

REVIEW

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UAV- based Photogrammetry and Geocomputing for Hazards and Disaster Risk Monitoring – A Review

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Abstract

Background: The unraveling of the human-induced climate-change crisis has put to the forth the ability of human-beings to impact the planet as a whole, but the discourse of politics has also emphasized the ability of the human race to adapt and counterweigh the environmental change, in turn increasing the public expectation that one should be able to control nature and its affects. Such cozy and reassured society consequently puts an increasing amount of pressure on hazards assessors, emergency and disaster managers “to get it right”, and not only to save the majority, but to save all. To reach such level of competency, emergency relief teams and disaster managers have to work always faster with an increasing need of high quality, high-resolution geospatial data. This need is being partly resolved with the usage of UAV (Unmanned Autonomous Vehicles), both on the ground and airborne.

Results: In this contribution, we present a review of this field of research that has increased exponentially in the last few years. The rapid democratization of the tool has lead to a significant price reduction and consequently a broad scientific usage that have resulted in thousands of scientific contributions over the last decade. The main usages of UAVs are the mapping of land features and their evolution over time, the mapping of hazards and disasters as they happen, the observation of human activity during an emergency or a disaster, the replacement of telecommunication structures impacted by a natural hazards and the transport of material to isolated groups.

Conclusion: Those usages are mostly based on the use of single UAVs or UAVs as single agents eventually collaborating. The future is most certainly in the ability to accomplish complex tasks by leveraging the multiple platforms possibilities. As an example, we presented an experiment showing how multiple UAV platforms taking imagery together at the same time could provide true 4D (3D in time) of geo-processes such as river-bed evolution, or rockfalls, etc.

Keywords: UAV, Drone, Disaster, Natural hazards, Disaster risk, Geotechnical monitoring, Disaster management framework

Introduction

At the end of 2015, the COP21 in Paris ended with a series of more or less binding agreements, which received large media coverage because of the increasing sense of urgency that has emerged over the last few years. In this context of accelerating climate change that will continue exacerbating existing weather hazards and disaster risk, Japan, countries of Western Europe and North America are also experiencing a major demographic shift as the baby-boomers are hitting retirement age (MacKellar,

2004). This environmental and human shift is going to have tremendous effects on the sciences: how many researchers can a society afford, what research can be funded and what should be prioritized. In a country like Japan, where the external debt has reached 2.8 trillion US dollars in 2014, the number of children does not meet the generation renewal with only 1.4 children per couple. On the contrary, the 65 years old and more already account for 25% of the population, and their number is growing. This shift will have important consequences on what countries can afford, and ultimately it will impact the fields of pure and applied sciences as we know them.

Because of those imperatives, the development of automated solutions to reduce the needs of human resources is essential, and so are the development in robotics and

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artificial intelligence (Gomez et al. (2015a); Gomez et al., 2016), including the usage of UAVs (Unmanned Aerial Vehicles) for hazards, disaster risk and emergency management. Despite the eventual difficulties to fund research and sciences and consequently the potential reduction of human resources, the governmental obligations to survey and protect population against environmental hazards remain unchanged, and most probably so will the expectations of citizen.

Within this framework, the present contribution will provide a non-exhaustive review of the usage of UAVs in three key areas of geological risk-related geosciences – earthquakes, volcanic activity and landslides. In the discussion, we also present some of the expected future developments, and particularly, the usage of multiple UAVs in swarms for photogrammetry in 4D.

Unmanned Aerial Vehicle (UAV) is also referred to as Unpiloted Aerial Vehicle and Remotely-Piloted Aircraft (RPA). To qualify in this category the flying aircraft must be without any pilot on board and it has to be reusable. Despite of appearances, UAV isn't new and the first one was flown as early as 1918 in the USA as a pilotless flying bomb: the Kettering Bug (Gillespie, 2009). As it lacked the artificial intelligence, or the control link with a pilot on the ground, it reached a given destination by using a set of propeller rotation and a gyroscope. Therefore, the evolution of UAVs over the 20th century and the early 21st hasn't been about the concept of flying vehicles without pilots, but the possibility to control them with more accuracy and have them more autonomous.

