Response to EC1 again:

Authors: Thank you for consideration of our paper. The respond to your comment is as flowing:

Dear Authors, considering the comments received from the reviewers, I ask you to revise the manuscript according to their comments. Please upload a revised version of the paper, with detailed answers to the reviewers’ comments. Please try to complete the work in three weeks time.

Authors: Now, we have revised our manuscript according to the comments received from the reviewers, at the same time, a point-by-point reply to the comments and a marked-up manuscript version showing the changes had been uploaded.

Besides point-by-point revise according to the comments of reviewers, another main changes include as follows:

1. We changed the title “Method and application of using unmanned aerial vehicle for emergency investigation of single geo-hazard” to “A method for using unmanned aerial vehicles for emergency investigation of single geo-hazards and sample applications of this method”, may be more suitable.

2. We invited native English speaker conversant with photogrammetric terminology, to help us improve the English writing of the revised paper.

3. We checked, modified, and improved all figures and tables.

We would like to express our great appreciation to you and reviewers for comments on our paper. Looking forward to hearing from you.

Response to RC1 again:

Authors: Thank you for your interests about our paper and valuable comments to improve it. The responds to your comments are as flowing:

GENERAL COMMENTS The paper describes a drone specifically design by the authors for emergency investigations. This UAV was been applied in 3 practical cases to demonstrate its efficacy. In my opinion, there are 3 limits in this paper:

1. The paper contains no mentions of Direct Photogrammetry (DF) approach, but in a drone specifically designed for emergencies and rapid mapping, this approach has to be applied. I suggest the use of DP techniques to measure directly in field external orientation parameters and the application of a post processing BBA to refine the external orientation parameters directly measured. Could this UAV be equipped with sensors for DF? In the case of affirmative answer, I suggest to the authors to include some details of this solution (kind of IMU/GNSS sensors, real time or post processing, used software tools,
and so on);

Authors: Thank you for commenting and suggesting about the DF. Actually, although the DF is not mentioned in the paper, this approach is used, especially in the site investigation and the site fast processing. Specifically, when the GNSS signal can be used during the site investigation, the location information will be automatically wrote into the captured photos, to ensure that the use of fast SfM processing method can generate coarse-precision results with a real space coordinate system in the site fast processing step, please see lines 269-282. If there is no GNSS signal, the layout and measurement of GCPs is indispensable to support the SfM photogrammetric processing, i.e., introducing GCPs to ensure generate results with a real space coordinate system, please see lines 243-246, 299-308. According to the suggestion, the details of DP, including IMU/GNSS sensors (lines 270-282), post processing (lines 299-308), used software tools (lines 277-280, 304-306, 407-409) had been added to the revised paper.

2. Paper don’t describe innovative approach to SfM survey using UAV: merely, there are some details of practical suggestions for UAV survey and some reports of applicative examples, actually known in scientific literature. To complete these descriptions, I suggest to complete the practical details including, in Paragraphs 5.1, 5.2 and 5.3, some information on number of acquired image, flight plan, time spent for the acquisition and post processing, number of points of dense point clouds, density of point cloud, obtained accuracy.

Authors: Thank you for the suggestion. These detailed information had been added in the revised paper, please see lines 424-438, 463-480, 497-506.


Authors: Thank you for the suggestion. These references had been carefully read and added to the appropriate location in the revised paper, please see lines 45-57.

Detailed corrections: - Rows 110, 172, 179, 183, 220, 223, 246, 290, 301, 381, 384, 396, 411, 433, 467 Replace GPS with GNSS - Row 320 Replace facade in façade

Authors: Thank you for the corrections. These comments had been reflected in the revised paper.

In addition, three main changes include as follows:

4. We changed the title "Method and application of using unmanned aerial vehicle for emergency investigation of single geo-hazard" to "A method for using unmanned aerial vehicles for emergency investigation of single geo-hazards and sample applications of this method", may be more suitable.
5. We invited native English speaker conversant with photogrammetric terminology, to help us improve the English writing of the revised paper.  
6. We checked, modified, and improved all figures and tables.

We have tried our best to revise our manuscript according to your valuable comments, and hope that the correction will meet with approval.

Response to RC2 again:

Authors: Thank you for your interests about our paper and valuable comments to improve it. The responds to your comments are as flowing:

GENERAL COMMENTS This paper aims to describe a RPAS and processing pipeline specifically developed for the management of small hazard events. Authors discuss both the platform/sensor technology and the main steps followed during the complete UAV mission workflow. Finally, performance evaluation is carried out on three test cases. Although the core concept is interesting and may represent an interesting issue for the scientific community, several main issues should be addressed by the authors.

1. General remark: the English is very poor and this may prevent a full comprehension of the paper. Photogrammetry-related terminology is vague and often incorrect (e.g. “high-definition photos”, “...for the photos, the definition, scope and overlap rate...”, “planar digital terrain”, etc...). A proofreading by a native English speaker conversant with photogrammetric terminology is strongly required.

Authors: Thank you for the comment. After revised the contents of the paper, we had invited a native English speaker conversant with photogrammetric terminology, to help us improve the English writing of the revised paper.

2. The scientific significance and novelty of the paper should be proved. Which are the advantages of the developed platform/sensor/pipeline compared to other commercial or in-house developed systems? The literature review addresses only general concepts and does not show the novelty and advantages of the newly developed system.

Authors: Thank you for the comment about the scientific significance and novelty of the paper. In fact, The main aim of this paper is to conclude and establish a complete method of using UAV for emergency investigation of small hazard events. In the revised paper, we had strengthened the literature review about this aspect, please see lines 45-63, 70-79.

3. The application field is vague. Authors say that the RPAS is developed for emergency investigation of “single” geo-hazards. What do you mean with the term “single”? If it refers to a limited spatial extension of the natural hazard, this should be better clarify and a clear idea of the intended area size should be given.
Authors: Thank you very much for the comment and suggestion. Indeed, the “single” geo-hazard refers to a limited spatial extension of a natural hazard, so we add a better clarify and a clear idea of the intended area size in the revised paper, please see lines 61-63.

4. No accuracy figures are given. Authors generally refer to “meter-level error” or “centimeter- even millimeter- level accuracy”. How did you evaluate accuracy? Did you adopt Control Points to check the accuracy of orientation results? Did you evaluate the accuracy of the final product? Although accuracy is not the main aim of rapid mapping, a metric evaluation of the methodology is necessary to confirm and support the conclusions. Authors: Thank you for the comment about the accuracy. And the accuracy is indeed an important indicator of the availability of results, in our method, the GCPs were used for accuracy assessment, simply, the root-mean-square error (RMSE) of GCPs was used as an important indicator. So, we add the accuracy results in 5. three application examples, please see lines 430-437, 472-477, 502-505.

5. Why is direct geo-referencing not dealt with?
Authors: In fact, the direct geo-referencing is used in our method, especially in the site investigation and the site fast processing. Specifically, when the GNSS signal can be used during the site investigation, the location information will be automatically wrote into the captured photos, to ensure that the use of fast SfM processing method can generate geo-referencing results. If there is no GNSS signal, the GCPs layout and measurement is indispensable to support the SfM photogrammetric processing, i.e., introducing GCPs to ensure generate geo-referencing results. Accordingly, above detailed processing method, such as SfM and so on had been added to the revised paper, please see lines 270-274, 277-282, 300-301, 304-308, 402-409.

