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UAV-UGV imagery for disaster scenario mapping: aerial-terrestrial data fusion and comparison

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ABSTRACT

This paper introduces a mobile robotic system equipped with RBG (Red, Green, Blue) and IRT (InfraRed Thermography) sensors, designed in a joint industrial research project, which aims to develop low-cost technologies for the survey of dangerous scenarios in remote mode. The methodology adopted for mapping a landslide scenario, based on aerial and terrestrial unmanned systems, is presented. The UAV (Unmanned Aerial Vehicle) has been employed to map the damaged buildings and the landslide slope, by planning ten survey missions; the UGV (Unmanned Ground Vehicle) has been employed as a complementary mobile photogrammetry technique to obtain high-resolution ground data, by planning three missions, each consisting of two passes along the same paths simulating a two-camera setting. UAV and UGV-derived datasets have been processed using the Structure-from-Motion technique in order to obtain photogrammetry products such as ortho-photomosaics, digital terrain models, point clouds and 3D models of the building. Aerial and terrestrial models have been integrated, using GCPs (ground control points) coordinates and natural/artificial control points, and have been exploited for the spatial analysis.

An accuracy assessment has been carried out in CloudCompare using the Cloud-to-Cloud function and local modelling: the aerial and terrestrial models of buildings facades have been independently compared with a reference model, obtained from a stationary photogrammetry survey. The results highlight the higher reliability of the terrestrial model for accurate surfaces reconstruction, proving the potential of terrestrial mobile photogrammetry as an effective low-cost mapping solution for hazardous environments. Moreover, UGV mission settings, datasets characteristics and potential improvements are discussed in order to portray the benefits and limitations of this approach.

KEY WORDS: UAV, UGV, photogrammetry, disaster response, emergency mapping.

INTRODUCTION

In the last decade, the use of UAVs has known a great diffusion, making these platforms an everyday tool for several scientific and commercial applications. Their limited cost, in addition to the higher resolution of the collected data, represents the main advantage of this technology if compared to traditional methods; their flexibility allows to adopt different solutions depending on the operative conditions, the extension of the area and the typology of application (Nex & Remondino, 2019). Today there is a high number of platforms available on sale, ranging from very low-cost platforms to expensive ones, integrating different kind of sensors. This flexibility makes UAVs useful for regular scenarios as well as attractive for emergency surveillance (Boccardo et al., 2015). Many UAV-assisted disaster management applications have been tested in each stage of the disaster management, i.e., the pre-disaster preparedness, disaster assessment, response and recovery (Erdelj & Natalizio 2016); mission planning strategies for emergencies and rapid mapping have also been developed (Glock & Meyer 2020).

Over the years UGVs (Unmanned Ground Vehicles), also known as UTVs (Unmanned Terrestrial Vehicles) or USVs (Unmanned Surface Vehicles) have been developed and used in many fields for several different applications, ranging from the automation of farm tasks and the precision agriculture field (Bechtis et al., 2017) to mine inspection (Szrek et al., 2020). Moreover, mobile terrestrial systems are recently reported to be increasingly used for agricultural science applications (Nguyen et al., 2020). Moreover, mobile robots have been exploited for search and rescue (SAR) operations in various dangerous environments, to enhance efficiency but also to improve the safety of the rescue personnel. The design and sensor configuration of these platforms are very varied, it depends on the missions and tasks they have been developed for (Toschi et al., 2015) In addition, terrestrial MMS (Mobile Mapping Systems) have been developed and tested in many application fields, combining digital imaging devices and positioning sensors for spatial data acquisition, providing high recording rate, and remote acquisition mode, while the accuracy requirements differ in each application.

When it comes to mapping, aerial methods sometimes are not enough to accurately map ground scenarios, especially vertical and sub-vertical surfaces. Oblique photogrammetry is being widely used and can partially represent an effective solution. Nonetheless, if higher accuracy is required, ground data could help to achieve it. In fact, ground-based surveys not only acquire higher accuracy data but are also capable of detecting those elements which are incomplete or not visible using aerial methods, such as facades, complicated structures, interiors, etc. (Kedzierski & Fryskowska, 2014). For example, damage assessment and management require reliable, accurate and high-resolution spatial information especially in cases where building damages have occurred (Wegscheider et al., 2013). Therefore, the integration of aerial and terrestrial techniques is necessary, as comprehensive aerial and ground-based datasets lead to obtain the most accurate models (Yamazaki et al., 2015).

