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# REVIEW ARTICLE: THE USE OF REMOTELY PILOTED AIRCRAFT SYSTEMS (RPAS) FOR NATURAL HAZARDS MONITORING AND MANAGEMENT

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## ABSTRACT

The number of scientific studies that consider possible applications of Remotely Piloted Aircraft Systems (RPAS) for the management of natural hazards effects and the identification of occurred damages are strongly increased in last decade. Nowadays, in the scientific community, the use of these systems is not a novelty, but a deeper analysis of literature shows a lack of codified complex methodologies that can be used not only for scientific experiments but also for normal codified emergency operations. RPAS can acquire on-demand ultra-high resolution images that can be used for the identification of active processes like landslides or volcanic activities but also for the definition of effects of earthquakes, wildfires and floods. In this paper, we present a review of published literature that describes experimental methodologies developed for the study and monitoring of natural hazards.

## 1. INTRODUCTION

In last three decades, the number of natural disasters showed a positive trend with an increase in the number of affected populations. Disasters not only affected the poor and characteristically more vulnerable countries but also those thought to be better protected. Annual Disaster Statistical Review describes recent impacts of natural disasters over population and reports 376 natural triggered disasters in 2015 (ADSR, 2015). This is less than the average annual disaster frequency observed from 2005 to 2014 (380), however natural disasters is still responsible for a high number of casualties (22,765). In 2015, hydrological disasters (175) had the largest share in natural disaster occurrence (46.5%), followed by meteorological disasters (127; 33.8%), climatological disasters (45; 12%) and geophysical disasters (29; 7.7%) (ADSR, 2015). To face these disasters, one of the most important solutions is the use of systems able to provide an adequate level of information for correctly understanding these events and their evolution. In this context, survey and monitoring of natural hazards gained in importance. In particular, during the emergency phase it is very important to evaluate and control the phenomenon evolution, preferably operating in near real time or real time, and consequently, use this information for a better risk scenario assessment. The available acquired data must be processed rapidly to ensure the emergency services and decision makers promptly.

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Recently, the use of remote sensing (satellite and airborne platform) in the field of natural hazards and disasters has become common, also supported by the increase in geospatial technologies and the ability to provide and process up-to-date imagery (Joyce et al., 2009; Tarolli, 2014). Remotely sensed data play an integral role in predicting hazard events such as floods and landslides, subsidence events and other ground instabilities. Because their acquisition mode and capability for repetitive observations, the data acquired at different dates and high spatial resolution can be considered as an effective complementary tool for field techniques to derive information on landscape evolution and activity over wide areas.

In the contest of remote sensing research, recent technological developments have increased in the field of Remotely Piloted Aircraft Systems (RPAS) becoming more common and widespread in civil and commercial context (Boccardo et al., 2008). In particular, the development of photogrammetry and technologies associated (i.e. RLS digital cameras and GNSS/INS systems) allow to use of RPAS platforms in various applications as alternative to the traditional remote sensing method for topographic mapping or detailed 3D recording of ground information and a valid complementary solution to terrestrial acquisitions too (Nex and Remondino, 2014) (Fig.1).

RPAS systems present some advantages in comparison to traditional platforms and, in particular, they could be competitive thanks to their versatility in the flight execution. Mini/micro RPAS are the most diffused for civil purposes, and they can fly at low altitudes according to limitations defined by national aviation security agencies. Stöcker et al. (2017) published a review of different state regulations that are characterized by several differences regarding requirements, distance from the takeoff and maximum altitude. Another important added value of RPAS is their adaptability that allows their use in various typologies of missions, and in particular for monitoring operations in remote and dangerous areas. The possibility to carry out flight operations at lower costs compared to ones required by traditional aircraft is also a fundamental advantage. Limited operating costs make these systems also convenient for multi-temporal applications where it is often necessary to acquire information on an active process (like a landslide) over the time.

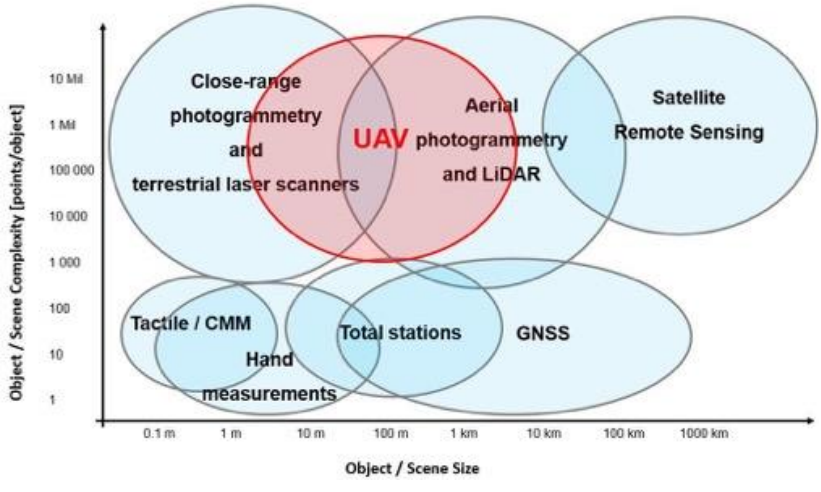


Figure 1. Available geomatics techniques, sensors, and platforms for topographic mapping or detailed 3D recording of ground information, according to the scene dimensions and complexity (modified from Nex and Remondino, 2014).



RPASs are used in several fields as agriculture, forestry, archaeology and architecture, traffic monitoring, environment and emergency management. In particular, in the field of emergency assistance and management, RPAS platforms are used to reliably and fast collect data of inaccessible areas. Collected data can be mostly images but also gas concentrations or radioactivity levels as demonstrated by the tragic event in Fukushima (Sanda et al., 2015; Martin et al., 2016). Focusing on image collection, they can be used for early impact assessment, to inspect collapsed buildings and to evaluate structural damages (Chou et al. 2010; Molina et al. 2012; Murphy et al., 2008; Pratt et al., 2009). Environmental and geological monitoring can profit from fast multi-temporal acquisitions delivering high-resolution images (Thamm and Judex 2006; Niethammer et al. 2010). RPAS can be considered a good solution also for mapping and monitoring different active processes at the earth surface such as: glaciers (Immerzel et al., 2014, Ryan et al., 2015), Antarctic moss beds (Lucieer et al., 2014b), costal areas (Delacourt et al., 2009; Klemas, 2015), river morphodynamic (Juad et al., 2016) and river channel vegetation (Dunford et al., 2009).

The incredible diffusion of RPAS has pushed many companies to develop dedicated sensors for these platforms. Besides the conventional RGB cameras other camera sensors are nowadays available on the market. Multi- and hyper-spectral cameras, as well as thermal sensors, have been miniaturized and customized to be hosted on many platforms.

The general workflow of a UAV acquisition is presented in Figure 2 below. The resolution of the images, the extension of the area as well as the goal of the flight are the main constraints that affect the selection of the platform and the typology of the sensor. Large areas can be flown using fixed wing (or hybrid) solutions able to acquire nadir images in a fast and efficient way. Small areas or complex objects (like steep slopes or buildings) should be acquired using rotor RPAS as they are usually slower but they allow the acquisition of oblique views. If the information different from the visible band is needed, the RPAS can host one or more sensors acquiring in different bands. The flight mission can be planned using dedicated software: they range from simple apps installed on smartphones in the low-cost solutions, to laptops connected to directional antennas and remote controls for the most sophisticated platforms. According to the typology of the platform, different GNSS and IMU can be installed. Low-cost solutions are usually able to give positions with few meters accuracy and need GCP (Ground Control Points) to geo-reference the images. On the other hand, most expensive solutions install double frequency GNSS receivers with the possibility to get accurate geo-referencing thanks to RTK or PPK corrections. If a quick mapping is needed, the information delivered by the navigation system can be directly used to stitch the images and produce a rough image mosaicking. In the alternative, the typical photogrammetric process is followed: (i) image orientation, (ii) DSM generation and (iii) orthophoto generation. The position (geo-referencing) and the attitude (rotation towards the coordinates system) of each acquisition is obtained by estimating the image orientation. In the dense point cloud generation, 3D point clouds are generated from a set of images, while the orthophoto is generated in the last step combining the oriented images projected on the generated point cloud, leading to orthorectified images. Point clouds can be very often converted in Digital Surface Models (DSM), and Digital Terrain Models (DTM) can be extracted removing the off ground regions (mainly buildings and trees).

The outputs from the last two steps (point clouds and true-orthophotos) as well as the original images are very often used as input in the scene understanding process: classification of the scene or extraction of features (i.e. objects) of interest using machine learning techniques are the most common applications. 3D models can also be generated using the point cloud and the oriented images to texturize the model.

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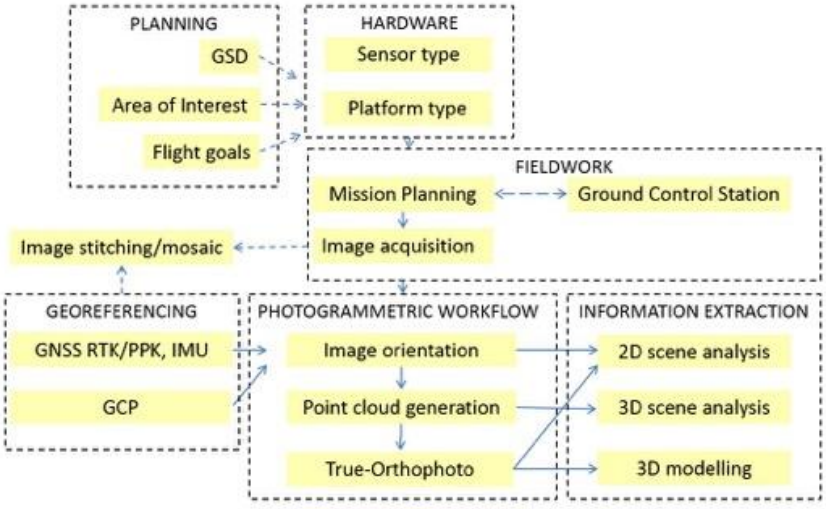


Figure 2. Acquisition and processing of RPAS images: general workflow

In this paper, the authors present an analysis and evaluation concerning the use of RPAS as alternative monitoring technique to the traditional methods, relating to the natural hazard scenarios. The main goal is to define and test the feasibility of a set of methodologies that can be used in the monitoring and mapping activities. The study is focused in particular on the use of mini and micro RPAS systems (Table 1). The following table listed the technical specifications of these two RPAS categories, again based on the current classification by UVS (Unmanned Vehicle Systems) International. Most of the mini or micro RPAS systems available integrate a flight control system, which autonomously stabilizes these platforms and enables the remotely controlled navigation. Additionally, they can integrate an autopilot, which allows an autonomous flight based on predefined waypoints. For the monitoring and mapping applications, mini- or micro RPAS systems are very useful as cost-efficient platforms for capturing real-time close-range imagery. These platforms can reach the area of investigation and take several photos and videos from several points and different angles of view. For mapping applications, it is also possible to use this flight control data to geo-register the captured payload sensor data like still images or video streams (Eugster and Nebiker, 2008).