6. The experimental part is very poor. No details are given regarding the image dataset (GSD?), the accuracy achieved, the time required. This gives limited support to the conclusion drawn by the authors.
Authors: Thank you for the comment. More practical details including the number of acquired image, time spent for the acquisition and post processing, obtained GSD and accuracy, etc., had been added in the revised paper, please see lines 424-438, 463-480, 497-506.

In addition, We changed the title “Method and application of using unmanned aerial vehicle for emergency investigation of single geo-hazard” to “A method for using unmanned aerial vehicles for emergency investigation of single geo-hazards and sample applications of this method”, may be more suitable. Moreover, We checked, modified, and improved all figures and tables.

We have tried our best to revise our manuscript according to your valuable comments,
and hope that the correction will meet with approval.
Method—A method and application offer using unmanned aerial vehicles for emergency investigation of single geo-hazards and sample applications of this method

Abstract. In recent years, the unmanned aerial vehicles (UAVs) have began to become widely used in the emergency investigations of major natural hazards in over a large areas, but less; however, UAVs are less commonly employed to investigate for the single geo-hazards. Based on a number of successful practices in the Three Gorges Reservoir Area, China, a complete UAV-based method for performing emergency investigation methods of single geo-hazards is concluded described. Firstly, a customized UAV system consisting of a multi-rotor UAV subsystem, an aerial photography subsystem, a ground control subsystem and a ground surveillance subsystem is described in detail. The implementation process, which includes four steps, i.e., indoor preparation, site investigation, site fast processing and application, is then elaborated, and two investigation schemes including automatic and manual, that are used in the site investigation step are put forward. Moreover, some key techniques and methods, e.g., the layout and measurement of ground control points (GCPs), route planning, flight control and image collection process control, are explained. Finally, three applications are given. Experience has shown that, using the UAVs for emergency surveys of single geo-hazards can not only greatly reduce the time, strength-intensity and risks of associated with on-site work, but also provides valuable, high-accuracy, high-definition information to support the emergency treatment responses.

Keywords. single geo-hazard; landslide; emergency investigation; unmanned aerial vehicle (UAV); emergency response

1 Introduction

The aim of the emergency investigation of geo-hazards is to provide basic and essential information, including disaster characteristics, damages and environmental conditions, etc., for use in emergency decision-making and effective treatment response. These investigations are therefore a top priority, and need to emphasize the speed and efficiency of the implementation process, and the accuracy of the results must be further improved (Liu, 2006; Liu et al., 2010; Lu and Xu, 2014). In general, the traditional methods of emergency investigation for geo-hazards are used, i.e., the specialists go around and inspect on the disaster body affected area with cameras and simple measurement tools, then conclude report their conclusions information based on the field investigation and professional knowledge. There is no doubt that these efforts in using the traditional method require more substantial manpower, longer working hours and
greater highly intense work-intensity, and; moreover, they often face difficulties because in the inaccessibility of humans to certain areas parts of the geo-hazards, such as high cliffs or areas covered by lush vegetation covered, are inaccessible to humans. In particular, these on-site investigators have to take the great must contend with the considerable risks of further associated with additional disasters that may occur during the process of the emergency investigation. In addition, the conclusions of these investigations are often inaccurate; because they are most primarily local, qualitative or and speculative-based, e. Even some quantitative results, such as the length, width, or area of a geo-hazard, may have a large deviation deviate strongly from the actual situation. Therefore, relying solely on the traditional ground-based emergency investigation methods would inevitably reduces the efficiency and effectiveness for the geo-hazard emergency decision-making and the treatment responses associated with geo-hazard emergencies.

Remote sensing of features is fast and, macroscopic, covers large areas at high resolution, and it has the irreplaceable considerable advantages in the fields of emergency investigation of major natural hazards (Joyce et al., 2009; Boccardo and Tonolo, 2015). Along with the rapid development of unmanned aerial vehicle (UAV) remote sensing technology, it has been widely used in mapping (Aicardi et al., 2015), environmental investigation (Aicardi et al., 2016) and emergency investigation (Boccardo et al., 2015), especially. Remote sensing from UAVs has been especially widely used in the emergency investigation of geo-hazards emergency investigation for some given its unique advantages, such as low cost, easy manipulation of operation, less minimal risk and efficient image acquisition, etc. (Lewis, 2007; Adams et al., 2014; Li et al., 2014; Fernandez Galarreta et al., 2015). For example, in the USA, the UAVs were used to perform damage inspections after the Hurricane Katrina (Pratt et al., 2006) and Hurricanes Wilma and Ike (Steimle et al., 2009); in Taiwan, a helicopter UAV was used to collect imagery to support post-disaster reconnaissance, disaster restoration and reconstruction assessments after the Typhoon Morakot (Chou et al., 2010); In addition, the UAVs have gradually become the an indispensable means for disaster investigation and assessment after earthquakes, e.g. e.g., the Wenchuan earthquake in 2008 (Zhou et al., 2008), the L’Aquila earthquake in 2009 (Quaritsch et al., 2010), the Haiti earthquake in 2010 (Huber, 2010), the Japan earthquake in 2011 (Ackerman, 2011), and the Lushan earthquake in 2013 (Xu et al., 2014); etc. However, the above applications show that the UAVs are mainly used in the emergency investigations or the loss assessment of associated with major natural hazards, e.g., earthquakes or their secondary geo-hazards, e.g. (landslides and rock collapses) in that cover large area caused by major natural hazards. These UAV systems are usually large, complex and costly, and the acquisition of the final results also requires a very involved professional process with a that requires long large amounts of time. Actually Moreover, in the annual occurrence of the the large number of geo-hazards that occur annually, the “single” disasters with limited spatial extension extents (such disasters usually have an area that extends from a few hundred to several million square meters) and limited volumes (which usually extend from a few thousand to tens of millions of cubic meters) accounted for the vast majority, e.g.
example, in 2015, a total of 8,224 geo-hazards (landslides accounted for the vast majority of which most were landslides) occurred in the mainland area of China, of which. Of these events, 8,180 were medium- (0.1-1.0 million m$^3$) and small- (less than 0.1 million m$^3$) sized, accounting. These events accounted for 99.5% of the total number of events, and the direct economic losses from these events were 200 million USD, accounting which represents for 55.8% of the total direct losses (Mlr P.R. China, 2015). It can be seen, On the one hand, it can be seen that the emergency investigation and treatment of single geo-hazards and the response to such events is very necessary for the prevention and mitigation of disasters prevention and mitigation, o. On the other hand, because of the potentially greater losses and huge amounts, it usually requires more efficient and effective methods are typically required; e.g., only a few days or even hours to be given are usually available to propose the treatment response measures. In this case, more a simple, flexible and small-sized UAV system, as well as a more quickrapid, efficient on-site image acquisition method and UAV-based remote sensing results processing method had to must be used, to ensure that in the shortest possible time to complete the whole airborne-based emergency investigation procedures can be completed in the shortest possible time, thusen providing valuable information for the subsequent works-efforts, such as ground-based investigation or the design of emergency treatmentemergency response-designs. However, there is no complete, systematic and effective method of using UAVs for the investigation of single geo-hazard emergency investigation exists presently exists, and many challenges, e.g., such as the lack of customized UAV systems and, the lack of a-sound on-site implementation process and methods, etc., are hampering the use of UAVs in specific applications.