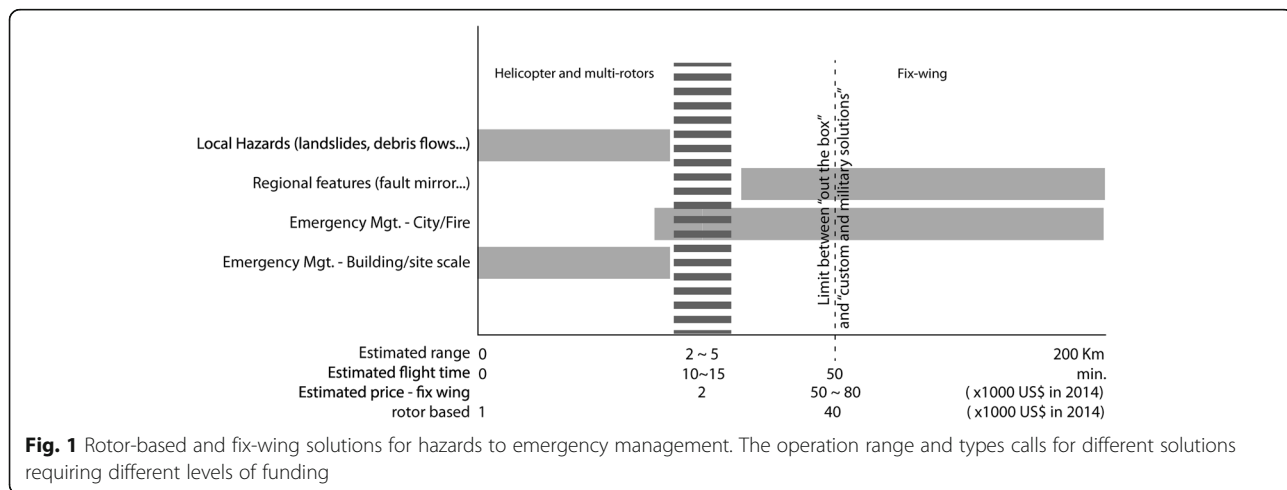
In recent years, such research and the decreasing price of electronic components have allowed the commercialization of "straight from the shelves" solutions that can be flown by the public, generating a market worth 5,400 million Euros in 2013 alone (Colomina and Molina, 2014). The evolution of onboard computing and ground connection also permits the accomplishment of complex tasks (Maza et al., 2011)

and semi-autonomous flight (Rathbun et al., 2002), which in turn has led to the development of applications for industrial monitoring with UAV – e.g. (Hausmann et al., 2005) - and environmental and engineering structures monitoring with UAV - e.g. (Gonzales-Jorge et al., 2014).

In the same fashion, the versatility of UAVs can provide support for hazard assessment and emergency management – e.g. Quadritsch et al., 2010 - at both the local and the regional scale, depending on the usage of different platforms (Fig. 1).

At the local or site scale, helicopter and multi-rotor systems are best adapted, as most of the commercial solutions have a range of up to ~2 km corresponding to flight times of 15 min (some large platform can fly up to an hour but they remain costly) and they allow stationary flight over precise site or the investigation of local site with complex vertical extensions, such as cliffs, rockfall walls, etc. (The Press, 2014). At the regional scale, the use of fix-wings is more appropriate and allows the coverage of large areas over short period of time, for the survey of volcanic eruption, fire evolution. For fix-wings, different companies offer several "from the shelf" solutions that cost up to 50–80 k. US\$, from which more expensive custom solutions can also be purchased. This high versatility, relatively low-cost, the availability of "easy-to-fly" platforms and the possibility to multiply the frequency of flights over time has led to a real boom of UAVs in disaster risk reduction (Fig. 2). The number of publications on UAVs and disasters has exploded from none in 2000 to 81 in a single year in 2014. This growth follows an increasing interest for the field, with 6 publications in 1990 on UAVs that peaked in 2014 to 2164 (as per Scopus search).

UAVs have imposed their presence in the field of hazards, disaster risk and emergency management, because of their recent price decrease but also because onboard electronic is now advanced enough to provide semi-controlled pilot systems and aided-pilot controls, in such a way that



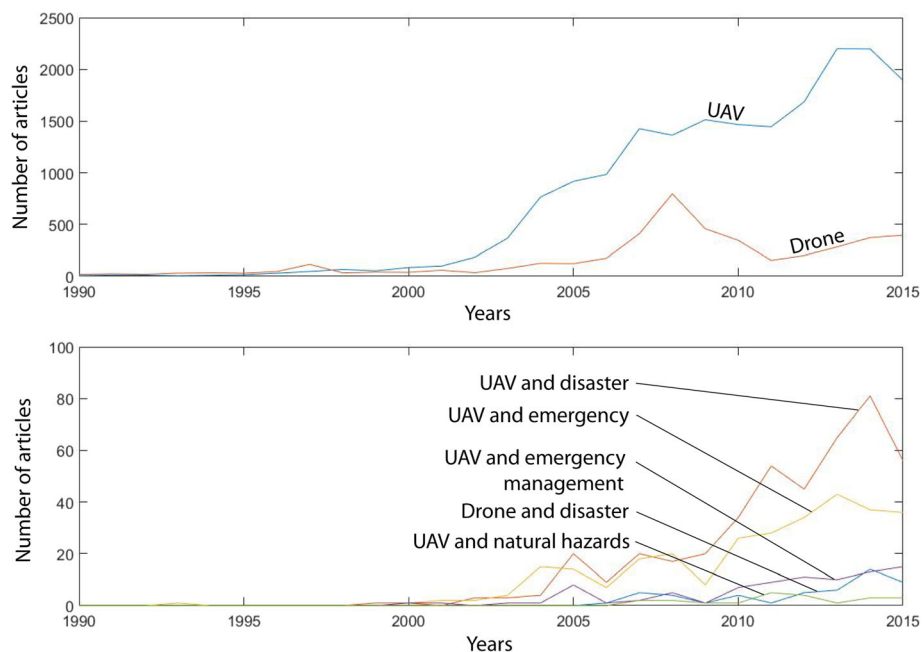


Fig. 2 Number of references about UAV, drones, hazards, disaster and emergency from Scopus search (another table about UAS and its usage in commercial and military purposes can be found in Colomina and Molina 2014:80)

non-specialists can operate them. This development translates in term of scientific interests with 434 entries under “UAV and Disaster” in scopus (as per December 2015), 166 entries for “UAV and Hazard” and 87 entries for “UAV and Emergency management”.

