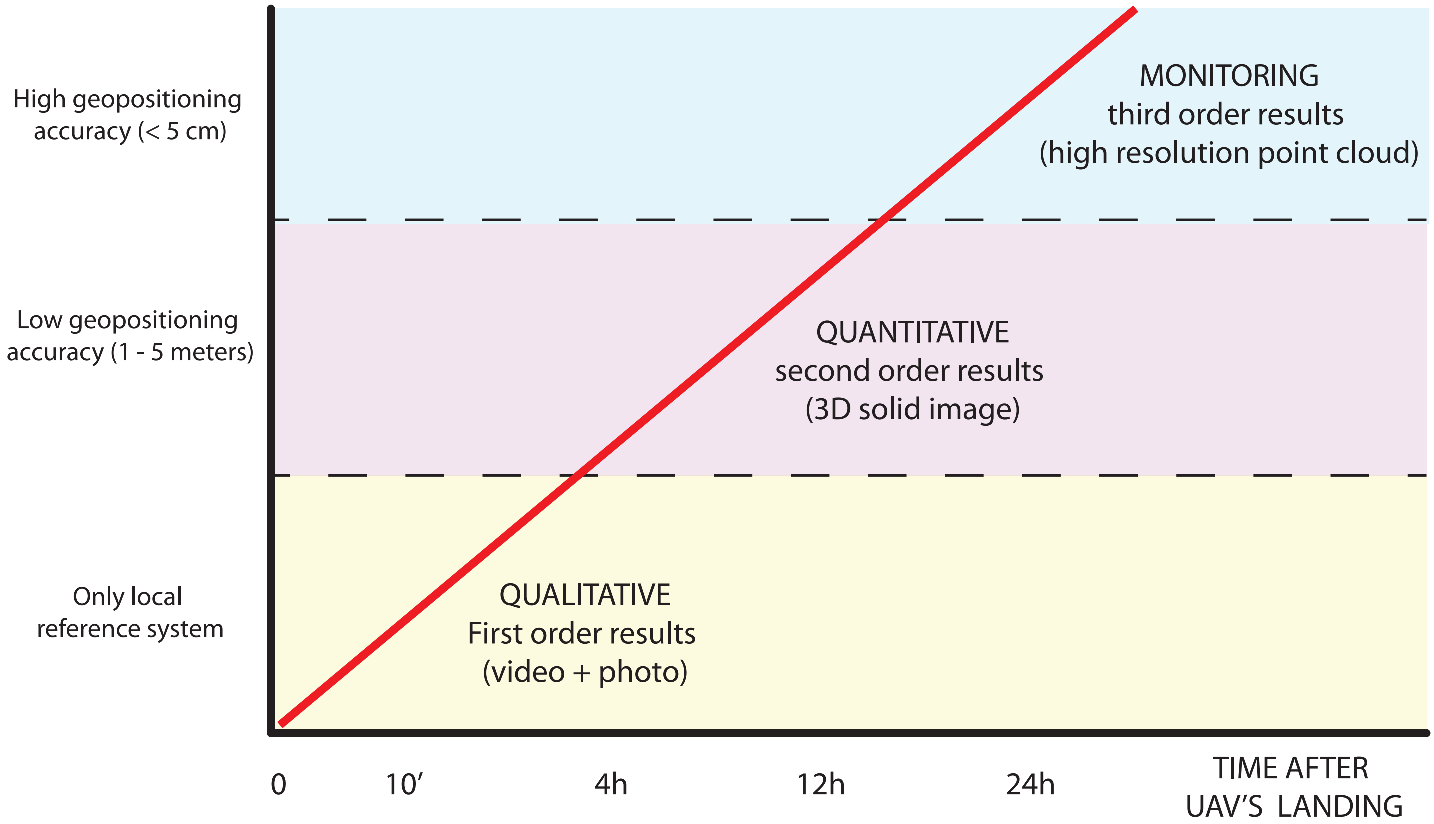
Figure 2: shaded relief of the studied area with the indication of the dimension of the instable sector (red area). The DSM of the instable area before the rock fall event derived from the ©GoPro dataset allows to define the orientation of the main discontinuities: the principal shear plane has an orientation of 178/45 (dip direction/dip) and the lateral one of 325/81(dip direction/dip). The maximum opening of the main fracture (continuous line on the picture) is 83 cm. These results have been obtained in ca. 3 hours processing time with ©Agisoft Photoscan, by considering an AMD Phenom X4 955 CPU (3.2 GHz), 10GB RAM.

Figure 3: Schematic representation of the different results obtainable from micro-UAVs surveys in rock fall scenarios. Considering time starting after the UAV's landing, there is a direct relationship between the orthorectification accuracy level of the obtained results and the processing time. Times in the chart are indicative for a study area similar to the San Germano event, which can be considered as representative of rock fall phenomena involving the road network that can be studied through micro-UAV's surveys. The processing time is also dependent on the areal extent of the study area and computational availability.


Italy
N
0
5
10 m
A
Bottom valley
S.P. 168
Pramollo
B



9.5 m
34 m
4.3 m
9 m
Pramollo
S.P. 168
Bottom valley


High geopositioning accuracy (< 5 cm)
Low geopositioning accuracy (1 - 5 meters)
Only local reference system
MONITORING
third order results
(high resolution point cloud)
QUANTITATIVE
second order results
(3D solid image)
QUALITATIVE
First order results
(video + photo)
0
10'
4h
12h
24h
TIME AFTER UAV'S LANDING