The main aim of carrying out this study is expected to base on to describe a number of successful practices examples of using UAVs to perform emergency investigation of geo-hazards in the Three Gorges Reservoir AreaReservoir area of, China, in recent years and, to conclude and establish a complete method of using UAVs for emergency investigation of single geo-hazards which include the. This method includes a customized UAV, the implementation process of UAV-based investigation, the key techniques and methods used during the investigation and the processing of the results processing. And, In addition, finally, three applications are given provided to demonstrate the applicability of the proposed method.

2 Customized UAV

Most of the single geo-hazards (which mainly refers to include landslides, rock collapses and debris flows) that need to be require emergency investigatedinvestigation, although they are generally of medium or small size, are often located in mountainous areas with rugged topography, where only a limited range of visible area can be observed from the ground view, and with that experience changeable meteorological conditions, e.g., uncertain wind power-speed and direction. Besides, In addition, they are often located in the traffic arteries or crowded places, such as tourist attractions, where there are usually have many buildings and a variety of public facilities, e.g., telecommunications and power towers and power lines, etc., which may revolve arounds surround or cross through the entire disaster body area affected by a given disaster. Therefore, in order to fully adapt to the
In complex environments in which geo-hazards may be located, the UAVs used for emergency investigations should meet some basic requirements, such as small size, lightweight, quick assembling, easy take-off and landing, no special site requirements, simple, flexible, and convenient control of flight and taking photos; a stable flight control system and a reliable, perfect failure protection function; strong wind resistance and a reliable aerial gimbal system for carrying the camera; a powerful ground control station and a stable image and data transmission system; and a certain endurance that guarantees a flight can cover the entire area affected by the single geo-hazards.

According to the above requirements, combined with the comprehensive considerations of applicability, security, stability, and economy (which mainly refers to the low cost of initial construction and later maintenance of the UAV system), a number of on-site tests and practical applications were carried out for single landslides in the Three Gorges Reservoir Area, China. Finally, a UAV system was customized. A photograph of this system is shown in Fig. 1, and the system architecture and the main function modules are shown in Fig. 2, and the core components and main features of the customized UAV are shown in Table 1.

The customized UAV system consists of four subsystems, including a multi-rotor UAV subsystem, an aerial photography subsystem, a ground control subsystem and a ground surveillance subsystem, details as follows which are described in detail below:

1. A customized four-axis and eight-rotor carbon fiber airframe is used. The outstanding advantages of this design include its high strength, strong power and light weight (the whole aircraft with its camera and the aerial gimbal system is less than 5 kg). And, In addition, compared with the fixed wing aircraft, it has smaller size, better maneuverability and more enhanced fixed-point hovering capability. In particular, special sites for taking off and landing are not required, which is very important for the use of using UAVs to quickly investigate the single geo-hazards which are usually located in complex environments. Although the endurance battery life is poor, i.e., (it provides approximately 20 minutes of flight time), if calculated at an average flight speed of 5 m/s, the resulting flight distance of approximately 5 km guarantees that one flight is sufficient to cover the whole area of the single geo-hazards. Even if multiple flights are required, only the battery needs to be replaced.

2. The flight control system, which directly controls the processes of flight and taking photos, is the "brain" of the UAV system, and its performance and stability directly determine the functioning and the security of the whole system. Nowadays, there are many mature commercial products of flight control systems exist, however, but they are closed-source systems. Thus, in the event of failure, the only thing to do is to return the unit to the factory for repair or re-purchased, resulting in high economic and time...
costs in money and time. Therefore, a widely used open source flight control system, i.e., Pixhawk 2.4.5 (Meier et al., 2012) that with has dual processors, is used, and its The high robustness and powerful data processing capacity of this unit have been recognized. Equipped with a high-performance Global Navigation Satellite System (GNSS) module, data and image transmission modules, etc., the flight control system can totally provide complete support for several necessary functions, such as route planning, flight positioning, real-time data and image transmission, and so on.

(3) The aerial photography subsystem, which is used for to collect overhead or oblique shooting high-resolution images of the geo-hazards, to serve as the core data source of the emergency investigation information. Thanks for to the rapid development of new digital photogrammetric technologies, especially represented by the Structure from Motion (SfM) photogrammetry (Westoby et al., 2012; Li et al., 2013), which is developed based on computer vision algorithms, the requirements of early aerial photography equipment have been greatly reduced. Therefore, only a Sony HX200 digital camera, with 18 mega effective megapixels, and a Vario Sonnar T* 4.8-1444mm F/2.8–5.6 lens, is used to take the photographs. And In addition, in order to keep the camera stability stable to ensure clear shooting the collection of clear images, or accurately adjust the lens orientation according to actual needs, a three-axis brushless aerial gimbal systems is used to carry the camera. The camera shutter and the aerial gimbal systems are entirely all-controlled by the flight control system.

(4) The ground control subsystem, mainly includes the ground control station, which is a notebook computer equipped with the UAV’s ground control software. To match For compatibility with the Pixhawk flight control system, the corresponding open source ground station software, i.e., Mission Planner 1.3.37 (Team, 2016) is used. And In addition, by interacting with the flight control system, the software can achieve some carry out several core functions, including UAV’s the debugging and maintenance of the UAV, parameter setting setting parameters, and route planning, monitoring and control, etc. In a word, by using the ground control station and the flight control system, the whole process of flight and photos shooting image collection can be fully automated. In addition, a remote controller remote control provides manual control of the flight is used to control the flight by manual way in case of emergency.

(5) The ground surveillance subsystem should be established to display real-time flight images and flight state data, which This subsystem provides timely and accurate information for that enables operators to make effectively judgment judgements, decisions, and manipulations, to ensure the flight safety. There is a key on-screen-display (OSD) module, by which the flight state data are are superimposed on the real-time flight images. And In addition, then, all these of this information are transmitted to the ground terminal monitor by using the image transmission system (including the image delivery module on the aircraft, and the image receiving module on the ground terminal monitor).

The customized UAV system (including the Sony HX200 digital camera, but not including the computer which that is equipped with the ground control software) only costs only $-1825, which is equal to the price of
the DJI Phantom 4 pro, a current and very popular consumer-level UAV. But however, the image quality of the Sony HX200 digital camera is clearly better, and more. Moreover, the customized UAV has displays better power performance and wind resistance. In short, our customized UAV system has carried out more than 20 missions of emergency investigation of single geo-hazards in the Three Gorges Reservoir Area. Besides, the satisfactory photographs of every geo-hazard have been obtained, and there has not been a runaway accident, which fully proved demonstrates that the system has a positive applicability, safety and reliability, and is very suitable for the emergency investigation of single geo-hazards, even in the mountainous environments just like that of the Three Gorges Reservoir Area.

3 Implementation process

The implementation process of using a UAV to perform emergency investigations of single geo-hazards can be divided into four steps, i.e., indoor preparation, site investigation, on-site fast processing and application, and indoor comprehensive processing and application. Fig. 3 shows this process in detail and the tasks involved in every step, elaborated as follows which are described below.