Table 1. Classification of mini and micro UAV systems

| **Category** | Max. Take Of Weight | Max. Flight Altitude | Endurance | Data Link Range |
|---|---|---|---|---|
| **Mini** | <30kg | 150-300m | <2h | <10km |
| **Micro** | <5Kg | 250m | 1h | <10km |

## 2. USE OF RPAS FOR NATURAL HAZARDS DETECTION AND MONITORING

According to the definitions used by Annual Disaster Statistical Review (ADSR, 2015), the paper considers in particular phenomena that can be analyzed using RPAS and in particular: i) landslides, ii) floods iii) earthquakes v) volcanic activity vi) wildfires. For each considered category of natural hazard, the paper



131 presents an analysis of published methodologies and provide results, underlining strengths and limitations
132 in the use of RPAS.

133

## 134 2.1 Landslides

135 Landslides are one of the major natural hazards that produce each year enormous property damage
136 regarding both direct and indirect costs. Landslides are rock, earth or debris flows on slopes due to gravity.
137 The event can be triggered by a variety of external elements, such as intense rainfall, water level change,
138 storm waves or rapid stream erosion that cause a rapid increase in shear stress or decrease in shear
139 strength of slope-forming materials. Moreover, the pressures of increasing population and urbanization,
140 human activities such as deforestation or excavation of slopes for road cuts and building sites, etc., have
141 become important triggers for landslide occurrence. Because the factors affecting landslides can be
142 geophysical or human-made, they can occur in developed and undeveloped areas.

143 In the field of natural hazards, the use of RPAS for landslides study and monitoring represents one of the
144 most common applications. The number of papers that present case studies or possible methodologies
145 dedicated to this topic has strongly increased in last few years and now the available bibliography offers a
146 good representation of possible approaches and technical solutions.

147 When a landslide occurs, the first information to be provided is the extent of the area affected by the event
148 (figure 3). The landslide impact extent is usually done based on detailed optical images acquired after the
149 event. From these acquisitions, it is possible to derive Digital Elevation Models (DEMs) and orthophotos
150 that allow detecting main changes in geomorphological figures. In this scenario, the use of the mini-micro
151 RPAS is practical for small areas and optimal for landslides that often cover an area that range from less
152 than one square kilometres up to few square kilometres. Ultra-high resolution images acquired by RPAS can
153 support the definition not only of the identification of studied landslide limit, but also the identification and
154 mapping of main geomorphological features (Fiorucci et al., 2017). Furthermore, a sequence of RPAS
155 acquisitions over the time can provide useful support for the study of the gravitational process evolution.

156 According to Scaioni et al. (2014), applications of remote sensing for landslides investigations can be
157 divided into three classes: i) landside recognition, classification and post-event analysis, ii) landslide
158 monitoring, iii) landslide susceptibility and hazard assessment.

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Figure 3. Example of RPAS image of a rockslide occurred on a road. The image was acquired after the rockslide occurred in 2014 in San Germano municipality (Piemonte region, NW Italy). As presented in Giordan et al. (2015a), a multi-rotor of local Civil Protection Agency was used to evaluate occurred damages and residual risk. RPAS images can be very useful to have a representation from a different point of view of the occurred phenomena. Even not already processed using SFM applications, this dataset can be very useful for decision makers to define the strategy for the management of the first phase of emergency.

### 2.1.1 Landslides recognition

The identification and mapping of landslides are usually performed after intense meteorological events that can activate or reactivate several gravitational phenomena. The identification and mapping of landslides can be organized in landslides event maps. Landslides event mapping is a well-known activity obtained thought field surveys (Santangelo et al., 2010), visual interpretation of aerial or satellite images (Brardinoni et al., 2003; Ardizzone et al., 2013) combined analysis of LiDAR DTM and images (Van Den Eeckhaut et al., 2007; Haneberg et al., 2009; Giordan et al., 2013; Razak et al., 2013; Niculita et al., 2016). The use of RPAS for the identification and mapping of a landslide has been described by several authors (Niethammer et al 2009; Niethammer et al 2010; Rau et al., 2011; Carvajal et al., 2012; Travelletti et al., 2012; Torrero et al., 2015; Casagli et al., 2017). Niethammer et al. (2009) showed how RPAS could be considered a good solution for the acquisition of ultra-high resolution images with low-cost systems. Fiorucci et al. (2017) compared the results of the landslide limit mapped using different techniques and found that satellite images can be considered a good solution for the identification and map of landslides over large areas. On the contrary, if the target of the study is the definition of landslide's morphological features, the use of more detailed RPAS images seemed to be the better solution. As suggested by Walter et al., (2009) and Huang et al., (2017) one of the most critical elements for a correct georeferencing of acquired images are the use of Ground Control Points (GCPs). The in situ installation and positioning acquisition of GCPs can be an important challenge in particular in dangerous areas as active landslides. Very often, GCPs are not installed in the



most active part of the slide but on stable areas. This solution can be safer for the operator, but it can also reduce the accuracy of the final reconstruction.

Another parameter that can be considered during the planning of the acquisition phase is the morphology of the studied area. According to with Giordan et al., (2015b), slope materials and gradient can affect the flight planning and the approach used for the acquisition of the RPAS images. Two possible scenarios can be identified: i) steep to vertical areas (>40°); ii) slopes with gentle to moderate slopes (<40°). In the first case, the use of multi-copters with oblique acquisitions is often the best solution. On the contrary, with more gentle slopes, the use of fixed-wing systems can assure the acquisition of wider areas.

### 2.1.2 Landslides monitoring

The second possible field of application of RPAS is the use of multi-temporal acquisitions for landslides monitoring. This topic has been described by several authors (Turner and Lucieer 2013, Travelletti et al., 2012, Lucieer et al. 2014a; Turner et al., 2015; Marek et al., 2015). In these works, numerous techniques based on the multi-temporal comparison of RPAS datasets for the definition of the evolution of landslides have been presented and discussed. Niethammer et al. (2010 and 2012) described how the position change of geomorphological features (in particular fissures) could be considered for a multi-temporal analysis with the aim of the characterization of the landslide evolution. Travelletti et al. (2012) introduced the possibility of a semi-automatic image correlation to improve this approach. The use of image correlation techniques has been also described by Lucieer et al. (2014a) who demonstrated that COSI-Corr (Co-registration of Optically Sensed Imaged and Correlation - LePrince et al. 2007, 2009; Ayoub et al., 2009) can be adopted for the definition of the surface movement of the studied landslide. A possible alternative solution is the multi-temporal analysis of the use of DSMs. The comparison of digital surface models can be used for the definition of volumetric changes caused by the evolution of the studied landslide. The acquisition of these digital models can be done with terrestrial laser scanners (Baldo et al., 2009) or airborne LiDAR (Giordan et al., 2013). Westoby et al. (2012) emphasized the advantages of RPAs concerning terrestrial laser scanner, which can suffer from line-of-sight issues, and airborne LiDAR, which are often cost-prohibitive for individual landslide studies. Turner et al. (2015) stressed the importance of a good co-registration of multi-temporal DSM for good results that could decrease the accuracy of results. The use of benchmarks in areas not affected by morphological changes can be used for a correct calibration of rotational and translation parameters.

### 2.1.3 Landslides susceptibility and hazard assessment

Landslides susceptibility and hazard assessment are often performed at basin scale (Guzzetti et al., 2005) using different remote sensing techniques (Van Westen et al., 2008). The use of RPAS can be considered for single case study applications to help decision makers in the identification of the landslide damages and the definition of residual risk (Giordan et al., 2015a). Saroglou et al., (2017) presented the use of RPAS for the definition of trajectories of rock falls prone areas. Salvini et al. (2017) and Török et al., (2017) described the combined use of TLS and RPAs for hazard assessment of steep rock walls. All these papers considered the use of RPAS as a valid solution for the acquisition of DSM over sub-vertical areas. Török et al., (2017) and Tannant et al., 2017 also described in their manuscripts how RPAS DSMs can be used for the evaluation of slope stability using numerical modelling.