A large number of studies in the last years have integrated aerial data with complementary ground-based traditional data using different typologies of sensors. In the last years, a synergistic aerial and ground-based approach was regularly used in order to map both anthropic (Zhu et al., 2020) and natural environments. (Mikita et al., 2016). High-resolution aerial and terrestrial images have been used to obtain detailed 3D models of damaged buildings in a post-earthquake damage assessment campaign (Soulakellis et al., 2019); the aerial-terrestrial combination also enabled terrain reconstruction in the photogrammetric corridor mapping over linear extensions of sandy shores (Nahon et al., 2019). This integrated approach triggered data fusion research, making it a very relevant topic today.

In recent years, various studies focused on integrating data collected by fully unmanned systems, aerial and terrestrial, developing integrated methodologies. Their potential applications range from military to commercial (Zacarias et al., 2018), and this approach aims to exploit the advantages of multiple technologies and platforms by overcoming the limitations of each of them. One of the main problems is to obtain accurate 3D models of the environment based on different robotic systems using different typologies of sensors (Potena et al., 2019) and 3D integration, semi-automated registration and segmentation framework are being proposed for heterogeneous unmanned robotic systems, performed on large-scale datasets representing outdoor environments (Balta, 2020). The high complexity of these environments represents the main challenge, especially for the autonomous robotic systems, as their perception capability directly affects the understanding of the scene. Mapping unknown environments is one of the main applications and how to make this process autonomous and safe is an open issue for research.

Over the last years, UAV-UGV synergistic systems have been successfully built up for different purposes such as automatic exploration of disaster scenarios, providing an up-to-date overview of the affected area to guarantee situational awareness (Batzdorfer et al., 2017) as well as simultaneously mapping obstacles in large areas without previous knowledge of the environment (Garzon et al., 2013). The aforementioned systems have been exploited to cooperatively perform various tasks ranging from power pylon inspection (Cantieri et al., 2020) to radiation search (Peterson et al., 2019); an integrated methodology for carrying out measurements of the tombolo geomorphic landform in the littoral zone, using UAV and USV, was presented achieving reliable determination of the scale and variability of the phenomenon (Specht et al., 2020).

Recent advances in Computer Vision represented by Structure-from-Motion (SfM) (Snavely et al., 2007), made photogrammetry become a valid low-cost option, able to effectively replace expensive survey methods such as laser scanning in a large number of recent studies. The quality of the 3D models has been improved thanks to powerful image-matching techniques and terrain extraction algorithms, leading to obtain decimetre-scale vertical accuracy which can be achieved even for sites with complex topography and a range of land-covers (Westoby et al., 2012). The availability of open-source processing software allows to create a three-dimensional model processing high-quality images with a home desktop computer, obtaining high-resolution results. Although its accuracy has been proved to be inferior to laser scanning (Kalvoda et al., 2020), photogrammetry allows to avoid high equipment costs associated with expensive options such as terrestrial and mobile laser scanning.

This technique has been exploited for UAV surveys and stationary ground-based photogrammetry has been used as a complementary technique to UAV photogrammetric surveys in various fields. More recently, ground-based mobile photogrammetry methods are being integrated in PMTS (Personal Mobile Mapping Systems) (Campos et al., 2018) as well as new MMS applications (Roberts et al., 2019) in several fields.

The research project SMUREP, an Italian acronym for "Multi-sensor system for disaster scenarios mapping", is an industrial research project in partnership with the University of Bari, the company Niteko S.r.l. and the Geographisches Institut of Mainz.

Within this project, a low-cost UAV-UGV system has been employed in the photogrammetric survey of a disaster scenario in Pomarico (MT). The aim is to remotely perform low-cost mobile photogrammetric surveys in emergency operations both aerial and terrestrial, mapping natural and anthropogenic elements in areas affected by paroxysmal events such as landslides, earthquakes or floods, without exposing crew members to danger. The system consists of a commercial UAV and a UGV robotic system developed in the research project. While the UAV has been used to obtain the traditional photogrammetry products, the UGV has been used to perform mobile terrestrial photogrammetry, focusing on vertical and sub-vertical surfaces. Datasets have been processed with the SfM technique; aerial and terrestrial products have been merged to obtain a multi-scale model. The model has been compared with a reference model obtained with traditional stationary photogrammetry, in order to assess its accuracy.