3.1 Indoor preparation

Performing the necessary indoor preparation can improve the efficiency of on-site emergency investigation, and mainly includes battery charging, initial inspection of the UAV system, and preliminary route planning.

3.1.1 Battery charging

At present, our system components are used lithium battery-powered. To protect the efficiency and prolong the service life of all lithium batteries, when they are not in use, the voltage of every lithium cell should be maintained at 3.8 v or so (Broussely, 2002), that is, neither fully charged nor fully-empty. Therefore, fully charging of all lithium batteries of used by every component, including the UAV, the camera, the remote controller, the notebook computer equipped with the ground control station, and the terminal monitor, etc., is the primary indoor work task.

3.1.2 Initial inspection of the UAV system initial inspection

The primary purpose of the initial inspection of the UAV system is to avoid the failure of the core components that cannot be restored quickly during the site investigation process. In addition, the task is to detect whether the main components, e.g., the flight control system, propellers, GNSS and compass, data and image transmission module, aerial gimbal systems and camera, ground control station, terminal monitor, and remote controller, etc., are working properly.

3.1.3 Preliminary route planning
In addition, if the location of a geo-hazard can be determined, it is very necessary to carry out the indoor preliminary route planning indoors based on the publicly available satellite maps, e.g., Google Earth, Bing Maps, AutoNavi Maps, etc., in the Mission Planner software package. Typically, the preliminary flight routes are simply designed as a regular grid pattern in plan view that can covers the whole range of area affected by the geo-hazard (Fig. 4). In a word, preliminary route planning can help to save the time of spent on on-site detailed route planning on-site. Of course, if the location cannot be determined in advance, the indoor preliminary route planning has to be ignored, but it does not affect the subsequent on-site investigation by using the UAV.

3.2 On-site investigation

Without a doubt, the on-site investigation is the most important step. We believe that there is an important principle to be followed: that is, the ultimate goal is fast and efficient collection of high quality photographs of the geo-hazard for the subsequent processing and applying, but it must be the premise that this collection must meet safety requirements. That is, if security, i.e., ensuring the safety of all on-site personnel, buildings and public facilities must be ensured from the threat of using UAV, as well as ensuring the own and the safety of the UAV system must be taken into consideration.

3.2.1 Environmental assessment

Before commencing a formal on-site investigation, the environmental assessment is required to determine the UAV-based investigation scheme. Usually, an assessment of the surrounding environment surrounding the geo-hazard and its characteristics, as well as geo-hazard characteristics, and the implementation conditions are needed. The former includes the local topography, local and meteorological conditions, the distribution of aerial and ground facilities distribution, visual range and intervisibility, flight range and other judgments. Assessment of the geo-hazard characteristics includes the topography of disaster body, the area affected by the hazard, its length, width, area, plane shape, and elevation change, and the risk it poses. In addition, assessment of the implementation conditions includes the number of GNSS satellites numbers, the signal strength and stability of the signal, the stability of the electronic compass stability, the layout of ground control points (GCPs), and the location of used for takeoff-off and landing, etc.

3.2.2 Two UAV-based investigation scheme

Based on a number of previous investigations, two investigation schemes including automatic and manual investigation are concluded described as follows.

(1) Automatic scheme
Automatic scheme means that using the automatic scheme, the UAV system is capable of autonomous flight in accordance with the routes established during detailed planning, as well as automatic photo shooting/image collection, by using the UAV’s own GNSS, compass and barometer data. This scheme requires no manual intervention under normal conditions, and is therefore safer and more reliable than the manual methods. At the same time, the acquisition of high quality photographs can be better guaranteed and is more likely in this mode, and which can automatically meet some requirements of the following subsequent photogrammetric processing, e.g., the frontal and side overlap ratios between photographs. In view of this, as long as there are more than five stable GNSS satellite signals in the geo-hazard area, the vast majority of emergency investigations should use the automatic investigation scheme.

And in addition, this scheme is divided into six steps (Fig. 3), which are described below.

- **GCPs Layout and measurement of GCPs**
  To improve the accuracy of the photogrammetric processing results, the setting-establishment and measuring measurement of GCPs in the field is essential (Niethammer et al., 2012; Lucieer et al., 2014; Niu et al., 2014). Usually, three to five GCPs should be set established in or around the geo-hazard (see section 4.1 for details), then the real-time kinematic (RTK) differential Global Positioning System (DGPS) techniques, which have the advantage of including speed, fast, high efficiency and high precision, should be used to measure the 3D coordinates of all GCPs.

- **Assembly of the UAV system**
  A modular design is used in our customized UAV system. The transport of disassembled components can not only saves the space but also are, and the components are also protected from squeezing or crushing during the transport process. Therefore, after arriving at the disaster site, the modules need to be quickly assembled to form the complete UAV system.

- **Full inspection of the system**
  After the system has been assembled, all of the subsystems need to be fully checked in the case of with the power turned on. The main purpose is to eliminate hidden dangers on the ground, then and to ensure flight safety and normal photo shooting/image collection. This step is very important and cannot be ignored.

- **Detailed route planning**
  Automatic investigations must rely on detailed route planning. If the indoor preliminary route planning has been carried out indoors (section 3.1.3), the detailed route planning should be based on this preliminary plan; otherwise, detailed route planning should be carried out at the site. The core of this step is the determination of the route types according to the geo-hazard characteristics of the geo-hazard, as well as the accurate establishment of the waypoint positions and the actions of the UAV, the aerial gimbal system, and the cameras. See section 4.2 for details.
**Parameters setting**

Parameter setting is the last and not negligible step before flight, and it cannot be neglected. Several important control parameters must be set according to the actual scene. Typically, the recommended flight rate is 5 to 20 metres per second, and the camera shooting rate should not be less than 1 picture per second. It is important to remember to import all of the parameters into the flight control system on board the UAV from the ground control station, and then these parameters can take effect.

**Autonomous flight and automatic photo collection**

A relatively flat and open place should be selected as the takeoff and landing site. After taking off, the UAV should follow the planned route for autonomous flight and automatic photo collection under normal circumstances. During the flight, the status of the UAV and camera should be closely monitored (see section 4.3 for details). In the event of an abnormal state, the UAV should be switched to the manual mode for emergency treatment to permit emergency response. After the flight is completed, the UAV system and the quality of the photos should be checked immediately.

(2) Manual scheme

Manual scheme means that the entire UAV flight and the process of photo collection have to be manually controlled by using the remote controller. This scheme requires no route planning, which can save time of in situ investigation, but it requires a superb driving skill and excellent piloting skills, and flight safety and photo image quality are susceptible. Accordingly, the flight process should be monitored intensively. Therefore, the use of the manual scheme should try to avoid, unless, although, in some places, such as mountainous areas or canyons, etc., where the GNSS signals are unstable or even absent, or the scope of the geo-hazard is extremely limited, the manual scheme may be more suitable. In addition, this scheme is divided into 4 steps (Fig. 3), which are briefly described below.

- **Layout and measurement of GCPs**
  If there is no GNSS signal, the captured photographs do not have to be associated with GPS GNSS data locations. In this case, the layout and measurement of GCPs is indispensable to support the photogrammetric processing. The setting of GCPs is the same as in the automatic scheme (see section 4.1 for details). However, the use of a total station measurement is the recommended technique to measure the GCPs under the situation of nowhere GNSS signals are absent.