A review of the recent contributions published in the last few years (Table 1) show that the research field is interested by the usage of UAVs in area that are difficult to access, and also as a temporary replacement of local infrastructure (like cellphone towers). Another type of research has been more interested in capturing spatial data by rigging different sensors to the flying platforms (Table 1).

Review

Structure-from-Motion Photogrammetry from UAVs for hazards, disaster risk and emergency management

One of the sensors commonly rigged to the UAV is a camera or a video camera, fixed by a gimbal to limit the vibration and the effects of rolling of the UAV. Such configuration has seen a real boom in the field of geosciences in recent years, because of its very low-cost, high versatility and provides the possibility to calculate 3D models using the Structure from Motion (SfM) algorithm (Clapuyt et al., 2015; Hugenholtz et al. 2013). Structure from Motion or Structure and Motion is traditionally part of the research field of close-range photogrammetry. The SfM algorithm has been developed in the engineering field of computer vision in the 1970s (Ullman, 1979), and it has benefited of the development of pose-estimation and bundle adjustment (Hartley and Wisserman 2004) and image matching

(Furukawa and Ponce 2010). At the same time, the ever-increasing computing capacities and the number of “ready-solutions” have made the method very popular, and allowed the development of specific solutions (Table 1).

Although the combination of SfM with airborne photography is mostly used as a low-cost replacement to LiDAR (Light Detection And Ranging), it can also be used to work from historical data, providing 3D dataset of periods when laser technologies were not existing and computing in its infancy - 1940s or 1950s for instance - (Gomez et al. (2015b)). Furthermore, the possibility to use nadir photographs combined with photographs taken from different angles allows the detailed recording of subvertical surfaces and cavities as well (Gomez and Kato, 2014).

The main appeal of SfM combined with UAVs is the ability to run the data collection for a very low-cost on a platform that is easy to transport (in a backpack) and that can be launched from virtually any site. The data processing has also been facilitated by the development of numerous proprietary or open-source software that offers the non-specialist the ability to recreate 3D models.

Data collection

Despite the use of gimbal to stabilize the camera, the aircraft movements, or the time to resolve focal or any unintended movement due to wind turbulence for instance can result in blur photographs. Usable photographs are therefore not equal to the number of photographs taken. Results from personal unpublished work has provided an average of 72% of usable images for data taken from a small quadcopter

Table 1 Recent studies in UAVs and hazards, disaster risk and emergency management, showing the main research directions

Nb.	Type		Hazard Assessment	Vulnerability	Emergency	Disaster Recovery	(A)pplied (T)est; (Th)ory	Hazard Denomination	Key concepts	References
	rotor	Fix-wing								
1	x	x			x		T		Mapping; Compared fixed wings against multirotor & rapid photogrammetry processing against precise slow method.	Boccardo et al. (2015)
2	x				x		Th		Discuss the use of UAV in disasters and accident as a new frontier in human activity observations and provide technical developments	Choi and Lee (2011), Di Franco and Salvatori (2015)
3	x			x	x		T, Th		Use UAVs as telecommunication relay replacement in disaster impacted areas/simulation of network efficiency	Bupe et al. (2015), Dalmaso et al. (2012), Tuna et al. (2014)
4		x			x	x	T, A	Earthquake	UAV photogrammetry at different altitude for Sichuan Earthquake Recovery Mgt	Merdaway and Guvenc (2015)
5		x	x	x	x		A	Flood	Urban flood mapping using random forest algorithm from UAV acquired data	Xie et al. (2014), Feng et al. (2015)
6			x		x		T		Real time mapping and communication with authorities for hazard and emergency mapping	Suzuki et al. (2008)
7	x			x	x	x	Th		Food and relief material transport	Nedjati et al. (2016)
8	x			x		x	Th, T	Earthquake	Use photographs and pointclouds acquired from the ground and UAV to detect earthquake impacts on buildings	Vetrivel et al. (2015)
9		x	x	x		x	A	Landslides and debris flows	Use of a fix-wing based imagery for post-landslide and debris-flow	Liu et al. (2015)
10				x		x	A		UAV-based imagery to monitor change in different environments including post-disaster	Ezequiel et al. (2014)

with a standard deviation of almost 26%, depending on the type of surface, wind speed, luminosity. Data present in the literature also reflect a similar pattern with photographs usable for photogrammetry representing 30% to 90% (Fig. 3). It therefore pays to increase the number of planned photographs by almost two folds to be absolutely certain to capture the necessary data. Such strategy is reflected in the disparity of photographs used and the area analyzed (please note that the flying altitude are all similar, as the objectives to capture land movements were all similar, regardless of the area investigated). This disparity calls for the creation of protocols of data collection, in order to homogenize existing dataset and increase the possibility of comparisons between the different data collections.