This paper briefly presents the mobile robotic system and describes the methodology used to map the study area, providing also an overview of the photogrammetry products obtained from the survey campaign and the spatial analysis. The relative accuracy assessment of UAV-derived and UGV-derived models is described and discussed to evaluate the potential of terrestrial mobile photogrammetry for 3D mapping. Where possible, survey choices are discussed in order to describe the most relevant issues affecting the terrestrial acquisition.

The complexity and advanced degree of specialization characterizing the use of unmanned platforms for different applications emerge from the recent bibliography review. The possibility of multiple platform-sensor combinations, associated with the rapid advances of technologies, has allowed the development of dedicated and specific systems and methodologies. This research represents an advancement of knowledge and experience (from the Latin word "experiri", which means "to experiment") that has investigated the potential and issues of unmanned platforms usage in the context of reality capture for the emergency management. The system developed and the results obtained were guided by an interdisciplinary approach that integrates remote sensing, geomorphology, geo-informatics and mechatronics, in which advanced knowledge relating to different fields was exploited for innovation, providing a new low-cost approach, tool and methodology, as an alternative to more expensive laser systems, for the remote mapping in the emergency response and recovery.

STUDY AREA

The study area is located in the municipality of Pomarico (MT), where a landslide occurred in January 2019 (Fig. 1), affecting the sandy clayey deposits of the western part of the hill, causing the collapse of a road and destroying or heavily damaging several buildings (Potente et al., 2020) which had been previously evacuated. The area is classified as "R2 – medium hazard" in the geo-hydrological hazard map drawn by the local authority, Autorità Interregionale di Bacino della Basilicata. Another portion of the slope which didn't collapse in the January 2019 landslide event, lies within the same perimeter. The village is located upon a hill, in the southernmost section of the Padano-Adriatic Forethrough, which is characterized by the outcropping of Subapennine Clay Formation overlaid by yellow sand ascribed to Monte Marano Sand, and locally by sandy marine terraced deposits (Bozzano et al., 2002). Slopes surrounding the hill are characterized by badlands in the SW and by the presence of extensive debris deposits, mainly sandy and clayey, originating by erosion and landslide in the NE. The frequent landslides phenomena that historically affected this area are mainly composite, retrogressive, translational-rotational slide (Cherubini et al., 1985).

MATERIAL AND METHODS

UNMANNED GROUND VEHICLE

The mobile robotic system development is based on the commercial platform Jaguar 4x4 wheel (DrRobot Inc., Canada, average cost 4500 €). This platform is designed for indoor and outdoor operation, it is driven by four powerful (80W) motors, one for each wheel, it is rugged and lightweight (< 20 Kg), fast (max 14 km/h), with high ground clearance (88mm), compact, weather and water-resistant. It is designed for tough terrains and capable of running over vertical step up to 155 mm. The robot integrates outdoor GPS and 9 DOF IMU (Gyro/Accelerometer/Compass) for autonomous navigation. The integrated high-resolution video provides the remote operator with detailed information of the surrounding. The Jaguar-4x4-wheel is a wireless networked robot, coming with a wireless 802.11 AP/router. The human operator carrying the host controller PC can use the head-mounted display and the included game-pad controller in the outdoor environment to monitor and control the operator under any outdoor lighting environment. The "Jaguar Control" program can be used to see all the sensor information from the robot, and the video streamed from the camera on the robot. The system is powered by a LiPo 22.2V 10Ah rechargeable battery and the nominal operation time is 2 hours.

Two sensors have been integrated into the platform: an RGB camera and an IRT camera. The digital imaging device is a commercial camera GoPro Hero 8 Black: it is a small (66.3 x 48.6 x 28.4 mm) and light (126 g) action camera, 1.2/3 CMOS sensor, 12 MP resolution. The RGB camera was stabilized by integrating a HAKRC Storm32, a 3-axis brushless gimbal suitable for the camera weighing less than 250 g. The RGB sensor system is powered by a LiPo 11.1V 2200mAh rechargeable battery and it is positioned on a plate located on the top of an aluminium stand, 170 cm from the ground.