- **Assembly of the UAV system**
  This step is the same as in the automatic scheme.

- **Full inspection of the UAV system**
  This step is the same as in the automatic scheme.
This step is the same as in the automatic scheme.

- **Manual flight and photo shooting/image collection**

Compared with the automatic scheme, the system status and the quality of the photographs should be paid more attention to monitored more carefully during the flight process (see section 4.3 for details), as well as—the quality of the photo shooting. In addition, it is more important to check the system and the photographs after the flight, especially for In particular—the photos, the quality, scope and overlap rate of the photographs must are most need to be evaluated.

### 3.3 On-site fast processing and applying/reprocessing and application

After on-site UAV-based investigation is completed, the low-resolution photographs with low resolution can be subjected to fast photogrammetric processing by using a portable computer on the spot in the field. In general, in only ten to several tens of minutes, some rough results with about approximately meter-level accuracy can be generated, e.g., including the digital surface models (DSMs), the digital orthophotos, and three-dimensional models, etc., this also means, fast processing focuses on the speed with which the results generating speed are generated, not their precision. Although the accuracy is relatively poor, these emergency investigation results that can be obtained quickly in the field still provide important support for the rapid on-site development of the preliminary emergency response plans for the geo-hazards, and which. This high speed is the most prominent advantage of the UAV-based method for emergency investigation of single geo-hazards, compared to the traditional methods. This processing is divided into 4 steps (Fig. 3).

- **Photos pretreatment/preprocessing of photographs**

Photos pretreatment includes selecting photo albums that covers the appropriate range of the geo-hazard, removing poor-quality photographs with bad quality, e.g., blurred images), etc., and checking the GNSS information associated with the photographs. In general, the photographs that taken using the manual scheme require more time for pretreatment than those collected by using the automatic scheme.

- **Fast SfM processing and generation of coarse-precision results generating**

Compared with traditional digital photogrammetry method, the SfM photogrammetric method is recommended to be used in the processing of UAV-based photographs, because it is simpler and more efficient (Snavely, 2008; Westoby et al., 2012; James et al., 2016), e.g., the camera position can be automatically calculated only by using the GNSS data associated with each photograph, so-and information on the attitude of the aircraft, such as its roll, pitch, and yaw, etc., obtained from the inertial measurement unit (IMU) were no longer needed (Huang et al., 2017). The fast SfM photogrammetric processing consists of reducing the resolution of the original
photosphotographs, resolution, making performing the aerial triangulation and bundle adjustment, and generating the three-dimensional point clouds. Then, using the dense point cloud, the coarse-precision results of the geo-hazard, including the DSM, the digital orthophoto and the three-dimensional model, etc., can be further-generated. The Pix4Dmapper software package (Strecha et al., 2012; Mesas-Carrascosa et al., 2015) was used to process the photographs by SfM photogrammetric methods. For fast processing, the lower image scale is set, first, and only then is the GNSS data associated with each photograph used during the aerial triangulation and bundle adjustment, i.e., the coordinates of the GCPs were not introduced during this stage to improve the absolute spatial position accuracy. Because the M8N GPS module with a nominal positioning accuracy of 2.5 m was used in our aircraft, the fast SfM processing results were generally displayed coarse-precision with a meter-level error.

**Coarse quantification and display of the geo-hazard**

Based on the coarse-precision results for the geo-hazard, by using geographic information system (GIS) or remote sensing (RS) software, the basic characteristics of the geo-hazard can be quantified, e.g., These characteristics include, length, width, area, and elevation change, etc. In addition, the three-dimensional scene of the geo-hazard and its surroundings can be vividly displayed.

**Supporting the development of the preliminary emergency response plan**

The quantitative characteristics and the intuitive three-dimensional scene of the geo-hazard provide the basis and macro-level information for the rapid on-site development of the preliminary emergency response plan. As to the results, the meter-level error of the results, basically essentially does not affect the feasibility appropriateness of such the qualitative-based plans.

### 3.4 Indoor comprehensive processing and applying the results

The design of the detailed emergency response plans is an important basis for step in the implementation of disaster prevention and mitigation efforts, so the basic data such as terrain representations and orthophotos that are obtained in the design must be accurate and clear. The purpose of comprehensive processing is to obtain such high quality results data. So, the original photographs would be reprocessed by high-performance desktop computers or graphic workstations indoors. The comprehensive processing generally takes one to several hours, but all of the results have centimeter-level accuracy because the GCPs are introduced. This also means, comprehensive processing focus on the precision of the results, not the speed with which they are generated. It is divided into 3 steps (Fig. 3).

**Comprehensive SfM processing and generation of high-precision results generating**
The comprehensive SfM processing workflow is the same as that used in the fast processing. The differences include that the original photographs with high resolution are used, and the GCPs are introduced before generating the point clouds. Accordingly, the products of the comprehensive SfM processing are the same as those of the fast processing, i.e., the DSMs, the digital orthophotos, and the three-dimensional model, etc. are produced, but these products are high-precision and high-definition. Likewise, Pix4Dmapper software was used for the comprehensive SfM processing. Firstly, the full-scale photographs with GNSS data were used, and then, during the process of aerial triangulation and bundle adjustment process, the GCPs were introduced to improve the absolute spatial position accuracy. Because the 3D coordinates of the GCPs were measured by using the RTK-DGPS technique with a nominal positioning accuracy of 2 cm, the comprehensive SfM processing results were generally high-precision with a centimetre-level error.

- **Accurate quantification and display of geo-hazards**
  Using the high-precision and high-definition results for the geo-hazard, the basic characteristics of the geo-hazard can be accurately quantified. Accordingly, the three-dimensional scene of the geo-hazard and its surroundings can be more accurately and vividly displayed.

- **Supporting the design of emergency response plans**
  Based on the accurate quantitative characteristics, with the high-precision and high-definition DSM, orthophoto, and three-dimensional scene of the geo-hazard, a large-scale topographic map and plan can be produced, and accurate design data can be obtained from the high-precision and high-definition DSM, orthophoto, and three-dimensional scene of the geo-hazard. This information provides important support for the design of emergency response plans.

### 4 Key techniques and methods

#### 4.1 GCPs layout and measurement

Due to the limited precision of the GNSS units carried by UAVs (e.g., the M8N GPS module onboard used in our aircraft has a nominal positioning accuracy of 2.5 m), it is necessary to set and measure GCPs in the field at the same time with the UAV flight and image collection to improve the accuracy of the photogrammetric processing results. In addition, the GCP layout and measurement of the GCPs should be implemented quickly and efficiently, but the results should be high-precision.

Firstly, in the flight range area covered by the flight, some obvious ground feature points, e.g., house corners, road intersections, exposed bedrock, etc., can be directly used as GCPs, as long as they can be clearly identified both on the ground and on photographs. Otherwise, several GCP markers that
can also be identified in photographs need to be placed on the ground. Usually, for the single geo-hazards, only three to five GCPs need to be established in or around the geo-hazard, and the distribution should be as uniform as possible, e.g., networks made up of constituting the equilateral triangles or quadrilateral networks are appropriate. It is worth noting that, the layout of the GCPs should be completed before the UAV flight and photo shooting image collection, to ensure that the photographs contain all of the GCPs.