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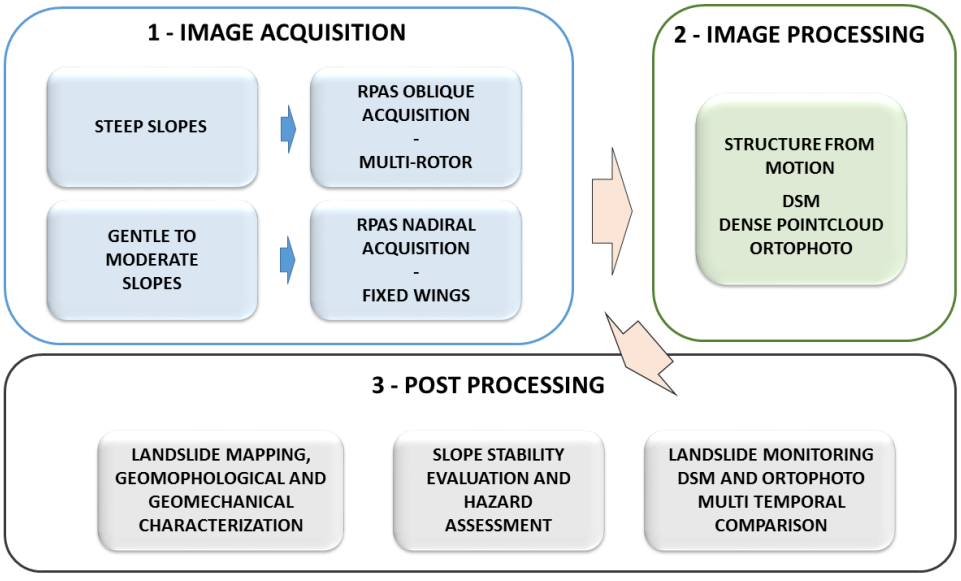


Figure 4. Acquisition, processing and post-processing of RPAS images applied to i) landslides recognition, ii) hazard assessment and iii) slope evolution monitoring

## 2.2 Floods

Disastrous floods in urban, lowland areas often cause fatalities and severe damage to the infrastructure. Monitoring the flood flow, assessment of the flood inundation areas and related damages, post-flood landscape changes, and pre-flood prediction are therefore seriously required. Among various scales of approaches for flood hazards (Sohn et al., 2008), the RPAS has been adopted for each purpose of the flood damage prevention and mitigation because it has an ability of quick measurement at a low cost (DeBell et al., 2016; Nakamura et al., 2017). Figure 5 shows an example of the use of RPAS for prompt damage assessment by a severe flood occurred on early July 2017 at northern Kyushu area, southwest Japan. The Geospatial Information Authority of Japan (GSI) utilized an RPAS for the post-flood video recording and photogrammetric mapping of the damaged area with flood flow and large woody debris.

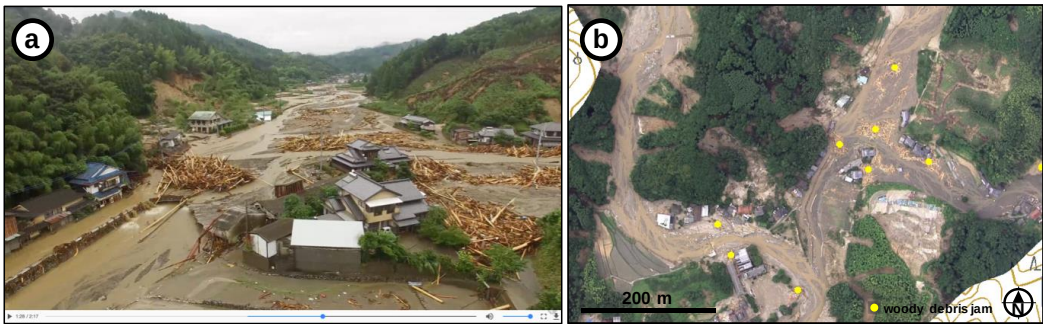



Figure 5. Image captures of flood hazard using RPAS just after the 2017 Northern Kyushu Heavy Rain in the early July (southwest Japan), provided by GSI. (a) A screenshot of the aerial video of a flooded area along the Akatani River, Asakura City in Fukuoka Prefecture. (b) Orthorectified image of the damaged area. Locations of woody debris jam are mapped and shown on the online map (GSI, 2017). The video and map products are freely provided (compatible with Creative Commons Attribution 4.0 International).

### 2.2.1. Potential analysis of flood inundation

The risk assessments of flood inundation before the occurrence of a flood is crucial for the mitigation of the flood-disaster damages. RPAS is capable of providing quick and detailed analysis of the land surface information including topographic, land cover, and land use data, which are often incorporated into the hydrological modelling for the flood estimate (Costa et al., 2016). As a pre-flood assessment, Li et al. (2012) explored the area around an earthquake-derived barrier lake using an integrated approach of remote sensing including RPAS for the hydrological analysis of the potential dam-break flood. They proposed a technical framework for the real-time evacuation planning by accurately identifying the source water area of the dammed lake using a RPAS, followed by along-river hydrological computations of inundation potential. Tokarczyk et al. (2015) showed that the UAV-derived imagery is useful for the rainfall-runoff modelling for the risk assessment of floods by mapping detailed land-use information. As a key input data, high-resolution imperviousness maps were generated for urban areas from UAV imagery, which improved the hydrological modelling for the flood assessment. Zazo et al. (2015) and Şerban et al. (2016) demonstrated hydrological calculations of the potentially flood-prone areas using UAV-derived 3D models. They utilized 2D cross profiles derived from the 3D model for the hydrological modelling.

### 2.2.2. Flood monitoring

Monitoring of the ongoing flood is potentially important for the real-time evacuation planning. Le Coz et al. (2016) mentioned that the movies captured by a RPAS, which can be operated by not only research specialists but also general non-specialists, is potentially useful for the quantitative monitoring of floods including flow velocity estimate and flood modelling. This can also contribute to the crowdsourced data collection for flood hydrology as the citizen science. In case of flood monitoring, however, areas under water is often problematic by image-based photogrammetry because the bed is not often fully seen in aerial images. If the water is clear enough, bed images under water can be captured, and the bed morphology can be measured with additional corrections of refraction (Tamminga et al., 2015; Woodget et al., 2015), but the flood water is often unclear because of the abundant suspended sediment and disturbing flow current. Another option is the fusion of different datasets using a sonar-based measurement for the water-covered area, which is registered with the terrestrial datasets (Flener et al., 2013; Javernick et al., 2014). Image-based topographic data of water bottom by unmanned underwater vehicle (UUV, also known as an autonomous underwater vehicle, AUV) can also be another option (e.g., Pyo et al., 2015), although such the application of UUV to flooding has been limited.

Not only the use of topographic datasets derived from SfM-MVS photogrammetry, the use of orthorectified images concurrently derived from the RPAS-based aerial images is advantageous for the assessment of hydrological observation and modelling of floods. Witek et al. (2014) developed an experimental system to monitor the stream flow in real time for the prediction of overbank flood inundation. The real-time



prediction results are also visualized online with a web map service with a high-resolution image (3 cm/pix). Feng et al. (2015) reported that the accurate identification of inundated areas is feasible using UAV-derived images. In their case, deep learning approaches of the image classification using optical images and texture by UAV successfully extracted the inundated areas, which must be useful for flood monitoring. Erdelj et al. (2017) proposed a system that incorporates multiple RPAS devices with wireless sensor networks to perform the real-time assessment of a flood disaster. They discussed the technical strategies for the real-time flood disaster management including the detection, localization, segmentation, and size evaluation of flooded areas from RPAS-derived aerial images.

#### 2.2.3. Post-flood changes

Post-flood assessments of the land surface materials including topography, sediment, and vegetation are more feasible by RPAS surveys. Smith et al. (2014) proposed a methodological framework for the immediate assessment of flood magnitude and affected landforms by SfM-MVS photogrammetry using both aerial and ground-based photographs. In this case, it is recommended to carefully select appropriate platforms for SfM-MVS photogrammetry (either airborne or ground-based) based on the field conditions. Tamminga et al. (2015) examined the 3D changes in river morphology by an extreme flood event, revealing that the changes in reach-scale channel patterns of erosion and deposition are poorly modelled by the 2D hydrodynamics based on the initial condition before the flood. They also demonstrate that the topographic condition can be more stable after such an extreme flood event. Langhammer et al. (2017) proposed a method to quantitatively evaluate the grain size distribution using optical images taken by a RPAS, which is applied to the sediment structure before and after a flash flood.

As a relatively long-term study, Dunford et al. (2009) and Hervouet et al. (2011) explored annual landscape changes after the flood using RPAS-derived images together with other datasets such as satellite image archives or a manned motor paraglider. Their work assessed the progressive development of vegetation on a braided channel at an annual scale, which appears to be controlled by local climate including rainfall, humidity, and air temperature, hydrology, groundwater level, topography, and seed availability. Changes in the sediment characteristics by a flood is another key feature to be examined.

## 2.3 Earthquakes

Remote sensing technology has been recognized as a suitable source to provide timely data for automated detection of damaged buildings for large areas (Dong and Shan, 2013). In the post-event, satellite images have been traditionally used for decades to visually detect the damages on the buildings to prioritize the interventions of rescuers. Operators search for externally visible damage evidence such as spalling, debris, rubble piles and broken elements, which represent strong indicators of severe structural damage. Several researches, however, have demonstrated how this kind of data often leads to the wrong detection, usually underestimating the number of the collapsed building because of their reduced resolution on the ground. In this regard, airborne images and in particular oblique acquisitions (Tu et al., 2017; Nex et al., 2014; Gerke and Kerle 2011) have demonstrated to be a better input for reliable assessments, allowing the development of automated algorithms for this task (Figure 6). The deployment of photogrammetric aeroplanes on the strike area is however very often unfeasible especially when the early (in the immediate hours after the event) damage assessment for response action is needed.

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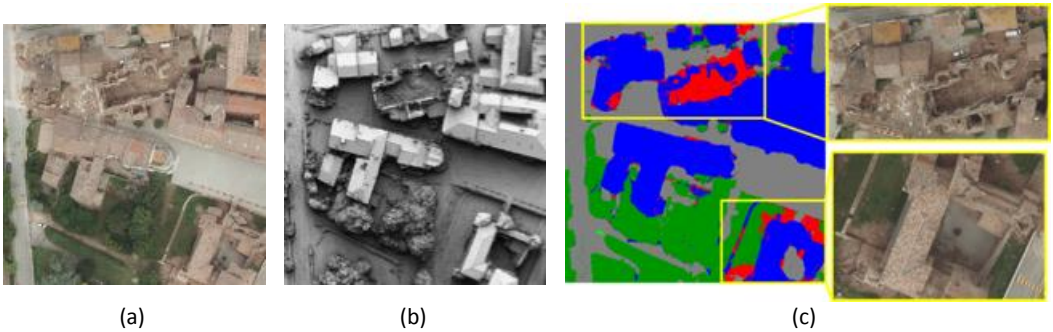

(a) (b) (c)

Figure 6. True-orthophoto, Digital Surface Model and damage map of an urban area using airborne nadir images (Source: Nex et al., 2014).