The thermal imaging device is a Optris Lightweight PI 450 (average cost 5000 €). It is a radiometric thermal camera, optical resolution 382 x 288 pixels, spectral range 8–14 µm, thermal sensitivity, 40 mK, ±2 °C accuracy. It is compact (46 x 56 x 68–77 m) and light (237–251 g depending on lens) as well. The IRT camera was stabilized by integrating a 3-axis BMG4108-130 brushless motors gimbal. The IRT sensor system is powered by a LiPo 11.1V 5000mAh rechargeable battery and it is located in a lower position. As shown in Fig. 2, an anchoring system was designed and built to integrate the platform and the sensor systems, using 3D-printed and aluminium components. The sensor system

Fig. 1 - View and location of the study area. On the left: collapsed road, damaged and collapsed buildings and rubble accumulations on the upper part of the slope. On the right: view of the landslide slope.

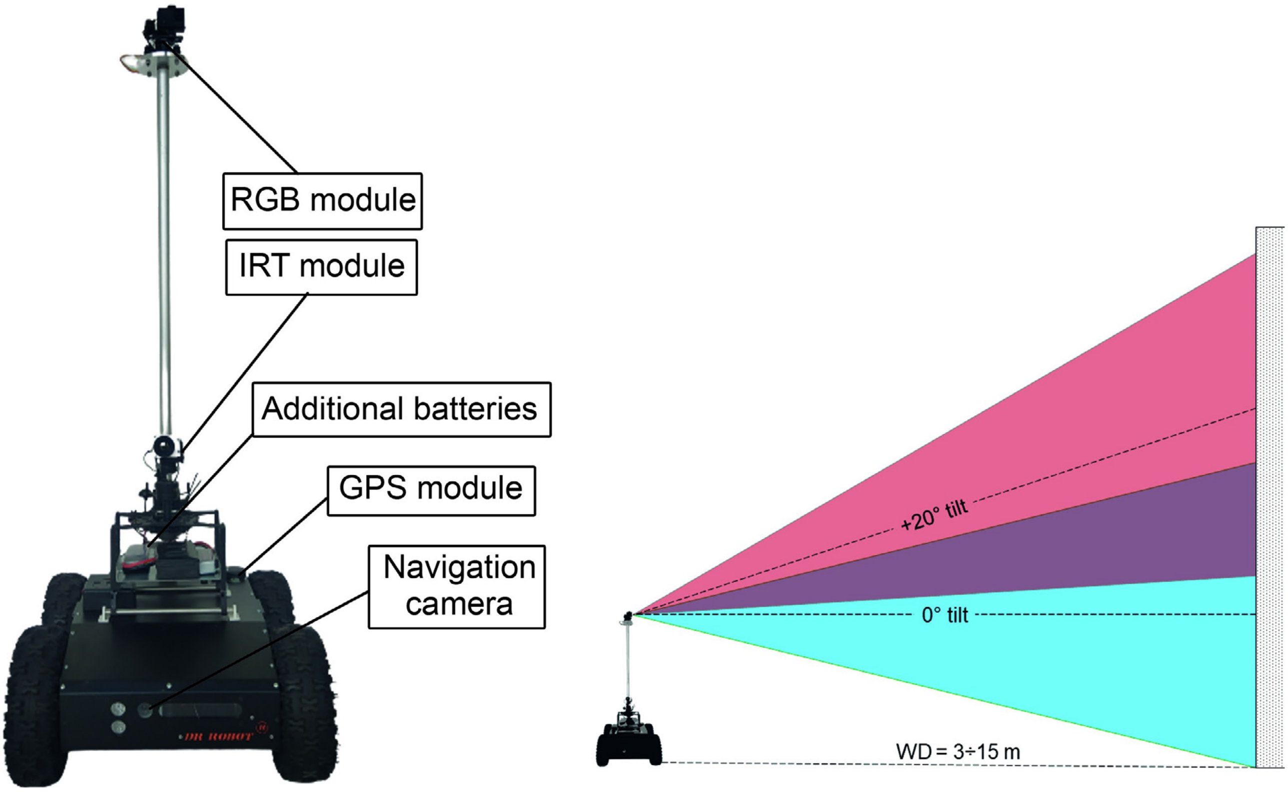

Fig. 2. UGV main components and schematic of the two-camera set-up simulation.

was interfaced with a programmable multi-channel radio controller Futaba T6J 2.4 GHz, with an integrated 7' LCD monitor. The system was tested in different environments in order to optimize its configuration before being employed in the case study scenario.