As for the GCPs measurement, regarding the measurement of the GCPs, the RTK-DGPS techniques with which has advantages in that it is advantage of fast, and has high efficiency and high precision, should be used preferentially as long as there are stable GNSS signals, regardless of whether in the automatic or manual scheme is used, to measure the 3D coordinates of all of the GCPs. On the other hand, while in mountainous areas, canyons, etc., with unstable or even no GNSS signals, the total station measurement techniques would be a good choice, and sometimes the non-prism total station measurement techniques may be the only option (Huang et al., 2017). Moreover, then, the measurement can be carried out at any time during the on-site investigation process, but if it is performed at the same time as the collection of photo shooting images by the UAV, the GCPs markers should not be covered.

4.2 Route planning

According to the characteristics of the single geo-hazards, proper route type selection and accurate motion design are key to ensuring the safety and efficiency of UAV-based emergency investigation. Based on a number of practice examples, three typical route types are summarized as follows (Fig. 5).

1. Planar grid pattern for slightly inclined slopes (Fig. 5a). This pattern is suitable for geo-hazards that cover large areas (typically, e.g., several million square meters area) geo-hazard on the gentle slopes (the slope is typically less than 40°), such as gently-inclined landslide bodies. The primary purpose of the emergency investigation for this kind of disaster is to obtain a digital terrain model and an orthophoto. Therefore, the planning route consists of a regular planar grid which can cover the whole planar area of the geo-hazard. And, in addition, the camera lens always points vertically down to the ground (i.e., the lens orientation is held at 0°). It is worth noting that the flying height of the route should be dynamically adjusted to meet the elevation changes of the disaster and slope i. In principle, it is advisable to keep the flying height of the UAV at a constant distance (i.e., the h in Fig. 5a) from the ground, and practice shows that h in 50 m ~ 100 m is proper. Because lower flights require more routes and increased flight time, and the flight safety will decreases; conversely, higher flights will reduce the resolution of photographs and the processing results.

2. Vertical grid pattern for steep slopes (Fig. 5b): This pattern is suitable for geo-hazards whichs that...
are developed on the steep slopes (the slope is typically more greater than 60 °), such as dangerous rock masses on the cliffs. The emergency investigation for this kind of disaster should aim at obtaining the facade orthophotos and 3D models rather than digital terrain and vertically downwards orthophotos. In this case, the planning route consists of a regular vertical grid which can cover the whole facade area of the geo-hazard. In addition, the camera lens always points horizontally to the disaster body (i.e., lens orientation keeps is held at 90 °). The plane positions of all of the horizontal routes can overlap, but they are at different altitudes. In addition, it is advisable to keep the UAV flying at a constant distance (i.e., the \( d \) in Fig. 5a) from the disaster body area affected by the disaster (practice shows that, a \( \text{a} d \) of 40 m ~ 80 m is proper).

(3) Combined grid pattern for transitional terrain (Fig. 5c): This pattern is suitable for the geo-hazard whichs that are located on the transitional terrain, i.e., including both gentle and steep slopes, such as the combination of a dangerous rock mass on the cliff and the corresponding collapse accumulation mass on the gentle slope. The main purposes of emergency investigation for this kind of disaster is not only to get the a digital terrain model and an orthophoto, but also, as well as to get the facade orthophoto and a 3D model. Therefore, the combined grid pattern of planning route should be adopted for the planned route. That is, i.e., using a regular planar grid is used to cover the areas with gentle slopes, and a vertical grid is used to cover the areas with steep slopes. Accordingly, the camera lens points vertically down to the ground at the within the part with the planar grid (i.e., the lens orientation keeps remains at 0 °), and gradually lifts rises from the low route position to the high route position in the part with the vertical grid (i.e., the lens orientation changes from 0 ° to 90 °). The flying height \( h \) and flying distance \( d \) in Fig. 5c can be set as in the planar and vertical grid patterns, respectively.

In particular applications, the planning route should be selected, combined or flexible changed from the three typical route types listed above; alternatively, these routes can be changed flexibly or combined, based on the spatial distribution characteristics of the specific geo-hazard being investigated. However, in any case, the planning route must meet the requirements that the obtained pictures’ frontal overlap ratios must bear at least 75%, and the side overlap ratios must bear at least 60%. Otherwise, it will seriously affect the scope and accuracy of the post-processing results will be seriously affected.

In addition, the detailed route planning in the field should also account for the following points:

① Whether a preliminary route planning has been carried out or not, it is necessary to accurately calibrate the flight route and range based on the actual location of the UAV’s own GNSS data.

② The route coverage should be larger than the actual area affected by distribution scope of the geo-hazard, to ensure that the photos of the disaster have enough overlap rates overlap sufficiently.
③ The starting point and route should be set near the foot of the disaster body, and the ending point should be set near the top, so as to keep the flying of. Thus, the altitude of the UAV will progress from low to high altitude during the emergency investigation (Fig. 5), because the UAV will be more stable during the upward flight, which is more conducive to taking clear photographs.

④ After carefully checking, the planned route must be imported into the flight control system of the UAV to take effect.

4.3 Flight and shooting process control

It is essential to carry out the pre-flight inspection after importing the accurate planned route data and setting the flight parameters. This inspection mainly includes assessments of the battery capacity, GNSS signal, propeller, aerial gimbal system, camera, data and image transmission modules, remote controller and the ground control station, etc. Then, using the UAV can then be used to take photographs for the emergency investigation of single geo-hazards.

During the flights, it is best to have three technical staff involved in the implementation to ensure the flight safety and photo quality. The primary operator, in the automatic scheme, is responsible for monitoring the flight and shooting state through the ground control station during the normal autonomous process, or switching to manually operated manual operation of the flight and photo shooting in the event of an abnormal state. When the manual scheme is in use, the primary operator is always responsible for manually performing the taking off, flight and landing of the UAV using the remote controller. The primary supervisor, is always responsible for monitoring the real-time flight images and changes to the important parameters (e.g., the height, the speed, the battery capacity, and the GNSS signal, etc.) through the ground terminal monitor. The primary supervisor immediately notifies the flying states to the primary operator of changes in the UAV’s flying state, regardless of whether in the automatic or manual scheme is in use. Meanwhile, the deputy operator and monitoring personnel, in the two schemes, is responsible for real-time tracking of the posture changes of the UAV and observing the surroundings through the forward route ahead of the UAV through the spotting scope, so as to detect the aircraft anomalies or flight obstacles as early as possible, and promptly notifies the primary operator for emergency treatment.

4.4 SfM photogrammetric processing

At present, the traditional digital photogrammetry and the newly developed SfM photogrammetric method,
which is based on computer vision algorithms, can both be used for the processing of UAV images, but the latter is more simple and more efficient. Because in contrast to traditional photogrammetry methods, which require not only a single stereo pair, but also of images in addition to the 3D locations and pose-orientations of the cameras, or the 3D locations of a series of GCPs, to be known, in contrast, the SfM technique only requires only multiple, overlapping photographs as input (Westoby et al., 2012). The principles and workflow of SfM can be understood from have been described by Snavely (2008), Snavely et al. (2008), and Westoby et al. (2012). The Pix4Dmapper software package was used for the SfM photogrammetric processing, which can convert a large number of images into georeferenced 2D DSMs, digital orthophotos and 3D models (Huang et al., 2017).