For this reason, RPASs have turned out to be valuable instruments for the building damage assessment. The main advantages of RPASs are their availability (and reduced cost) and the ease to repeatedly acquire high-resolution images. Thanks to their high resolution, their use is not only limited to the early impact assessment for supporting rescue operations, but it is also considered in the preliminary analysis of the structural damage assessment.

### 2.3.1 Early impact assessment

The fast deployment in the field, the easiness of use and the capability to provide in real time high-resolution information of inaccessible areas to prioritize the operator's activities are the strongest point of RPASs for these activities (Boccardo et al., 2015). The use of RPASs for rescue operations started almost a decade ago (Bendea et al., 2008) but their massive adoption has begun only in the very last few years (Earthquake in Nepal 2015) thanks to the development of low cost and easy to use platforms. Initiatives like *UAViators* (http://uaviators.org/) have further increased the public awareness and acceptance of this kind of instruments. Several rescue departments have now introduced small UAVs as part of the conventional equipment of their teams. The huge number of videos acquired by UAVs and posted by rescuers online (i.e. Youtube) after the 2016 Italian earthquakes confirm this general trend.

The operators use RPASs to fly over the interest area and get information through visual assessment of the streaming videos. The quality of this analysis is therefore limited to the ability of the operator to fly the RPAS over the interest area. The lack of video geo-referencing usually reduces the interpretability of the scene and the accurate localization of the collapsed parts: only small regions can be acquired in a single flight. The lack of georeferenced maps prevents the smooth sharing of the collected information with other rescue teams limiting the practical exploitation of these instruments. UAVs are mainly used in daylight conditions as the flight during the night is extremely critical, and the use of thermal images is of limited help for the rescuers.

Many researchers have developed algorithms to automatically extract damage information from imagery (Figure 7). The main focus of these works is to reliably detect damages in a reduced time to satisfy the time constraints of the rescuers. In (Vetrivel et al., 2015) the combined use of images and photogrammetric point clouds have shown promising results thanks to a supervised approach. This work, however, highlighted how the classifier and the designed 2D and 3D features were hardly transferable to different datasets: each scene needed to be trained independently strongly limiting the efficiency of this approach.



In this regard, the recent developments in machine learning (i.e. Convolutional Neural Networks, CNN) have overcome these limits (Vetrivel et al., 2017), showing how they can correctly classify scenes even if they were trained using other datasets: a trained classifier can be directly used by rescuers on the acquired images without need for further operations. The drawback of these techniques is the computational time: the use of CNN, processing like image segmentation or point cloud generation are computationally demanding and hardly compatible with real-time needs. In this regard, most recent solutions exploit only images (i.e. no need to generate point cloud) and limit the use of most expensive processes to the regions where faster classification approaches provide uncertain results to deliver an almost real-time information (Duarte et al., 2017).

(a) (b) (c)

Figure 7. Examples of damage detection on images acquired in three different scenarios (a) Mirabello (source: Vetrivel et al. 2017) and (b) L'Aquila and Lyon (source Duarte et al., 2017).

### 2.3.2 Building damage assessment

The damage evidence that can be captured from a UAV is not sufficient to infer the actual damage state of the building as it requires additional information such as damages to internal building elements (e.g., columns and beams) that cannot be directly defined from images. Even though this information is limited, images can provide useful information about the external condition of the structure, evidencing anomalies and damages and providing a first important information for structural engineers. Two main typologies of investigations can be performed: (i) the use of images for the detection of cracks or damages on the external surfaces of the building (i.e. walls and roofs) and (ii) the use of point clouds (generated by photogrammetric approach) to detect structural anomalies like tilted or deformed surfaces. In both cases, the automated processing can only support and ease the work of the expert who still interprets and assess the structural integrity of the building.

In (Fernandez-Galarreta et al., 2015) a comprehensive analysis of both point clouds and images to support the ambiguous classification of damages and their use for damage score was presented. In this paper, the use of point clouds was considered efficient for more serious damages (partial or complete collapse of the building), while images were used to identify smaller damages like cracks that can be used as the basis for the structural engineering analysis. The use of point clouds is investigated in (Dominici et al., 2017): this contribution highlights how point clouds from UAVs can provide very useful information to detect asymmetries and small deformations of the structure.



## 2.4 Volcanic activity

RPAS is particularly advantageous when the target area of measurement is hardly accessible on the ground due to dangers of volcanic gas or risks of eruption in volcanic areas (Andrews, 2015). Although an equipment of RPAS can be lost or damaged by the volcanic activities, the operator can safely stay in a remote place. Various sensors can be mounted on a RPAS to monitor volcanic activities including topography, land cover, heat, gas composition, and even gravity field (Saiki and Ohba, 2010; Deurloo et al., 2011; Middlemiss et al., 2016). The photogrammetric approach to obtain topographic data is widely applied because RGB camera sensors are small enough to be mounted on a small aircraft. Larger aircrafts with a payload of kilograms are also utilized to mount other types of sensors to monitor various aspects of dynamic volcanic activities.

### 2.4.1. Topographic measurements of volcanoes

Long-distance flight of a RPAS enables quick and safe measurements of an emerging volcanic island. Tobita et al. (2014a) successfully performed a fixed-wing RPAS flight for a one-way distance of 130 km in total flight time of 2 hours and 51 minutes over the sea to capture aerial images of a newly formed volcanic island next to Nishinoshima Island (Ogasawara Islands, southwest Pacific). They performed SfM-MVS photogrammetry of the aerial images taken back from the RPAS to generate a 2.5 m resolution DEM of the island. The team also performed two successive measurements of Nishinoshima Island in the following 104 days, revealing the morphological changes in the new island covering a 1,600 m by 1,400 m area (Nakano et al., 2014; Tobita et al., 2014b).

Since the volcanic activities often last for a long period, it is also important to connect the recent volcanic morphological changes to those in the past. Although detailed morphological data of volcanic topography is often unavailable, historical aerial photographs taken in the past decades can be utilized to generate topographic models at a certain resolution. Some case studies have used archival aerial photographs in volcanoes for periods of more than 60 years, generating DEMs with resolutions of several meters for areas of 10 $km^2$ (Gomez, 2014; Darrien et al., 2015; Gomez et al. 2015). Although these DEMs are coarser than those derived from RPAS, they can be used as supportive datasets for the modern morphological monitoring using RPAS at a higher resolution and measurement frequency.

### 2.4.2. Gas monitoring and product sampling

Caltabiano et al. (2005) proposed the architecture of a RPAS for the direct monitoring of gas composition in volcanic clouds of Mt. Etna in Italy. In this system, the 2-m wide fixed-wing RPAS can fly autonomously up to 4000 m altitude with a speed of 40 km/h. Like this system, a RPAS with a payload of several kilograms can carry multiple sensors to monitor different compositions of volcanic gas. McGonigle et al. (2008) used a RPAS for volcanic gas measurements at La Fossa crater of Mt. Vulcano in Italy. The RPAS has 3 kg payload and allows to host an ultraviolet spectrometer, an infrared spectrometer, and an electrochemical sensor on board. The combination of these sensors enabled the estimation of the flux of $SO_2$ and $CO_2$, which are crucial for revealing the geochemical condition of erupting volcanoes. The monitoring of gas composition including $CO_2$, $SO_2$, $H_2S$, $H_2$, as well as the air temperature, can be used for the quantification of the



degassing activities and prediction of the conduit magma convection, as suggested by the test at Mt. Kirishima in Japan (Shinohara, 2013).

A RPAS can also transport a small ground-running robot (Unmanned Ground Vehicle: UGV) to slope head of an active volcano, where the UGV takes close-range photographs of volcanic ash on the ground surface by running down the slope (Nagatani et al., 2013). Protocols for direct sampling of volcanic products using a RPAS have also been developed (Yajima et al., 2014).

### 2.4.3. Geothermal monitoring

In New Zealand, Harvey et al. (2016) and Nishar et al. (2016) carried out experimental studies on the regular monitoring of intense geothermal environments using a small RPAS. They used thermal images taken by an infrared imaging sensor together with normal RGB images for photogrammetry, mapping both the ground surface temperature with detailed topography and land cover data. Chio and Lin (2017) further assessed the use of a RPAS equipped with a thermal infrared sensor for the high-resolution geothermal image mapping in a volcanic area in Taiwan. They improved the measurement accuracies using an onboard sensor capable of post-processed kinematic GNSS positioning. This allows accurate mapping with less ground control points, which are hard to place on such intense geothermal fields.