AERIAL SURVEY

In order to map the study area, aerial photogrammetric surveys were carried out using a DJI Phantom 3 Pro, a commercial platform that is currently in common use because it is quite easy in controlling and also available at an affordable cost (average cost 800 €). This system consists of a remotely controlled quadcopter, equipped with a lightweight and compact size 12 MP RGB camera (effective pixels: 12,4 M; total pixels: 12,76 M); CMOS 1.2/3" sensor; Focal length: 3,57 mm; Field of view (FOV) 94° 20 mm (35 mm format equivalent) f/2,8; Image size 4000 x 3000 pixels. The drone can be controlled by remote control within 1000 meters.

The missions were planned using the DJI GS Pro app, drawing and setting the waypoint navigation and focusing on the damaged buildings, which usually have a primary importance in the emergency response operations, then on the slope. The missions planning was carried out in the field and it was based on ground observation, local knowledge and a pre-flight survey. Two typologies of autonomous programmed flights were planned: one with the camera in nadiral position and one with the camera tilted 45°. Ten survey missions were performed, achieving a nominal GSD (Ground Sampling Distance) of 1.1 and 3.6 cm/pixel according to:

where:
– GSD = Ground Sampling Distance (cm/pixel)
– H = Flight height (m)
– Sw = Sensor width (mm)
– Fr = Focal lenght (mm)
– Iw = Image width (pixel)

The aerial missions can be grouped as follows:

- Damaged buildings survey: it consisted of two missions, one with the camera in nadiral position and one with the camera in oblique position. Main settings: Flight quote: 25 meters, Speed: 3 m/s; Nominal GSD: 1.1 cm/pixel Overlap 80%; Sidelap: 80%; Total area covered: 1.9 ha GCPs (ground control points): 20.
- Landslide slope survey: it consisted of eight missions, four with the camera in nadiral position and four with the camera in oblique position. Main settings: Flight quote: 60 meters, Speed: 3 m/s; Nominal: 3.6 cm/pixel Overlap 80%; Sidelap: 80%; Total area covered: 5.8 ha; GCPs: 16.

In the slope survey, GCPs were mainly positioned in the upper part close to the landslide scarp (10 GCPs) using "naturally occurring" points and artificial targets, then at different quotes along the western side of the slope (6 GCP). Because of the poor accessibility of the area, it wasn't possible to reach a homogeneous spacing in the area. In the survey of the damaged buildings, GCPs were placed close to the landslide scarp (12 GCPs) and also at different quotes in the so-called "red zone", covering the damaged buildings area (8 GCPs).

TERRESTRIAL SURVEY

A remote host controller PC was connected to the robot via wireless, as a Ground Control Station. The open-source desktop software Mission Planner was used to design the missions, defining the waypoints and configuring the autopilot settings for the UGV.

Imagery from mobile photogrammetric data was collected with the RGB camera, focusing on the facades, along two-way paths: the camera was mounted on a 1.7 m stand, positioned orthogonal to the direction of movement and the ground (0° tilt); then, it was tilted upward at an angle ranging from +10° to +20° in the return paths, simulating a two-camera set-up. Images were collected at every ~1.5 m, while the robot average speed was ~1 m/s in order to ensure appropriate overlap between images, needed for the photogrammetric processing:

$$\text{Overlap} = (C - D)/C$$

where:

D is the distance between photos

C is photo coverage in the direction of camera movement

The images overlap was calculated to range between 80% and 95%, based on the working distance (WD, distance between the sensor and the main vertical surface), which ranged from 3 m to 15 m. Three missions with different paths were planned within the study area.