Assessing the quality of results

The quality of DEMs and DSMs produced using the SfM method using UAV is traditionally done using the RMSE (Root Mean Square Error) method, which is assessed using known points on the ground, which are calculated either using laser technologies such as the terrestrial laser scanner (Obanawa et al., 2014) or Survey Grade Global Navigational Sattelite System (Turner et al., 2015). As the 3D pointcloud created by SfM is constrained using Ground Control points (GCPs), authors have used part of them as check-points. Turner have used 30% of the GCPs as check points and obtained a largest RMSE of 0.076 to 0.09 respectively horizontally and vertically. The quality of the results is difficult to interpret as it depends on the number of images, the distance of the camera to the

object and the characteristics of the field data. Moreover, the variation tends to locally follow either a positive trend or a negative trend, resulting in local over-estimation in z or a local under-estimation. Some work has shown a variation of ± 2 m for a surface of 200 m x 200 m (Westoby et al., 2012). They have also recorded the uncertainty with the GCPs themselves. For their field research in Wales, they recorded an average uncertainty in xyz of 0.003 m, while in Nepal they recorded an uncertainty of 0.226 m.

The high variability in the data collection is directly related to the issues raised with the data collection process, which needs to be streamlined in the field of geosciences, especially because the methods is being used in numerous areas such as earthquake, volcanic and landslides sciences.

UAVs and geo-hazards: earthquakes, volcanic eruptions and landslides

One should argue that earthquakes, volcanic eruptions and landslides aren't the only geo-hazards, but they are arguably the fields where the majority of UAV-related research has been progressed over the last decades, especially in the field of visual monitoring and photogrammetry.

UAVs and earthquakes

The spatio-temporal frequency of damaging earthquakes has, up to date, restricted the use of UAVs to post-earthquake research and work, but UAVs provide a precious post-earthquake survey tool to collect perishable data, especially for building that aren't safe to approach or inspect (Mitsuhiro et al., 2015; Meyer et al., 2015).

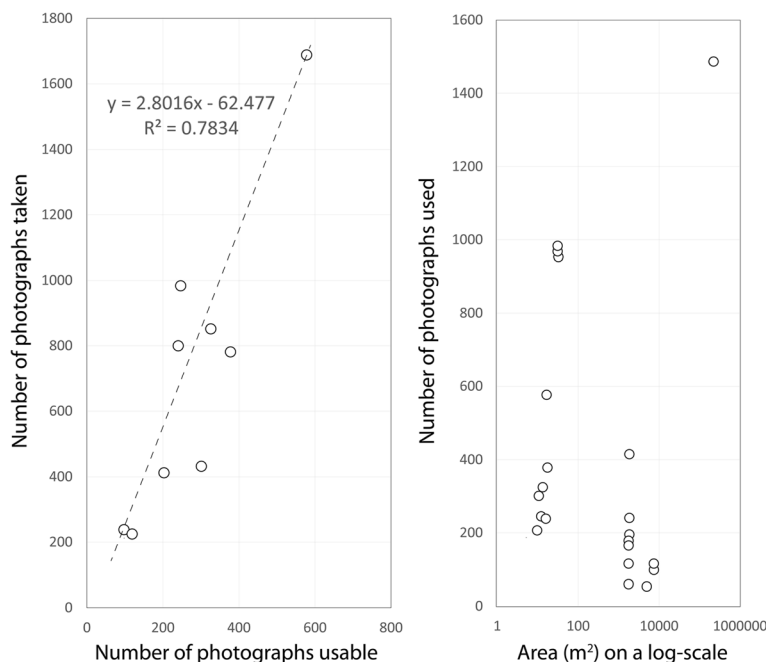


Fig. 3 Relation between photographs their usability and the survey area

UAVs are a complement to larger manned-aircraft photography and photogrammetry, because they can provide rapid solutions with virtually no infrastructure, like airport and airspace control. UAVs are also ideal to detect small-scale changes and cracks in buildings and on the ground. Indeed, low-cost solution UAVs usually can't cover large areas, but they provide a different dataset with an increased resolution. This pattern was demonstrated during the recent Kumamoto earthquake in South Japan (Kyushu Island), in the aftermath of which the authorities used small UAVs to survey the surface rupture of the fault (<https://youtu.be/DXTAAvB2M8>). The authorities of Japan also used UAVs to evidence historical building impacts that are difficult to see from a traditional aircraft, such as collapsed walls and structure with large trees around obstructing the nadir view (<https://youtu.be/BcWlJN9lnHs>). Images captured from UAVs can then easily be converted into 3D models. In the aftermath of L'Aquila earthquake in Italy, the state of the build environment was evaluated using UAV combined with the photogrammetric method of SfM (Dominici et al., 2016). UAV-based imagery can also be the source of more complex remote sensing methodologies to determine the impacts of earthquakes (Shaodan et al., 2015). The use of UAVs also goes beyond visual observations. In the Fukushima area for instance, the Japanese authorities have used UAVs to fly above and around the Fukushima power plant in order to measure radiation levels. It can be also used for the delivery of emergency goods, such as medical products (Thiels, 2015), but also food and other vital items, especially when roads and other communication infrastructures have been profoundly damaged (Nedjati et al., 2016).