## 2.5 Wildfires

Wildfires are a phenomenon with local and global effects (Filizzola et al., 2017). Wildfires represent a serious threat for land managers and property owners; in the last few years, this threat has significantly expanded (Peters et al., 2013). The literature also suggests that climate change will continue to enhance the potential forest fire activity in different regions of the world (McKenzie et al. 2014; Abatzoglou and Williams, 2016). Remote sensing technologies can be very useful in monitoring such hazard (Shroeder et al., 2016). Several scientists in the last few years used satellites in fire monitoring (Shroeder et al., 2016). More recently UAVs have been considered to be useful as well. Hinkley and Zajkowski (2011) presented the results of a collaborative partnership between NASA, and the US Forest Service established for testing thermal image data for wildfires monitoring. A small unmanned airborne system served as a sensor platform. The outcome was an improved tool for wildfire decision support systems. Merino et al. (2012) described a system for forest fire monitoring using a UAS. The system integrates the information from the fleet of different vehicles to estimate the evolution of the forest fire in real time. The field tests indicated that UAS could be very helpful for the activities of firefighting (e.g. monitoring). Indeed they cover the gap between the spatial scales given by satellites and those based on cameras. Wing et al. (2014) underlined the fact that spectral and thermal sensors mounted in UAVs may hold great promise for future remote sensing applications related to forest fires. UASs have greater potential to provide enhanced flexibility for positioning and repeated data collection. Tang and Shao (2015) summarize various approaches of remote drone sensing to surveying forests, mapping canopy gaps, measuring forest canopy height, tracking forest wildfires, and supporting intensive forest management. These authors underlined the usefulness in using drones for wildfire monitoring. UAVs can repeatedly fly to record the extent of an ongoing wildfire without jeopardizing crews' safety. Zajkowski et al. (2015) tested different UAVs (e.g. quadcopter, single wing) for the analysis of fire activity. Measurements included visible and long-wave infrared (LWIR) imagery, black carbon, air temperature, relative humidity and three-dimensional wind speed and direction. The authors also described in detail the mission's plan, including the logistics of integrating RPAS into a complex



operations environment, specifications of the aircraft and their measurements, execution of the missions and considerations for future missions. Allison et al. (2016) provided a detailed state of the art on fire detection using both manned and unmanned aerial platforms. This review highlighted the following challenges: the need to development of robust automatic detection algorithms, the integration of sensors of varying capabilities and modalities, the development of best practices for the use of new sensor platforms (e.g. small UAVs), and their safe and effective operation in the airspace around a fire.

## 3. Discussion and conclusion

In this paper, we analysed possible applications of RPAS to natural hazards. The available literature on this topic is strongly increased in last few years, according to the improvement of the diffusion of these systems. In particular, we considered: landslides, floods, earthquakes, volcanic activities and wildfires.

RPAS can support studies on active geological processes and can be considered a good solution for the identification of effects and damages due to several catastrophic events. One of the most important elements that characterized the use of RPAS is their flexibility and versatility, largely confirmed by the wide number of operative solutions available in the literature. The available literature pointed out the necessity of the development of dedicated methodologies that can be able to take the full advantage of RPAS. In particular, typical results of structure from motion software (orthophoto and DSM) that are considered the end of standard data-processing, can be very often the starting point of dedicated procedures specifically conceived for natural hazards applications.

In the pre-emergency phase, one of the main advantages of RPAS surveys is to acquire high resolution and low-cost data to analyse and interpret environmental characteristics and potential triggering factors (e.g. slope, lithology, geostructure, land use/land cover, rock anomalies, and displacement). The data can be collected with high revisit times to obtain multi-temporal observations. After the characterization of hazard potential and vulnerability, some areas can be identified by a higher level of risk. These cases request an intensive monitoring, to gain a quantitative evaluation of the potential occurrence of an event. In this context, the use of aerial data represents a very useful complementary data source concerning the information acquired through ground-based observations in particular for dangerous areas.

During the emergency phase, high-resolution imagery is asked to be acquired over the event site. The primary use of this data is for the assessment of the damage grade (extent, type and damage grades specific to the event and eventually of its evolution). They may also provide relevant information that is specific to critical infrastructures, transport systems, aid and reconstruction logistics, government and community buildings, hazard exposure, displaced population, etc. Concurrently, the availability of clear and straightforward raster and vector data, integrated with base cartographic contents (transportation, surface hydrology, boundaries, etc.) it is recognized as an added-value to support decision makers for the management of emergency operations. These applications very often need prompt and reliable interventions. RPAS should, therefore, deliver information promptly. In this regard, very few researchers have focused on this issue: most of the reported work present (often time-consuming and even manual) post-processing of the acquired data, precluding the use of their results from practical and real-life scenarios. A big effort should be taken by the research community to propose faster and automated approaches.



511 As in many other domains, RPAS present a disruptive technology where, beside conventional SfM
512 applications for 3D reconstructions, many dedicated and advanced methodologies are still in their
513 experimental phase and will need to be further developed in the incoming years. In the following years, it
514 would be desirable to witness the transfer of the best practices in the use of RPAS be then from the
515 Research community to Government Agencies (or private companies) involved in the prevention and
516 reduction of impacts of natural hazards. The Scientific community should contribute to the definition of
517 standard methodologies that can be assumed by civil protection agencies for the management of
518 emergencies.



519 # References

520 Abatzoglou, J.T. and Williams, A.P.: Impact of anthropogenic climate change on wildfire across western US
521 forests, PNAS, 113 (42), 11770-11775, 2016.

522 Astuti, G., Giudice, G., Longo, D., Melita, C. D., Muscato, G. and Orlando, A.: An overview of the "Volcan
523 project": An UAS for Exploration of volcanic environments, J Intell. Robot Syst., 54, 471-494, 2009.

524 Aicardi, I., Chiabrando, F., Lingua, A., Noardo, F., Piras, M. and Vigna, B.: A methodology for acquisition and
525 processing of thermal data acquired by UAVs: a test about subfluvial springs' investigations, Geomatics,
526 Natural Hazards and Risk. 8:1, 5-17, 2017. DOI: 10.1080/19475705.2016.1225229

527 Allison R.S., Johnston J.M., Craig G. and Jennings S.: Airborne Optical and Thermal Remote Sensing for
528 Wildfire Detection and Monitoring Sensors, 16(8), 1310, 2016. doi:10.3390/s16081310

529 Andrews, C.: Pressure in the danger zone [volcanoes], Eng. Technol., 10(7), 56–61,
530 doi:10.1049/et.2015.0720, 2015.

531 Ardizzone, F., Fiorucci, F., Santangelo, M., Cardinali, M., Mondini, A.C., Rossi, M., Reichenbach, P., and
532 Guzzetti, F.: Very-high resolution stereoscopic satellite images for landslide mapping. C. Margottini, P.
533 Canuti, K. Sassa (Eds.), Landslide Science and Practice, Landslide Inventory and Susceptibility and Hazard
534 Zoning, 1, Springer, Heidelberg, Berlin, New York, 95–101, https://doi.org/10.1007/978-3-642-31325-7_12,
535 2013.

536 Ayoub, F., LePrince, S. and Keene, L.: User's Guide to Cosi-Corr: Co-Registration of Optically Sensed Images
537 and Correlation; California Institute of Technology: Pasadena, CA, USA, pp. 38, 2009.

538 Baldo M., Bicocchi C., Chiocchini U., Giordan D. and Lollino G.: LIDAR monitoring of mass wasting processes:
539 The Radicofani landslide, Province of Siena, Central Italy, Gemorphology, 105, 193-201, 2009. DOI:
540 10.1016/j.geomorph.2008.09.015

541 Baiocchi, V., Dominici, D. and Mormile, M.: UAV application in post –seismic environment", International
542 Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XL-1/W2, UAV-
543 g2013, 4 – 6 September 2013, Rostock, Germany, pp. 21-25, 2013.

544 Bendea, H., Boccardo, P., Dequal, S., Tondo, G., Marenchino, D. and Piras, M.: Low cost UAV for post-
545 disaster assessment. Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci., 37, 1373–1379, 2008.

546 Boccardo, P., Chiabrando, F., Dutto, F., Tonolo, F.G. and Lingua, A.: UAV deployment exercise for mapping
547 purposes: Evaluation of emergency response applications, Sensors, 15(7), 15717-15737, 2015.

548 Bolognesi, M., Farina, G., Alvisi, S., Franchini, M., Pellegrinelli, A. and Russo, P.: Measurement of surface
549 velocity in open channels using a lightweight remotely piloted aircraft system. Geomatics, Natural Hazards
550 and Risk, 8:1, 73.86, 2016. DOI: 10.1080/19475705.2016.1184717

551 Brardinoni, F., Slaymaker, O., and Hassan, M.A.: Landslides inventory in a rugged forested watershed: a
552 comparison between air-photo and field survey data, Geomorphology, 54, 179-196,
553 https://doi.org/10.1016/S0169-555X(02)00355-0, 2003.



554 Brostow, G.J., Shotton, J., Fauqueur, J. and Cipolla, R.: Segmentation and Recognition Using Structure from
555 Motion Point Clouds. Proc. 10th European Conf. on Computer Vision: Part I, 44–57, 2008. DOI:10.1007/978-
556 3-540-88682-2_5]

557 Caltabiano, D., Muscato, G., Orlando, A., Federico, C., Giudice, G. and Guerrieri, S.: Architecture of a UAV
558 for volcanic gas sampling, in 2005 IEEE Conference on Emerging Technologies and Factory Automation, 1,
559 739-744, 2005.

560 Carvajal, F., Agüera, F. and Pérez, M.: Surveying a landslide in a road embankment using Unmanned Aerial
561 Vehicle photogrammetry, ISPRS Arch., 38, 1-6, 2011.

562 Casagli N., Frodella, W., Morelli, S., Tofani, V., Ciampalini, A., Intrieri, E., Raspini, F., Rossi, G., Tanteri, L. and
563 Lu, P.: Spaceborne, UAV and ground-based remote sensing techniques for landslide mapping, monitoring
564 and early warning, Geoenvironmental Disasters, 4(9), 1-23, DOI 10.1186/s40677-017-0073-1, 2017.

565 Chio, S.-H. and Lin, C.-H.: Preliminary Study of UAS Equipped with Thermal Camera for Volcanic Geothermal
566 Monitoring in Taiwan, Sensors, 17(7), 1649, doi:10.3390/s17071649, 2017.

567 Costa, D., Burlando, P. and Priadi, C.: The importance of integrated solutions to flooding and water quality
568 problems in the tropical megacity of Jakarta, Sustain. Cities Soc., 20, 199–209,
569 doi:10.1016/j.scs.2015.09.009, 2016.

570 Filizzola, C., Corrado, R., Marchese, F., Mazzeo, G., Paciello, R., Pergola, N. and Tramutoli, V.: RST-FIRES, an
571 exportable algorithm for early-fire detection and monitoring: Description, implementation, and field
572 validation in the case of the MSG-SEVIRI sensor, Remote Sensing of Environment Volume, 192, 2-25, 2017.