- Mission 1: Length = 134 m; waypoints = 20
- Mission 2: Length = 115 m; waypoints = 16
- Mission 3: Length = 168 m; waypoints = 32

A stationary traditional photogrammetric survey was carried out, along a 50 m line which is part of the path which the UGV followed in mission A. A DSLR (Digital Single-Lens Reflex) camera, NIKON D3100 and a survey rod were used. The design of the photogrammetric survey was optimized to obtain a reliable dataset and an accurate reference cloud. Stationary images were collected achieving an average Ground Sampling Distance of 1 cm/px.

DATA PROCESSING

The pre-processing step consisted of importing the high-resolution images collected in the photogrammetric suite Agisoft Photoscan v. 1.4.3, where a software tool was used only to assess the quality of each image and its suitability for processing. The tool assigns a quality value ranging from 0 to 1 to each image: the higher is the value, the higher is the image quality. A threshold of 0.5 was set to detect blurred or distorted images to discard. Terrestrial datasets were subsampled, discarding redundant images, in order to optimize the time of processing. Then, the brightness and contrast of the images were balanced using Adobe Lightroom, in order to optimize the images to facilitate the SfM processing.

The software MicMac (Multi-Images Correspondances, Méthodes Automatiques de Corrélation), an open-source photogrammetric suite software developed by the French Geographic Institute (IGN), was used in the processing. Its modular structure allowed the precise regulation of all the obligatory and optional parameters to process the dataset with the Structure from Motion (SfM) technique (Rupnik et al., 2017). GCPs measurements were used for the georeferencing, using a local coordinates system. Stationary datasets were also processed using the SfM technique. An ASUS laptop, Intel® Core™ i7-8550U processor, 16GB RAM was used for the processing.

Among the photogrammetry products, dense point clouds were obtained and imported in Cloud Compare, an open-source software that provides several tools to analyse point clouds, where non-significant points and noise were removed.

The clouds deriving from the damaged building survey and the landslide slope survey were aligned using artificial markers and 12 GCPs which were in common between the two surveys. These control points were used to compute statistical parameters (RMS, mean, standard deviation) for the aerial model after georeferencing. Additional parameters Skewness and Kurtosis were used to analyse the normality assumption i.e. the Gaussian distribution of the errors. The Skewness a measure of the asymmetry of the probability distribution, while the Kurtosis is a measure of the "tailedness" describing the shape of a probability distribution.

The aerial model was used to align and georeferencing the terrestrial models, deriving from UGV photogrammetry, using natural/artificial markers and control points in CloudCompare. A quantitative analysis of the landslide event was carried out exploiting the photogrammetry products (Point clouds, Ortho-photomosaic, DEMs) in CloudCompare and QGIS, computing 2D and 3D measurements.

CloudCompare software was also used to assess the relative accuracy of the terrestrial model i.e. the measure of the mutual position of the points in the processed model. This represents the internal consistency of the model, that is how accurately digitally reconstructed objects picture the real world. The "Cloud-to-Cloud Distance" (C2C) function was exploited to carry out the independent comparison between part of the aerial and terrestrial models with a reference model represented by the stationary photogrammetry model. The C2C function uses several algorithms, such as iterative closest point (ICP) to calculate clouds difference, using the nearest neighbour distance algorithm to compute the absolute distance between two entities. The compared cloud is the one on which distances are computed: CloudCompare computes the distances of each of its points relative to the reference cloud and the generated scalar field is hosted by this cloud. The reference cloud is recommended to have the widest extents and the highest density because it directly affects the accuracy of the results. If the reference point cloud is dense enough, approximating the distance from the compared cloud to the underlying surface represented by the reference cloud is considered acceptable.

In order to improve the accuracy of the nearest neighbour distance computation can be necessary to get a better model of the surface. In fact, it's more accurate to compute directly the distance from the compared cloud to a true global model when it's possible to compute a high-quality one (Cloud-to-Mesh Distance). Since it's generally not easy to get a clean and proper global model, CloudCompare provides an intermediate option to get a better approximation of the true distance to the reference surface, much easier to compute: the cloud surface is locally modelled by fitting a mathematical model on the nearest point and several of its neighbours. There are three types of local models, all based on the least-square best fitting plane that goes through the nearest point and its neighbours. The 2D1/2 type, which was used, performs the projection of the points on the plane to compute Delaunay's triangulation. The distance from each point of the compared cloud to its nearest point in the reference cloud is replaced by the distance to this model. This is statistically more precise and less dependent on the cloud sampling. Terrestrial and aerial models were compared with the reference model to assess their relative accuracy and to evaluate the improvement obtained by using UGV photogrammetry in the 3D reconstruction.