When the SfM photogrammetric processing method is used to process the photographs captured by the UAVs during the emergency investigation of the single geo-hazards, it is divided into on-site fast processing and indoor comprehensive processing (Fig. 3). In addition, the results of the SfM photogrammetric processing should also be targeted for the different types or characteristics of the geo-hazard; the results of SfM photogrammetric processing should also be targeted, e.g., for the type of disaster event shown in Fig. 5a, the main results should be the digital terrain model and an orthophoto; for the type of event shown in Fig. 5b, the core results can be the facade orthophoto and a 3D model; for the type of event shown in Fig. 3c, the results should include not only the digital terrain and orthophoto, but also, as well as the facade orthophoto and a 3D model.

5 Application examples

5.1 Emergency investigation of a slightly inclined landslide

At the beginning of September 2014, under the influence of continuous heavy rainfall, a whole mass movement occurred in the Three Gorges Reservoir Area, which threatened the safety of surrounding houses, the highway traffic and the villagers’ life and property of the local residents (Fig. 6a). Environmental assessment showed that, the landslide had a gentle slope and small size, but with a large potential threat range it threatened a large area. In addition, the environment was rather open and the GNSS signal was stable. Therefore, the automatic investigation scheme was adopted.

Firstly, the route planning was performed according to the pattern of Fig. 5a based on the position of the disaster mass movement and its influence area. At the same time, 4 GCPs were selected around the landslide (Fig. 6a), and RTK-DGPS was used for the measurement of the 3D coordinates of these GCPs. The establishment and measurement of the GCPs layout took approximately 50 minutes. Then, by autonomous flight and automatic photo shooting.
collection, 66 photographs were captured, together with route planning and UAV preparation, the entire working time by using the UAV only took about 30 minutes. Finally, by using SfM photogrammetric processing, an orthophoto with a ground sampling distance (GSD) of 4.25 cm (Fig. 6a), and a 3D texture model (Fig. 6b) were generated. For simplicity, the 4 GCPs were used as checkpoints for accuracy assessment, and the root-mean square error (RMSE) values were calculated. The results showed that, the fast SfM processing required only 28 minutes, but the spatial errors were 3.118 m ($X_{error} = 2.327$ m, $Y_{error} = 2.862$ m, $Z_{error} = 4.165$ m). On the contrary, the comprehensive processing took 65 minutes, while the spatial errors were reduced to 0.038 m ($X_{error} = 0.031$ m, $Y_{error} = 0.038$ m, $Z_{error} = 0.045$ m), because the GCPs were introduced during the SfM photogrammetric processing. In short, all of the on-site work, including the UAV-based investigation, the GCPs layout and measurement of the GCPs, and the fast photogrammetric processing, spent a total of 78 minutes. And, then, an orthophoto and a 3D texture model with an error of approximately 3 m could be generated on-site, which. These products could give the basis and macro-level information about the landslide and its surroundings.

Based on the results of the above emergency investigation, combined with ground investigations, the characteristics and effects of the landslide were quickly interpreted (Fig. 6c) and evaluated. These products revealed the conclusion that obvious head- and two side- scarps formed. Moreover, the drainage ditch that was located within the landslide was completely destroyed, and the collapse of the front loose soil mass blocked the gully, forming a free face, and leading to the emergence of a large number of tension cracks. All of these indications suggested that the landslide had an obvious and whole sliding represented an obvious mass movement, and the landslide had been in an unstable state. In addition, the landslide was a direct threat to the houses which were located outside adjacent to the right boundary of the landslide. Moreover, as the loose soil mass continuously accumulated in the gully, a debris flow disaster would be easily triggered by heavy rainfall, then seriously threatened the house and highway. Based on the above conclusions above, the following emergency treatment measures were put forward, including using professional monitoring techniques including such as GNSS, extensometers, rain gauges, and ground-based inspection to continuously track the process of deformation and induction of the landslide; building a citizen science-based monitoring and prevention system operated by mass people, which means to encourage the surrounding masses to observe the deformation signs of watch for signs of deformation within the landslide body, e.g., cracks, soil collapses, and houses cracks in houses, etc., especially in the event of heavy or continuous rainfall; and developing an emergency evacuation program to ensure the orderly avoidance and reduction of losses before the
This application shows that the results of UAV-based emergency investigation can provide a more large-scale perspective for the comprehensive evaluation of single geo-hazard characteristics and their potential impacts, which can make up for the defect of the ground-based investigations, which focus more on partial parts of geo-hazards but ignores the whole.

5.2 Emergency investigation of a dangerous rock mass on a steep cliff

In September 2015, a dangerous rock mass was found noted above a provincial highway on the left bank of the Yangtze River in the Three Gorges area, which was a serious threat to the safety of the highway traffic and the shipping along the Yangtze River. Only one side of the dangerous rock mass was attached to a vertical steep cliff, and it was located at least 100 m away from the lower highway, which led to the inaccessible of human beings. Therefore, the use of UAVs for emergency investigation would be the priority. Thanks to a stable GNSS signal existed at the study site, the automatic investigation scheme was adopted.

Firstly, the route planning was performed according to the pattern shown in Fig. 5b. At the same time, 3 GCPs were established along the highway and measured with the RTK-DGPS technique (Fig. 7c). In addition, it should be noted that, because the three GCPs were nearly in a straight line, for the limited environment, which couldn’t meet the processing requirements, another GCP was established, which located on the top of a hill behind the cliff, and its coordinates were measured according to the pre-existing topographic map. The camera lens direction was set at 45° to the steep cliff. Through autonomous flight and automatic photo shooting, 104 photos were captured, together with route planning and UAV preparation, the entire working time took 35 minutes. Finally, in order to obtain high-precision results for the design of the detailed emergency response plan, the comprehensive SfM processing was used directly, which took about 100 minutes, and the DSM and a 3D texture model were generated. Similarly, the 4 GCPs were used as checkpoints for accuracy assessment. Results: The results showed that, the spatial errors were 0.237 m ($X_{error} = 0.218$ m, $Y_{error} = 0.183$ m, and $Z_{error} = 0.310$ m), i.e., the accuracy was sub-meter-level, the main reason was primarily because the GCP on the
top of a hill could not be accurately measured. Even so, the sub-meter level accuracy had been able to meet the requirements of quantifying the size and generating large-scale topographic maps of the dangerous rock mass for use in its design of emergency control design measures, and would not have a substantial impact on the conclusions. Moreover, all of the investigation investigative work, including extending from the on-site UAV-based investigation to the generation of high-precision results, just took required only about 2 hours and 15 minutes, which was impossible for. Such a short time period could not be achieved through manual ground-based investigation, especially for an isolated dangerous rock mass on a cliff.

In view of the DSM and the 3D model, the results showed: the dangerous rock mass was 24 m high, 12 m wide, and 12 m thick and had a volume of 3456 m³. The lower and upper part of the rock mass had fallen, so it had lost completely unsupported. The left and right boundary cracks had been completely connected. All of these signs indicated that the dangerous rock mass was in an unstable state. Therefore, the relevant emergency investigation results described above had been submitted to the technical department for support the design of a detailed emergency response plan.

In this case, the UAV worked as the only reasonable means of performing an emergency investigation for this dangerous rock mass on a steep cliff, and the DSM and the 3D texture model provided both the whole and partial information which could well support the design of the emergency response plan.