573 Chou, T.Y., Yeh, M.L., Chen, Y. and Chen, Y.H.: Disaster monitoring and management by the unmanned
574 aerial vehicle technology. Int. Archives of Photogrammetry, Remote Sensing and Spatial Information
575 Sciences, 38(7B), 137-142, 2010.

576 DeBell, L., Anderson, K., Brazier, R. E., King, N. and Jones, L.: Water resource management at catchment
577 scales using lightweight UAVs: current capabilities and future perspectives, J. Unmanned Veh. Syst., 4(1), 7–
578 30, doi:10.1139/juvs-2015-0026, 2016.

579 Deffontaines, B., Chang, K.J., Champenois, J., Fruneau, B., Pathier, E., Hu, J.C., Lu, S.T. and Liu Y.C.: Active
580 interseismic shallow deformation of the Pingting terraces (Longitudinal Valley – Eastern Taiwan) from UAV
581 high-resolution topographic data combined with InSAR time series. Geomatics, Natural Hazards and Risk,
582 8(1), 120-136, 2017.

583 Delacourt, C., Allemand, P., Jaud, M., Grandjean, P., Deschamps, A., Ammann, J., Cuq, V. and Suanez, S.:
584 DRELIO: An Unmanned Helicopter for Imaging Coastal Areas. J. Coast. Res. 56, 1489-1493, 2009.

585 Deurloo, R., Bastos, L. and Bos, M.: On the Use of UAVs for Strapdown Airborne Gravimetry, pp. 255–261,
586 Springer, Berlin, Heidelberg., 2012.

587 Dominici, D,, Alicandro, M., Massimi, V.: UAV photogrammetry in the post-earthquake scenario: case
588 studies in L'Aquila. Geomatics, Natural Hazards and Risk, 8(1), 87-103, 2017.

589 Dong, L., Shan, J.: A comprehensive review of earthquake-induced building damage detection with remote
590 sensing techniques. ISPRS Journal of Photogrammetry and Remote Sensing, 84, pp. 85-99, 2013.



591 Duarte, D., Nex, F., Kerle, N., Vosseman, G.: Towards a more efficient detection of earthquale induced facad
592 damages using oblique UAV imagery. International Archives of the Photogrammetry, Remote Sensing and
593 Spatial Information Sciences. To be published. 2017.

594 Dunford, R., Michel, K., Gagnage, M., Piégay, H. and Trémelo M.-L.: Potential and constraints of Unmanned
595 Aerial Vehicle technology for the characterization of Mediterranean riparian forest, International Journal of
596 Remote Sensing, 30, 4915-4935, 2009.

597 Erdelj, M., Król, M. and Natalizio, E.: Wireless Sensor Networks and Multi-UAV systems for natural disaster
598 management, Comput. Networks, 124, 72–86, doi:10.1016/j.comnet.2017.05.021, 2017.

599 Feng, Q., Liu, J. and Gong, J.: Urban Flood Mapping Based on Unmanned Aerial Vehicle Remote Sensing and
600 Random Forest Classifier—A Case of Yuyao, China, Water, 7(4), 1437–1455, doi:10.3390/w7041437, 2015.

601 Fernandez Galarreta, J., Kerle, N. and Gerke, M. UAV - based urban structural damage assessment using
602 object - based image analysis and semantic reasoning. In: Natural hazards and earth system sciences
603 (NHESS) : open access, 15(6) pp. 1087-1101, 2015.

604 Filizzola, C., Corrado, R., Marchese, F., Mazzeo, G., Paciello, R., Pergola, N. and Tramutoli, V.: RST-FIRES, an
605 exportable algorithm for early-fire detection and monitoring: Description, implementation, and field
606 validation in the case of the MSG-SEVIRI sensor, Remote Sensing of Environment, 192, 2-25, 2017.

607 Fiorucci, F., Giordan, D., Santangelo, M., Dutto, F., Rossi, M., and Guzzetti, F.: Criteria for the optimal
608 selection of remote sensing images to map event landslides, Nat. Hazards Earth Syst. Sci. Discuss.,
609 https://doi.org/10.5194/nhess-2017-111, in review, 2017

610 Fonstad, M.A., Dietrich, J.T., Courville, B.C., Jensen J.L. and Carbonneau, P.E.: Topographic structure from
611 motion: a new development in photogrammetric measurement, Earth Surf. Process. Landforms, 38, 421-
612 430, 2013.

613 Gerke, M. and Kerle, N.: Automatic structural seismic damage assessment with airborne oblique pictometry
614 imagery. In: PE&RS = Photogrammetric Engineering and Remote Sensing, 77(9) pp. 885-898, 2011.

615 Giordan, D., Manconi, A., Facello, A., Baldo, M., dell'Anese, F., Allasia, P. and Dutto, F.: Brief Communication
616 "The use of UAV in rock fall emergency scenario", Nat. Hazards Earth Syst. Sci., 15, 163-169, 2015a.

617 Giordan, D., Manconi, A., Tannant, D. and Allasia, P.: UAV: low-cost remote sensing for high-resolution
618 investigation of landslides. IEEE International Symposium on Geoscience and Remote Sensing IGARSS, 26-31
619 July 2015, Milan, Italy, 5344-5347, 2015b.

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

623 GSI: Information on the 2017 Northern Kyushu Heavy Rain, Geospatial Inf. Auth. Japan [online] Available
624 from: http://www.gsi.go.jp/BOUSAI/H29hukuoka_ooita-heavyrain.html (Accessed 16 September 2017),
625 2017.

626 Guzzetti F., Reichenbach P., Cardinali M., Galli M. and Ardizzone F.: Probabilistic landslide hazard
627 assessment at the basin scale, Geomorphology, 72(1-4), 272-299, 2005.



628 Haneberg, W. C.: Using close range terrestrial digital photogrammetry for 3-D rock slope modeling and
629 discontinuity mapping in the United States, Bulletin of Engineering Geology and the Environment, 67(4),
630 457-469, 2008.

631 Harvey, M. C., Rowland, J. V. and Luketina, K. M.: Drone with thermal infrared camera provides high
632 resolution georeferenced imagery of the Waikite geothermal area, New Zealand, J. Volcanol. Geotherm.
633 Res., 325, 61–69, doi:10.1016/j.jvolgeores.2016.06.014, 2016.

634 Heller, J., Havlena, M., Sugimoto, A. and Pajdla, T.: Structure-from-Motion Based Hand-Eye Calibration
635 Using L∞ Minimization. CVPR, 3497-3503, 2011.

636 Hinkley, E. and Zajkowski, T.: USDA forest service-NASA: unmanned aerial systems demonstrations—
637 pushing the leading edge in fire mapping, Geocarto Int., 26(2), 103-111, 2011.

638 Hunag H., Long J., Lin H., Zang L., Yi W. and Lei B.: Unmanned aerial vehicle based remote sensing method
639 for monitoring a steep mountainous slope in the Three Gorges Reservoir, China, Earth Science Informatics
640 10 (3) 287-301, 2017.

641 Immerzeel, W.W., Kraaijenbrink, P. D. A., Shea, J. M., Shrestha, A. B., Pellicciotti, F., Bierkens, M. F. P. and
642 de Jonga, .S.M.: High-resolution monitoring of Himalayan glacier dynamics using unmanned aerial vehicles,
643 Remote Sensing of Environment, 150, 93-103, 2014.

644 Irschara, A., Zach, C., Frahm, J. M. and Bischof, H.: From Structure-from-Motion Point Clouds to Fast
645 Location Recognition, CVPR, 2599-2606, 2009.

646 Jaud, M.; Grasso, F.; Le Dantec, N.; Verney, R.; Delacourt, C.; Ammann, J.; Deloffre, J.; Grandjean, P.
647 Potential of UAVs for Monitoring Mudflat Morphodynamics (Application to the Seine Estuary, France).
648 ISPRS Int. J. Geo-Inf. 5(4), 50, 2016.

649 Joyce K. E., Belliss, S. E., Samsonov, S. V., McNeill, S. J. and Glassey, P. J.: A review of the status of satellite
650 remote sensing and image processing techniques for mapping natural hazards and disasters. Progress in
651 Physical Geography, 33, 83-207, 2009.

652 Jurecka, M. and Niedzielski, T.: A procedure for delineating a search region in the UAV-based SAR activities.
653 Geomatics, Natural Hazards and Risk, 8(1), 53-72, 2017.

654 Klemas, V. V.: Coastal and Environmental Remote Sensing from Unmanned Aerial Vehicles: An Overview,
655 Journal of Coastal Research, 31(5), 1260-1267, 2015.

656 Koutsoudisa, A., Vidmarb, B., Ioannakisa, G., Arnaoutogloua, F., Pavlidis, V. and Chamzasc, C.: Multi-image
657 3D reconstruction data evaluation, Journal of Cultural Heritage, 15, 73-79, 2014.

658 Lazzari, M. and Gioia D.: UAV images and high-resolution DEMs for geomorphological analysis and hazard
659 evaluation: the case of the Uggiano archaeological site (Ferrandina, southern Italy). Geomatics, Natural
660 Hazards and Risk, 8(1), 104-119, 2017.

661 Langhammer, J., Lendzioch, T., Miřijovskỳ, J. and Hartvich, F.: UAV-based optical granulometry as tool for
662 detecting changes in structure of flood depositions, Remote Sens., 9(3), doi:10.3390/rs9030240, 2017.

663 Le Coz, J., Patalano, A., Collins, D., Guillén, N. F., García, C. M., Smart, G. M., Bind, J., Chiaverini, A., Le
664 Boursicaud, R., Dramais, G. and Braud, I.: Crowdsourced data for flood hydrology: Feedback from recent



665 citizen science projects in Argentina, France and New Zealand, J. Hydrol., 541, 766–777,
666 doi:10.1016/j.jhydrol.2016.07.036, 2016.

667 Leprince, S.: Monitoring earth surface dynamics with optical imagery, EOS Trans. Am. Geophys. Union 89, 1-
668 2, 2008.