RESULTS

The processing of the damaged buildings dataset resulted in the dense point cloud, the 3D model and the updated orthophoto of the historic centre area affected by the phenomenon (Fig. 3a). It was possible to reconstruct the geometry of the scene, identifying the accumulations of rubble deriving from the buildings collapse, the cracks in the roadway, the rubble accumulation on the slope originating from the collapsed buildings, as well as some cracks on the ground surface and some tilted pillars. Using CloudCompare, it was possible to estimate the volume of debris resulting from the collapse of the buildings and the ground surface (about 25000 m^3).

The landslide slope survey led to obtain orthophotos (Fig. 3c), DEM and DTM of the entire landslide area. It was possible to extract the updated contour lines reconstructing the updated topographic profile of the slope in the QGIS environment. It was also possible to compute the total landslide surface landslide (34,000 m^2) and its perimeter (1.8 km). The comparison between the DTM before the event and the updated DTM allowed the calculation of the total volume of sediment collapsed along the slope (about 165000 m^3).

Statistical parameters were measured after georeferencing using the 12 common control points. The

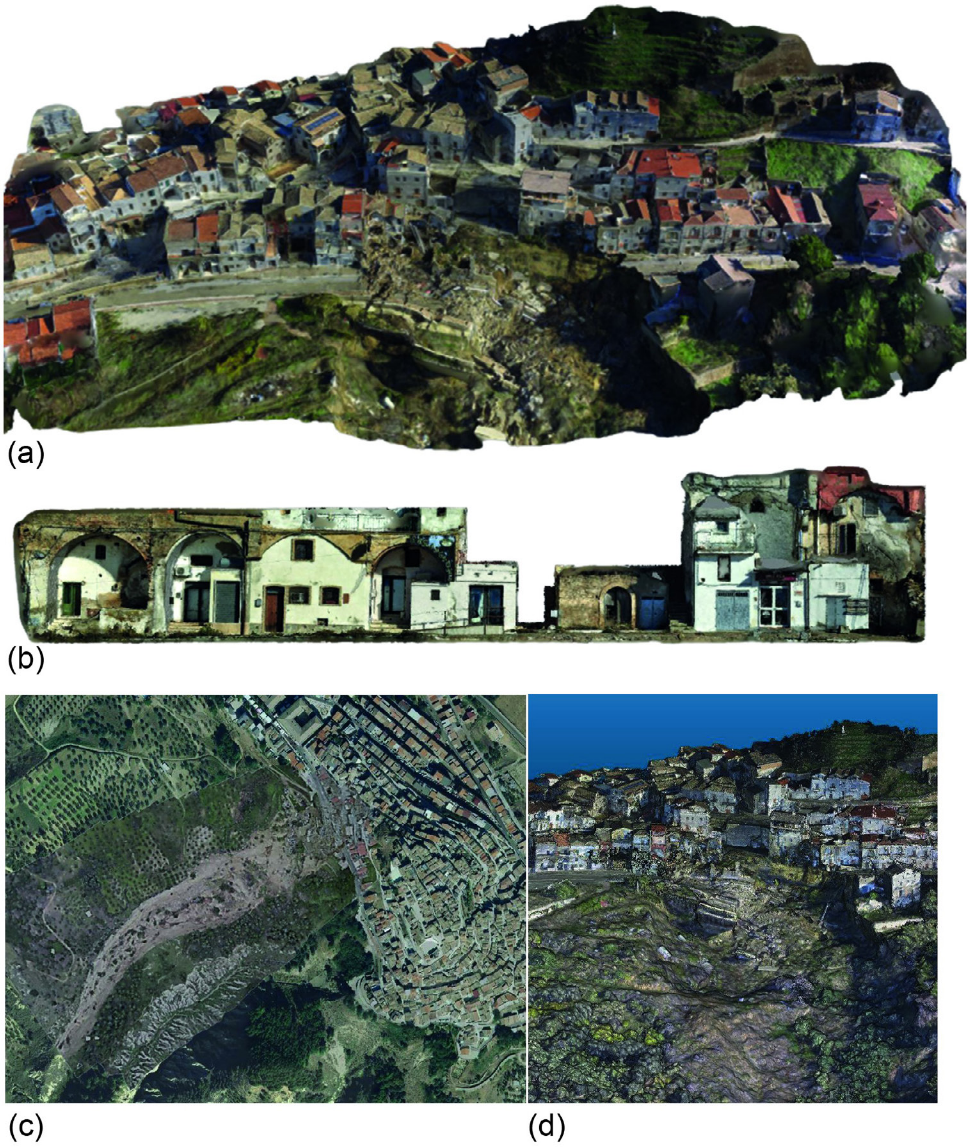

Fig. 3. Photogrammetry products: 3D model derived from the UAV buildings survey (a); example of a 3D model of buildings facades derived from UGV survey (b); otho-photomosaic derived from the UAV slope survey in Google Earth (c); point cloud detail in CloudCompare (d).

RMSE (Root Mean Square Error) values were calculated spatially and along the three spatial axes. The observed RMS value along the x-axis was 2.3 cm, RMS value along the y-axis was 22.08 mm, RMS value along z-axis was 1.4 cm, and the spatial RMS was 2.5 cm. The Skewness value ranges between -0.5 and 0.5, indicating an asymmetrical distribution of the data. The Kurtosis value is -0.7, which means that the data follows a platykurtic distribution indicating the small outliers in distribution.

Dense point clouds and high-resolution 3D models of buildings facades (Fig. 3b) were obtained from mobile terrestrial photogrammetry along the three mission paths.

Cloud-to-cloud comparison results are shown in Fig. 4. The compared clouds represent parts of the aerial (UAV-derived) and terrestrial (UGV-derived) models which were compared to the reference model, obtained from the stationary photogrammetry survey. Mean and standard deviation of the distance values were computed in CloudCompare for the two processed models: the mean of the distance value for the