5.3 Emergency investigation of a combined slope with transitional terrain

In January 2016, some rock falls occurred on an artificial high and steep artificial slope that had been controlled in the Three Gorges Reservoir Area, which presented a serious threat to the safety of the traffic on a lower provincial highway and the shipping on the Yangtze River below (Fig. 8a). The slope was located on the left bank of a tributary estuary of the Yangtze River, and three sides of it were surrounded by the rivers. Geomorphologically, the slope above the highway consisted of five steep cliffs (Fig. 8b), and the part portion of the slope below the highway has a gentle slope but is surrounded by the rivers. It could been seen that it was almost impossible to implement the ground-based investigation to find all of the potential geo-hazards, so the UAV was used and the automatic investigation scheme was adopted.

Firstly, the route planning was performed according to the pattern shown in Fig. 5c. At the same time, four GCPs were arranged along the winding highway and measured with the RTK-DGPS technique (Fig. 8a). The GCPs layout and measurement of the GCPs took approximately 4 hours and 15 minutes, which was impossible for. Such a short time period could not be achieved through manual ground-based investigation, especially for an isolated dangerous rock mass on a cliff.
40 minutes. Then, by Using autonomous flight and automatic photo shooting, image collection, 75 photographs were captured. Together with route planning and UAV preparation, the entire working time took only about 50 minutes. Finally, by using SfM photogrammetric processing, an orthophoto, a DSM and a 3D texture model with GSD of 5.02 cm were generated. The 4 GCPs were used as checkpoints for accuracy assessment. Results. The results showed that, the fast SfM processing took 40 minutes, the spatial errors were 3.686 m (X_{error} = 3.173 m, Y_{error} = 3.401 m, Z_{error} = 4.485 m). On the contrary, the comprehensive processing took 95 minutes, while the spatial errors were reduced to 0.061 m (X_{error} = 0.053 m, Y_{error} = 0.060 m, Z_{error} = 0.069 m) by introducing the GCPs. In short, all of the on-site work spent required a total of 90 minutes.

Based on all of the results, mainly the high-resolution 3D texture model, three potential geo-hazards were identified on this whole slope (Fig. 8): Above the highway, within the 4th section of the cliff and the left part of the 5th section of the cliffs, several isolated dangerous rock masses had formed because of the continuous development of the tension cracks. In the upper part of the 2nd section of the cliff and the left part of the 3rd section of the cliffs, a large number of broken rock masses that were easily dropped could fall easily for the had developed due to the continuous development of two sets of tension cracks. Below the highway, there was a tension crack existed on the right side of the slope. In addition, the detailed characteristics of every section of the cliffs could be accurately measured (Fig. 8b). The relevant results from the emergency investigation were submitted to the relevant departments for risk assessment and the design of control measures.

In this case, the flexibility and wide applicability of the UAV had been proved, which UAV-based methods could provide not only the high-definition visual 3D scenes and models, but also, as well as the accurate quantitative basic terrain data, to well supporting thus providing strong support in the evaluation or the design of single geo-hazards or the design of relevant control measures.

According to the application examples described above, it could be seen that, the on-site UAV-based investigations could be completed within 1 hour. If needed, coarse-precision results with meter-level error could also be generated on-site by using fast SfM processing, usually within 1 hour. That is to say, by using UAV-based emergency investigation methods and SfM photogrammetric processing technology, the macro-scale and three-dimensional information of a single geo-hazard could be obtained within 2 hours, which support the rapid on-site development of the emergency treatment plans, and it was. This rapidity is the most prominent advantage of this UAV-based method in comparison with, compared to the traditional methods. Moreover, by introducing the GCPs into the comprehensive SfM processing, the high-precision results with centimeter-level error could also be obtained, which...
support the design of the detailed emergency treatment plans, and the processing time required was typically several hours.

6 Conclusions

This paper comprehensively describes the method of using UAVs for emergency investigation of single geo-hazards. The main conclusions are summarized as follows:

1. According to the requirements of emergency investigation, combined with the comprehensive consideration of applicability, security, stability and economy, the UAV system is customized, and its core functions and modules include: a four-axis and eight-rotor carbon fiber airframe; a set of stable and reliable, open source and matched flight control hardware system that is compatible with the ground control station software, which can well-provides comprehensive support for route planning, autonomous flight and automatic photo shooting; an ordinary digital camera with a relatively high number of pixels or a single-lens reflex (SLR) camera, which is satisfactory for the shooting; a three-axis brushless aerial gimbal system is used to ensure the clear shooting of clear images and the flexible adjustment of the camera lens direction; and a ground surveillance subsystem, which is used to monitor the flight of the UAV system and the collection of images.

2. The implementation process of using the UAV to perform emergency investigations of single geo-hazards can be divided into four steps, i.e., indoor preparation, site investigation, on-site processing, and indoor comprehensive processing and application. It must be noted that during the on-site investigation, the automatic or manual scheme should be determined according to the environmental assessment. In addition, as long as there are more than five stable GNSS satellite signals in the geo-hazard area, the vast majority of emergency investigations should use the automatic scheme. The GCPs layout and measurement is also a vital work for the purpose of improving the accuracy of the photogrammetric processing results. The aim of fast processing is to support the rapid on-site development of the preliminary emergency treatment plans, and whereas the indoor comprehensive processing, which is performed indoors, is intended to support the design of the detailed emergency treatment plans. The SfM photogrammetric method is recommended to use for regardless of whether the fast processing or the comprehensive processing is employed.

3. Mastering the key techniques and methods contribute to a better use of UAVs for emergency investigation of single geo-hazards. The following points are worth noting: Before the on-site flight and shooting, three to five GCPs should be established in or around the geo-hazard, and their
distribution should be as uniform as possible, e.g., i.e., constituting the they should constitute equilateral triangles or a quadrilateral network. The RTK-DGPS techniques should be used preferentially as long as there are stable GNSS signals, and the, whereas total station measurement techniques would be a good choice in the area with unstable or even no GNSS signals. Proper route planning is key to ensuring the safety and efficiency of UAV-based emergency investigations. Three typical route types are recommended. The planar grid pattern is suitable for the large-area geo-hazards that cover large areas on the gentle slopes, the vertical grid pattern is suitable for the geo-hazards that are developed on the steep slopes, and the combined grid pattern is suitable for the geo-hazard which occurs on the transitional terrain, i.e., which includes both gentle and steep slopes. In particular applications, the planning route should be selected, combined or flexibly changed from the above three typical route types, based on the spatial characteristics of specific individual geo-hazards. But in any case, the planning route must meet the requirements that the obtained pictures’ frontal overlap ratios are at least 75%, and the side overlap ratios are at least 60%.

It is essential to carry out a pre-flight inspection after importing the accurate planning data and setting the flight parameters. Moreover, during the flights, it is best to have three technical staff members involved in the implementation on hand to ensure the flight safety and photo image quality. When the SfM photogrammetric processing method is used, the results should also be targeted according to the different types or characteristics of the different geo-hazards.

A number of successful practices described in this paper demonstrate that using UAVs for emergency investigation of single geo-hazards can not only greatly reduce the time, strength and risks associated with the on-site work, but also provide valuable, high-accuracy and high-definition information that supports the development of emergency treatment responses.

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