669 Leprince, S., Barbot, S., Ayoub, F. and Ayouac, J.P.: Automatic and precise orthorectification, co-
670 registration, and sub-pixel correlation of satellite images, application to ground deformation
671 measurements. IEEE Trans. Geosci. Remote Sens. 46, 1529-1558, 2007.

672 Li, Y., Gong, J. H., Zhu, J., Ye, L., Song, Y. Q. and Yue, Y. J.: Efficient dam break flood simulation methods for
673 developing a preliminary evacuation plan after the Wenchuan Earthquake, Nat. Hazards Earth Syst. Sci.,
674 12(1), 97–106, doi:10.5194/nhess-12-97-2012, 2012.

675 Lucieer, A., de Jong S. M. and Turner, D.: Mapping landslide displacements using Structure from Motion
676 (SfM) and image correlation of multi-temporal UAV photography, Progress in Physical Geography, 38(1),
677 97–116, 2014a.

678 Lucieer, A., Turner, D., King, D. H. and Robinson, S. A.: Using an Unmanned Aerial Vehicle (UAV) to capture
679 microtopography of Antarctic moss beds. International Journal of Applied Earth Observation and
680 Geoinformation. 27(a), 53–62, 2014b.

681 Manferdini, A.M.: A Methodology for the Promotion of Cultural Heritage Sites Through the Use of Low-Cost
682 Technologies and Procedures. In: proc. 17th Int. Conf. on 3D Web Technology Los Angeles, CA, August 4-5,
683 2012, 180, 2012.

684 Martin, P. G., Smith, N. T., Yamashiki, Y., Payton, O. D., Russell-Pavier F. S., Fardoulis, J. S., Richards D. A.
685 and Scott T. B.: 3D unmanned aerial vehicle radiation mapping for assessing contaminant distribution and
686 mobility, International Journal of Applied Earth Observation and Geoinformation, 52, 12-19, 2016.

687 Marek, L., Miřijovský, J. and Tuček, P.: Monitoring of the Shallow Landslide Using UAV Photogrammetry and
688 Geodetic Measurements, In: Lollino G., Giordan D., Crosta G.B., Corominas J., Azzam R. Wasowski J., Sciarra
689 N. (eds.) Engineering Geology for Society and Territory – Landslide Processes, Springer International
690 Publishing Switzerland, 2, 113-116, 2015.

691 Martinez-de Dios, J.R., Merino, L., Caballero, F. and Ollero, A.: Automatic forest-fire measuring using ground
692 stations and unmanned aerial systems. Sensors, 11(6), 6328-6353, 2011.

693 McKenzie, D., Shankar, U., Keane, R. E., Stavros, E. N., Heilman, W. E., Fox, D. G. and Riebau, A. C.: Smoke
694 consequences of new wildfire regimes driven by climate change, Earth's Future, 2(2), 35-59, 2014.

695 Merino, L., Caballero, F., Martínez-de-Dios, J.R., Iván, M. and Aníbal, O.: An unmanned aircraft system for
696 automatic forest fire monitoring and measurement, J. Intell. Rob. Syst., 65(1-4), 533-548, 2012.

697 McGonigle, A. J. S., Aiuppa, A., Giudice, G., Tamburello, G., Hodson, A. J. and Gurrieri, S.: Unmanned aerial
698 vehicle measurements of volcanic carbon dioxide fluxes, Geophys. Res. Lett., 35(6), 3–6,
699 doi:10.1029/2007GL032508, 2008.

700 Middlemiss, R.P., Samarelli, A., Paul, D.J., Hough, J., Rowan, S. and Hammond, G.D.: The First Measurement
701 of the Earth Tides with a MEMS Gravimeter, Nature, 531(1), 614, 2016.



Molina, P., Colomina, I., Vitoria, T., Silva, P.F., Skaloud, J., Kornus, W., Prades, R. and Aguilera, C.: Searching lost people with UAVs: the system and results of the close-search project. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 39(B1), 441-446, 2012.

Moslah, O., Guitteny, V., Couvet, S.: Geo-referencing Uncalibrated Photographs Using Aerial Images and 3D Urban Models. CORESA, 1–5, 2009.

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

Nagatani, K., Akiyama, K., Yamauchi, G., Otsuka, H., Nakamura, T., Kiribayashi, S., Yoshida, K., Hada, Y., Yuta, S., Fujino, K., Izu, T. and Mackay, R.: Volcanic ash observation in active volcano areas using teleoperated mobile robots - Introduction to our robotic-volcano-observation project and field experiments, in: proc. 2013 IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR), Linkoping, Sweden, 21-26 Oct. 2013, 1–6, 2013.

Nakano, T., Kamiya, I., Tobita, M., Iwahashi, J. and Nakajima, H.: Landform monitoring in active volcano by UAV and SFM-MVS technique, Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. - ISPRS Arch., 40(8), 71–75, 2014.

Nassar, K., Aly, E.A. and Jung, Y.: Structure-from-Motion for Earthwork Planning, in: proc. of 28th ISARC 2011, Seoul, Corea, 310–316, 2011.

Nex, F., Rupnik, E., Toschi, I., Remondino, F., 2014. Automated processing of high resolution airborne images for earthquale damage assessment. In: International Archives of Photogrammetry and Remote Sensing and Spatial Information Sciences, Vol. XL-1.

Niculiţă, M.: Automatic landslide length and width estimation based on the geometric processing of the bounding box and the geomorphometric analysis of DEMs, Nat. Hazards Earth Syst. Sci., 16, 2021-2030, https://doi.org/10.5194/nhess-16-2021-2016, 2016.

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

Niethammer, U., Rothmund, S., James, M.R., Travelletti, J. and Joswig, M.: UAV-based remote sensing of landslides. In Proceedings of the International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, Commission V Symposium, Newcastle upon Tyne, UK, 21–24 June 2010, 496–501, 2010.

Niethammer, U., Rothmund, S., Joswig, M.: UAV-based remote sensing of the slow-moving landslide Super-Sauze. In: Malet, J.-P., Remaître, A., Boogard, T. (Eds) Proceedings of the International Conference on Landslide Processes: from geomorpholgic mapping to dynamic modelling, Strasbourg, CERG Editions, pp. 69-74, 2009.

Niethammer, U., Rothmund, S., Schwaderer, U., Zeman, J., Joswig, M.: Open Source Image-Processing Tools for Low-Cost UAV-Based Landslide Investigations. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XXXVIII-1/C22, 2011 ISPRS Zurich 2011 Workshop, 14-16 September 2011, Zurich, Switzerland, 161-166, 2011.



739 Nishar, A., Richards, S., Breen, D., Robertson, J. and Breen, B.: Thermal infrared imaging of geothermal
740 environments and by an unmanned aerial vehicle (UAV): A case study of the Wairakei - Tauhara geothermal
741 field, Taupo, New Zealand, Renew. Energy, 86, 1256–1264, doi:10.1016/j.renene.2015.09.042, 2016.

742 Peters, M. P., Iverson, L. R., Matthews, S. N. and Prasad, A. M.: Wildfire hazard mapping: exploring site
743 conditions in eastern US wildland–urban interfaces, International Journal of Wildland Fire, 22, 567-578,
744 2013.

745 Piras, M., Taddia, G., Forno, M.G., Gattiglio, M., Aicardi, I., Dabove, P., Lo Russo, S. and Lingua, A.: Detailed
746 geological mapping in mountain areas using an unmanned aerial vehicle: application to the Rodoretto
747 Valley, NW Italian Alps, Geomatics, Natural Hazards and Risk, 8(1), 137-149, 2017.

748 Pollefeys, M., Gool, L. V., Vergauwen, M., Cornelis, K., Verbiest, F. and Tops, J.: Image-Based 3D Acquisition
749 of Archaeological Heritage and Applications. Proc. Conf. on Virtual Reality, Archeology, and Cultural
750 Heritage, 255–262, 2001.

751 Pratt, K.S., Murphy, R., Stover, S. and Griffin, C.: Conops and autonomy recommendations for VTOL small
752 unmanned aerial system based on Hurricane Katrina operations, Journal of Field Robotics, 26(8), 636-650,
753 2009.

754 Rau, J.Y., Jhan, J.P., Lo, C.F. and Lin Y. S.: Landslide mapping using imagery acquired by a fixed-wing UAV,
755 International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume
756 XXXVIII-1/C22, 2011 ISPRS Zurich 2011 Workshop, 14-16 September 2011, Zurich, Switzerland, 195-200,
757 2011.

758 Razak, K. A., Santangelo, M., Van Westen, C. J., Straatsma, M. W., and de Jong, S. M.: Generating an optimal
759 DTM from airborne laser scanning data for landslide mapping in a tropical forest environment,
760 Geomorphology, 190, 112-125, 25 https://doi.org/10.1016/j.geomorph.2013.02.021, 2013

761 Ryan, J. C., Hubbard, A. L., Box, J. E., Todd, J., Christoffersen, P., Carr, j. R., Holt, T. O., and Snooke, N.:
762 Repeat UAV photogrammetry to assess calving front dynamics at a large outlet glacier draining the
763 Greenland Ice Sheet, The Cryosphere, 9, 1-11, 2015.

764 Saiki, K. and Ohba, T.: Development of an unmanned observation aerial vehicle (UAV) as a tool for volcano
765 survey (in Japanese with English abstract), Bull. Volcanol. Soc. Japan Second Ser., 55(3), 137–146, 2010.

766 Salvini, R., Mastrorocco, G., Seddaiu, M., Rossi, D. and Vanneschi, C.: The use of an unmanned aerial vehicle
767 for fracture mapping within a marble quarry (Carrara, Italy): photogrammetry and discrete fracture
768 network modelling, Geomatics, Natural Hazards and Risk, 8(1), 34-52, 2017.

769 Sanada, Y. And Torii T.: Aerial radiation monitoring around the Fukushima Dai-ichi nuclear power plant
770 using an unmanned helicopter, Journal of Environmental Radioactivity, 139, 294-299, 2015.