UAVs and active volcanoes

Active and erupting volcanoes is an area of geosciences that has seen further development for the use of UAVs. Erupting volcanoes present numerous challenges to data collection. Sarah P. Williams wrote "In 1984, the volcano Mauna Loa erupted in Hawaii, sending ribbons of lava winding down its slopes. Geologist and former pilot David Pieri of the California Institute of Technology's Jet Propulsion Laboratory wanted to get measurements and observation of every part of the lava flow to predict its ultimate route and length. However, he only had one way to see the lava: with a helicopter. "I remember being so frustrated because you could only see what was right in front of you," says Pieri. "It was a 22-km lava flow and by the time we flew to the bottom, we had no idea what was going on at the top" (Williams, 2013). This introductory comment epitomizes the difficulties of working on active volcanoes, where researchers can often be at harm's way (e.g. the Unzen killed the Kraft husband and wife during the 1991–1995 eruption and 41 other TV crews and scientists).

The problems solved by UAV therefore concerns keeping scientists and researchers at a reasonable distance from danger, with duties spanning from visual observation of disasters (Sato and Nakanishi, 2014), measure of evolution from visual imagery and photogrammetry (Nakano et al., 2014), gas sampling (Mori et al., 2016), to sediment sampling using robotic sampling devices (Yajima et al., 2014).

UAVs are thus useful for collecting gas emanation above volcanoes, where flying in a manned-aircraft near the ground might be too hazardous, especially when heat creates strong turbulences. For instance, researchers have used a fix-wing UAV to collect SO₂ gas emission over Kirishima Volcano in South Japan (Shinohara, 2013), a multi-rotor to collect plume data during the 2014 Mt. Ontake eruption (Mori et al., 2016), different fix-wings and balloons at Costa Rica Volcano (Diaz et al., 2015).

The overwhelming majority of active volcanoes are located around the Ring Of Fire, with Japan and Indonesia being the two countries with the world highest numbers of active volcanoes. Along island arcs, volcanoes can thus often be at sea or in areas difficult to access. In such cases, UAVs have a strategic advantage as they can be operated remotely from floating platforms and boats. In Japan, Nishinoshima Volcano (Ogasawara Island group), which has emerged from the sea in November 2013 and has seen continuous eruption since, is a perfect example of a volcano at sea, where coasting is difficult and dangerous, and for which UAV monitoring has yield relative success. The Geospatial Information Authority of Japan has conducted a series of UAV flights departing from nearby Chichijima (GSJ, 2015), and used acquired visible imagery with SfM in order to produce 3D maps of the area over time to monitor the evolution of the volcano (Nakano et al., 2014).

UAVs in volcanic research have therefore been an extension of present activities, enabling safer data collection and easier data collection in remote areas. One can foresee that future development in this area should involve multiple aircrafts flying simultaneously, in order to improve the spatial distribution in time of phenomena that evolve rapidly, such as ash plumes for instance. A great advance in ash plume morphology simulation would be the collection of simultaneous photographs from swarms of UAVs, in order to collect the shape of ash plumes (or pyroclastic flow elutriated ash-clouds) in 4D (3D over time).

UAVs and landslides

A field strongly contributed by change monitoring from UAV is landslide research. Landslide monitoring necessitates measures of the rate of surface change, such as fracture openings (Niethammer et al., 2010; Stumpf et al., 2013), as well as differential measures of vertical and horizontal movements, in order to understand their mechanics (Akca, 2013; Dewitte et al., 2008). For slow-onset mass movements – i.e. compared to velocities at which we and our technology

moves – the measure of change over time can be performed from one single UAV over several years. The monitoring of those events is essential, especially because landslides produce casualties and important economic impacts every year (Schuster, 1996).

Consequently, the combination of photogrammetric methods and UAVs allow a high frequency revisit of landslide sites, providing the necessary data to create DSMs and DEMs, which allow the calculation of modification of the position of volumes and masses on a slope, as well as changes in topography (Marek et al., 2015). Results accuracy and precision are however still compared to GNSS data or other geomatic devices, in such a way that the method isn't absolutely free from ground-truthing.

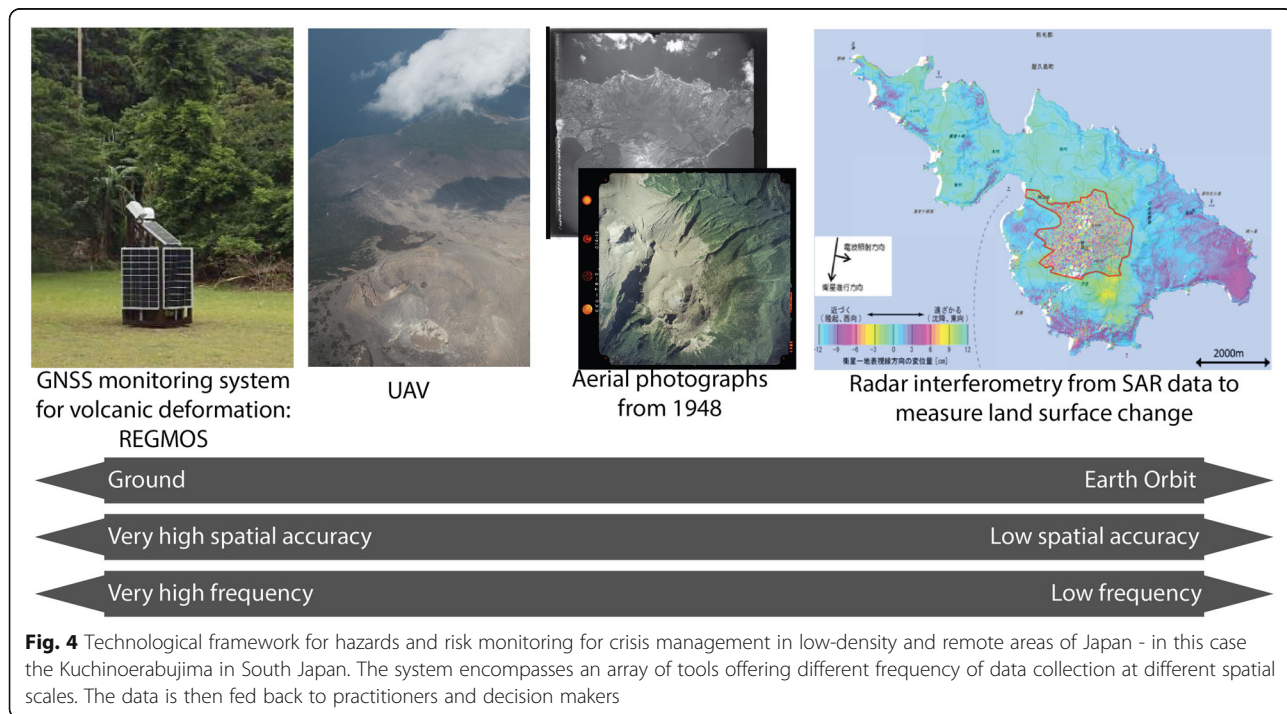
Evolution monitoring is also controlled by the rate of evolution/change in a landslide. Indeed, a location that moves very quickly will display important change in between two seasonal survey for instance, whereas other landslides might only show very limited change over the same period of time. The measured change has to be bigger than the error produced by the measurements, or in other words, one must choose the survey parameters based on the rate of change of the landslide compared to the field survey frequency for significant results. At the Super-Sauze landslide (France), average velocity of the mass movement ranged between 0.01 m/day to 0.1 m/day for the period May 2007 to Oct. 2008. This yearly measure was supported by data of RMSE = 0.31 m between the two surveys (Niethammer et al., 2012). Using a similar method on a landslide in the Zlinsky

region (Czech Republic), the $RMSE_z$ was also of similar value with 0.33 m (Marek et al., 2015), and the authors only used change value over the survey period that are greater than the RMSE, with value exceeding 8 m change over the period 2008–2013.

UAV monitoring of hazards and disaster sites is therefore a promising tool that has been rising in the last decade, but it is still constrained by (1) weather conditions and daylight conditions; (2) by the need of photogrammetric methods to still have some ground control points to reach maximum accuracy; (3) by the technical limitations, such as range, flying capacities, etc., and also more recently (4) UAV aviation laws due to the important rise of the drones. To complement this rapid review, the second section of the present contribution provides a series of example applications of photogrammetry and UAVs before providing some insights about what the author thinks is the future of the research field.

Multiscale integrated systems for hazard monitoring and crisis management in Japan

For natural hazards, risk, disaster and emergency management, Japan is certainly one of the best-prepared countries in the world, with efforts at different levels including the integration of UAV technology in their framework. UAVs are powerful platform to collect data for hazard assessment on their own, but also to bridge gaps between different survey methods and provide extra-layer of information (Fig. 4). In order to provide information to managers and the different authority levels, Japan has the Geospatial Authority of



Japan, which holds GIS data for the country and a stock of aerial imagery, including a section dedicated to hazards and disaster management. As part of their activity, they provide free of charge for non-commercial activity a set of data that includes ground station monitoring (weather or seismicity for instance), traditional aerial photographs of an area, satellite interferometry data, to which they have added in the recent years imagery from a custom long-range 2 m wingspan fix-wing UAV.

Discussion

UAVs have brought a lot of change to the field of natural hazards, disaster risk management, emergency and safety operation. The UAVs can be divided between long-range capabilities - dominated by fix wings -, and short-range "higher-precision" missions at the site level (fleet dominated by quadcopters in the second case). The choice of one type of engine over another can be guided by the following checklist:

- What is the size of the area that needs to be investigated? This will determine the type of UAV to be used.
- What precision, accuracy, type of data is needed? This will control the degree of overlaps between photographs and the altitude of flight, and also the type of camera, in turn influencing the type of UAV needed.
- What are the physical constraints of the landscape? This will control the choice of using an autopilot or a fully manual flight, the type and location of take off and landing.
- What is the location of the survey and the type of weather? Strong winds are usually difficult to handle with quadcopters, and fix-wing aircrafts can handle faster wind speeds.