771 Santangelo, M., Cardinali, M., Rossi, M., Mondini, A. C., and Guzzetti, F.: Remote landslide mapping using a
772 laser rangefinder binocular and GPS, Nat. Hazards Earth Syst. Sci., 10, 2539-2546,
773 https://doi.org/10.5194/nhess-10-2539-2010, 2010.

774 Saroglou, C., Asteriou, P., Zekkos, D., Tsiambaos, G., Clark, M., and Manousakis, J.: UAV-enabled
775 reconnaissance and trajectory modeling of a co-seismic rockfall in Lefkada, Nat. Hazards Earth Syst. Sci.
776 Discuss., https://doi.org/10.5194/nhess-2017-29, in review, 2017.



777 Scaioni, M., Longoni, L., Melillo, V. and Papini, M.: Remote Sensing for Landslide Investigations: An
778 Overview of Recent Achievements and Perspectives, Remote Sens. 6(10), 9600-9652, 2014,

779 Schroeder, W., Oliva, P., Giglio, L., Quayle, B., Lorenz, E. and Morelli,F.: Active fire detection using Landsat-
780 8/OLI data, Remote Sensing of Environment, 185, 210-220, 2016.

781 Şerban, G., Rus, I., Vele, D., Breţcan, P., Alexe, M. and Petrea, D.: Flood-prone area delimitation using UAV
782 technology, in the areas hard-to-reach for classic aircrafts: case study in the north-east of Apuseni
783 Mountains, Transylvania, Nat. Hazards, 82(3), 1817–1832, doi:10.1007/s11069-016-2266-4, 2016.

784 Shinohara, H.: Composition of volcanic gases emitted during repeating Vulcanian eruption stage of
785 Shinmoedake, Kirishima volcano, Japan, Earth Planets Sp., 65(6), 667–675, 2013.
786 doi:10.5047/eps.2012.11.001,

787 Silvagni, M., Tonoli, A., Zenerino, E and Chiaberge, M.: Multipurpose UAV for search and rescue operations
788 in mountain avalanche events. Geomatics, Natural Hazards and Risk, 8(1), 18-33, 2017.

789 Sohn, H., Heo, J., Yoo, H., Kim, S. and Cho, H.: Hierarchical multi-sensor approach for the assessment of
790 flood related damages, Proc. XXI Congr., 207–210, 2008.

791 Stöcker, C., Bennett, R., Nex, F., Gerke, M. and Zevenbergen, J.: Review of the current state of UAV
792 regulations, Remote Sensing 9(5), 459, doi:10.3390/rs9050459, 2017.

793 Tang, L. and Shao, G.: Drone remote sensing for forestry research and practices. J. For. Res., 26, 791-797,
794 2015.

795 Tannant, D. D., Giordan, D. and Morgenroth J.: Characterization and analysis of a translational rockslide on
796 a stepped-planar slip surface. Engineering Geology, 220, 144-151, 2017.

797 Tarolli, P.: High-resolution topography for understanding Earth surface processes: opportunities and
798 challenges, Geomorphology, 216, 295–312, 2014.

799 Tobita, M., Kamiya, I., Iwahashi, J., Nakano, T. and Takakuwa, N.: UAV aerial photogrammetry in
800 Nishinoshima Island and its analysis (in Japanese), Bull. Geospatial Inf. Auth. Japan, 125, 115–124, 2014a.

801 Tobita, M., Kamiya, I., Nakano, T., Iwahashi, J., Osumi, K. and Takakuwa, N.: Precise UAV aerial
802 photogrammetry in Nishinoshima Island (in Japanese), Bull. Geospatial Inf. Auth. Japan, 125, 145–154,
803 2014b.

804 Tokarczyk, P., Leitao, J. P., Rieckermann, J., Schindler, K. and Blumensaat, F.: High-quality observation of
805 surface imperviousness for urban runoff modelling using UAV imagery, Hydrol. Earth Syst. Sci., 19(10),
806 4215–4228, doi:10.5194/hess-19-4215-2015, 2015.

807 Torrero, L. Seoli, L. Molino, A. Giordan, D. Manconi, A. Allasia, P. and Baldo, M.: The Use of Micro-UAV to
808 Monitor Active Landslide Scenarios, in: Engineering Geology for Society and Territory, edited by: Lollino, G.,
809 Manconi, A., Guzzetti, F., Culshaw, M., Bobrowsky P., and Luino, F., Springer International Publishing
810 Switzerland, 5, 701-704, https://doi.org/10.1007/978-3-319-09048-1_136, 2015.

811 Török, Á., Barsi, Á., Bögöly, G., Lovas, T., Somogyi, Á., and Görög, P.: Slope stability and rock fall hazard
812 assessment of volcanic tuffs using RPAS and TLS with 2D FEM slope modelling, Nat. Hazards Earth Syst. Sci.
813 Discuss., https://doi.org/10.5194/nhess-2017-56, in review, 2017.



814 Travelletti, J., Delacourt, C., Allemand, P., Malet, J.P., Schmittbuhl, J., Toussaint, R. and Bastard, M.:
815 Correlation of multi-temporal ground-based optical images for landslide monitoring: application, potential
816 and limitations, ISPRS J Photogramm Remote Sens, 70, 39-55, 2012.

817 Tu, J., Sui, H., Feng, W., Sun, K., Xu, C. and Han, Q.: Detecting building facade damage from oblique aerial
818 images using local symmetry feature and the Gini Index. Remote Sensing Letters, 8(7), 676-685, 2017.

819 Turner, D. and Lucieer, A.: Using a micro unmanned aerial vehicle (UAV) for ultra-high resolution mapping
820 and monitoring of landslide dynamics. In Proceedings of the IEEE International Geoscience and Remote
821 Sensing Symposium, Melbourne, Australia, 25 July 2013.

822 Turner, D., Lucieer, A. and Watson, C.: An automated technique for generating georectified mosaics from
823 ultrahigh resolution unmanned aerial vehicle (UAV) imagery, structure from motion (SfM) point
824 clouds. Remote Sens., 4(12), 1392-1410, 2012.

825 Turner, D., Lucieer, A. and de Jong, S.M.: Time Series Analysis of Landslide Dynamics Using an Unmanned
826 Aerial Vehicle (UAV), Remote Sensing, 7(2), 1736-1757, 2015.

827 Van Den Eeckhaut, M., Poesen, J., Verstraeten, G., Vanacker, V., Nyssen, J., Moeyersons, J., van Beek, L. P.
828 H., and Vandekerckhove, L.: Use of LIDAR-derived images for mapping old landslides under forest, Earth
829 Surf. Proc. Land., 32, 754-769, https://doi.org/10.1002/esp.1417, 2007.

830 Van Westen J.C., Castellanos, E. and Kuriakose S.L.: Spatial data for landslide susceptibility, hazard, and
831 vulnerability assessment: An overview. Engineering Geology, 102(3–4), 112-131, 2008.

832 Vetrivel, A., Gerke, M., Kerle, N., Nex, F. and Vosselman, G.: Disaster damage detection through synergistic
833 use of deep learning and 3D point cloud features derived from very high resolution oblique aerial images,
834 and multiple-kernel-learning. ISPRS Journal of Photogrammetry and Remote Sensing, in Press.
835 https://doi.org/10.1016/j.isprsjprs.2017.03.001.

836 Vetrivel, A., Gerke, M., Kerle, N. and Vosselman, G.: Identification of damage in buildings based on gaps in
837 3D point clouds from very high resolution oblique airborne images. ISPRS Journal of Photogrammetry and
838 Remote Sensing, 105, 61-78, 2015.

839 Walter, M., Niethammer, U., Rothmund, S. and Joswig, M.: Joint analysis of the Super-Sauze (French Alps)
840 mudslide by nanoseismic monitoring and UAV-based remote sensing. EAGE First Break, 27(8), 75-82, 2009.

841 Wen, Q., He, H., Wang, X., Wu, W., Wang, L., Xu, F., Wang, P., Tang, T. and Lei, Y.: UAV remote sensing
842 hazard assessment in Zhouqu debris flow disaster, in: Remote Sensing of the Ocean, Sea Ice, Coastal
843 Waters, and Large Water Regions, Bostater, C.R., Ertikas, S.P., Neyt X. and Velez-Reyes, M. (eds.), , 8 pp.,
844 2011.

845 Westoby, M. J., Brasington, J., Glasser, N. F., Hambrey, M. J. and Reynolds, M. J.: Structure-from-Motion
846 photogrammetry: A low-cost, effective tool for geoscience applications. Geomorphology, 179, 300-314,
847 2012.

848 Wing, M. G., Burnett J. D. and Sessions, J.: Remote sensing and unmanned aerial system technology for
849 monitoring and quantifying forest fire impacts, Int J Remote Sens Appl., 4(1), 18-35, 2014.



850 Yajima, R., Nagatani, K. and Yoshida, K.: Development and field testing of UAV-based sampling devices for
851 obtaining volcanic products, in 2014 IEEE International Symposium on Safety, Security, and Rescue
852 Robotics, 27-30 Oct. 2014, Hokkaido, Japan, 1–5, 2014.

853 Yoon, W.S., Jeong, U.J. and Kim, J.H.: Kinematic analysis for sliding failure of multi-faced rock slopes,
854 Engineering Geology, 67, 51-61, 2002.

855 Zajkowski, T.J., Dickinson, M.B., Hiers, J.K., Holley, W., Williams, B.W., Paxton, A., Martinez, O. and Walker,
856 G.W.: Evaluation and use of remotely piloted aircraft systems for operations and research – RxCADRE 2012.
857 International Journal of Wildland Fire, 25, 114-128, 2015.

858 Zazo, S., Molina, J. L. and Rodríguez-Gonzálvez, P.: Analysis of flood modeling through innovative geomatic
859 methods, J. Hydrol., 524, 522–537, doi:10.1016/j.jhydrol.2015.03.011, 2015.