Once an operator has worked through this generic checklist, it is then possible to look at the details of specific flights, and how different methods can be combined, in order to produce the desired data. Indeed, for disaster management, the combination of the different UAV types with associated photogrammetry and automation can provide rapid, if not immediate data, on a situation, which in turn improves the decision making process, especially with the help of photogrammetric methods that do not need ground control [59]. The actual level of automation of those flights, and the potential for further development makes UAVs a robust tool to help fighting the challenges of climate change and aging economies.

The mobility and ability of different types of UAVs to reach disaster impacted areas is of particular importance, because very often disaster impacted areas experience life-line disruptions, including transport infrastructures (Berariu

et al., 2015). In such case, UAVs can also carry relief aid for instance. Fikar et al. (2016) have shown that UAVs were particularly adequate for 'the last-mile' delivery and that coordinated efforts could improve the delivery of relief through multipoints transport (Fikar et al., 2016). The authors have however emphasized that complex organized systems still need improvement as disaster-impacted areas holds a lot of unknown variables, which are difficult to predict.

Further combination of the dataset presented in this contribution can also increase the capacities of UAV-based solution. Two directions those research can take, is the usage of UAV-based SfM for emergency services on collapsed buildings and the acquisition of 4D imagery using swarms of vehicles.

UAV-based SfM for emergency services working on collapsed buildings

The exponential growth of articles on UAVs and emergency management has put the emphasis on the versatile aspects of UAV for first responders in disasters area. In the case of large earthquakes in city areas, numerous types of building collapses results in a variety of post-collapse 'topography', which can inform the severity or the necessity to act in one part of a city or another (Pham et al., 2014). New development in the automated recognition of direct threats in disaster areas, such as fires for instance now allow automated UAVs to operate in even more complex situations (Cook et al., 2015).

It is expected that future research in structural engineering and the 3D modelling of buildings before and after collapses should provide sufficient data on the location of pockets and gaps, where search and rescue should concentrate their efforts. UAVs should be able to locate eventual gaps by comparing the 3D dataset after collapse with a pre-collapse model of the building as well as the distribution of mass in a building, after which search activity can be concentrated on.

As part of a fully integrated data infrastructure for risk and disaster management, like the one developed in Japan, a first automated layer should provide disaster and emergency responders with the location of the geographical areas where relief is needed (Shaodan et al., 2015), and then on the individual site a second type of UAV work should provide sufficient details on the collapsed structure, in order to increase the chances to find survivors. Consequently, there is a need to integrate UAVs into the disaster management framework, but also to integrate different types of UAVs to operate at different scales and level of precision. Fix-wing platforms are certainly ideal to work at several kilometers scale, and rotor-based platform are certainly most indicated for small sites, where hovering flights might be necessary.

Such work can then be extended to situations where a disaster is unfolding, and for which swarms of UAVs are necessary, in order to capture the data in 4D (3D over time).

Acquisition of 4D imagery using swarms of UAVs for emergency management

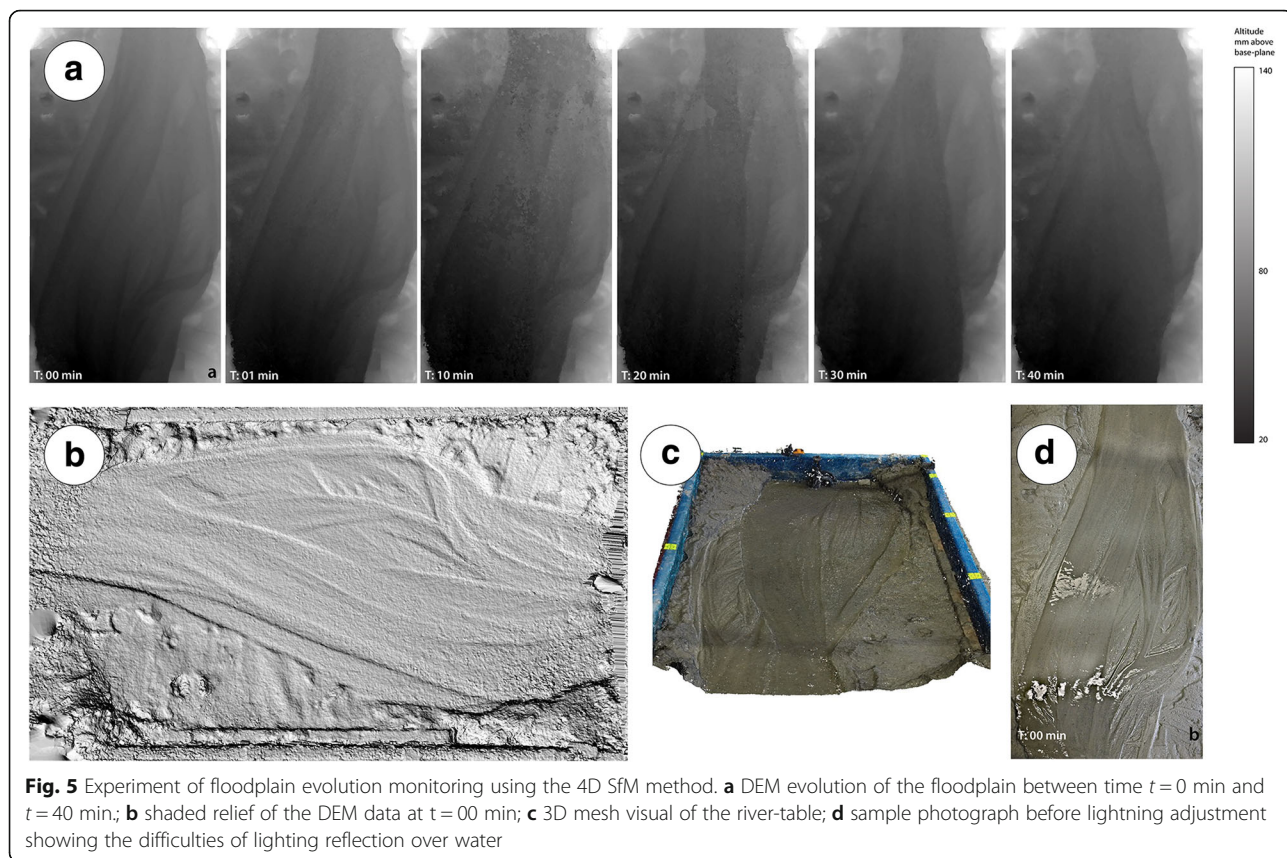
Over the last few years, the development of wireless sensor networks has provided the possibility to track movements and change in space, adding time-stamp to otherwise simple snapshot of the environmental. Combined with UAVs, such technology is allowing collaborations of sensors between UAVs and the ground (Rathbun et al., 2002), as well as the flight of swarms of collaborative UAVs that can be used for emergency management (Bupe et al., 2015). In disaster-impacted areas, clusters of UAVs have proven to be able to replace communication towers that would have been brought down by a disaster (Dalmasso et al., 2012; Merdaway and Guvenc 2015; Tuna et al., 2014) and also provide imagery for any post-disaster activity (Quadritsch et al., 2010). At the convergence between this development and the SfM method that I presented earlier, there is a new forthcoming development: real-time 4D evolution of features or 3D over time. Like traditional SfM can recreate in 3D a disaster zone, either at the building scale (Vetrivel et al. 2015) by taking a series of photographs from one camera, a swarm of vehicle can take a series of photographs from multiple-cameras at the same time. If the cameras are all synchronized, then it is possible to take photographs at a given rate and thus reconstruct the 3D environment over time, in order to see how a disaster environment evolves.

During rescue operations for instance, this would be an invaluable tool to monitor the evolution of a collapsed building for instance. In order to test this idea, the author has conducted a laboratory experiment for which he has used a series of 8 rigged Go-pro cameras triggered by one remote-control. The test was carried out over an evolving riverbed while the water flows using a 200 cm x 80 cm river-table. The experiment has proven that the technique was working (Fig. 5), although the vertical RMSE was 2 cm (for a vertical variability of 10 cm). This high variability is linked to the lack of cameras available for the experiments, and that limit the quality that the SfM algorithm produces.

Nevertheless, results in Fig. 5 clearly shows that a swarm of vehicles equipped with similar cameras have the ability to recreate series of 3Ds over a time period.

Conclusion

Although UAV technology has only hit the commercial-shelves in the last few years, its already relative low-cost and broad availability is expected to further its rapid expansion providing communities and emergency services the chance to add this tool for use in disaster areas – and not being limited to scientific use. In the present contribution, we reviewed the use of UAVs for hazards, disaster risk and emergency management, as well as the use for three of the most important geo-hazards: earthquakes, volcanic activity



and landslides. These three examples have emphasized the connection between survey-scales (time and space) and the scales of phenomena. The use of UAV is constrained by the predictability of events and their duration. Consequently, UAVs have been used in the aftermath of earthquakes for emergency management purposes, because earthquakes are highly unpredictable in time. It has been used in both emergency management and hazards and risks monitoring on volcanoes, because volcanic eruptions are much more predictable and last for periods of time that allow the deployment of one to several flights during its activity period. Finally, landslides are usually slower-onset events (not all though), which have offered the scientists the opportunity to do repeat flights over periods of months to years, from which the evolution of the landslide surfaces can be examined.

The natural next step in combined photogrammetry with UAVs – I think - is the development of swarms of vehicles that can work collaboratively, in order to capture rapid changes in 3D. For instance sea-waves or rockfalls have never been measured in 3D. There are numerous reconstruction based on one or several cameras using algorithms, but real 3D in time (or 4D measures) haven't been performed yet and could be very important to better understand physical processes in geosciences.

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Authors' contribution

CG authored the article and lead the research project the present publication is part of. HP contributed to the field work and the data creation for the present publication. She also helped improve the manuscript. Both authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

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