aerial model is 44.4 cm, standard deviation is 39.8 cm; the mean distance value for the terrestrial model is 4.2 cm, standard deviation is 5.1 cm. Moreover, 90% of the points are under 95.8 cm for the aerial model, while 90% of the points are at a distance smaller than 8 cm for the terrestrial model. Moreover, aerial and terrestrial models were merged and compared with the reference one: the mean distance value is 4.2 cm, standard deviation is 5.2 cm and 90% of the points are under 8.1 cm.

DISCUSSION

The Cloud-to-Cloud comparison provided eloquent information about the higher reliability of the terrestrial model when compared to the aerial one. In fact, the mean of the distance values as well as the absolute distance values for 90% of the points, are about ten times lower, indicating a considerable reduction of the error in the three-dimensional reconstruction. As it can be seen in Fig. 4(a), the highest error source is represented by surfaces that are not clearly visible using aerial methods, such as recessed surfaces.

Besides, the higher accuracy of the UGV-derived model is also coupled with a higher point density, which generates a much more detailed reconstruction of surface geometries, compared to the lower density and lack of information of the aerial model, as can be clearly visible.

It must be considered that the accuracy assessment was based on three different photogrammetry techniques (mobile aerial and terrestrial; stationary) and three different typologies of instruments were used for the acquisition (UAV camera, UGV camera and DSLR camera), so some issues should be taken into account:

- Every system has its own sources of uncertainties and can be more or less suitable for the specific design adopted in the survey;
- The compared point clouds can't exactly correspond to each other, because of how reconstruction algorithms work (number of images, density, etc.);
- The position of acquisition is different for each survey, and this contributes to generate differences in the surface reconstruction.

Moreover, the conditions for which the comparison results are valid, need to be taken into account. It should be considered that reference model data and UGV data were both acquired with terrestrial photogrammetry surveys (stationary and mobile) in which images were collected from a similar perspective, also in a limited area where a stationary survey is feasible and reliable.

The integration of aerial and terrestrial models is an important issue to discuss. The developed vehicle is equipped with a positioning system and, even if it is possible to reconstruct the UGV path (which is known if a mission planner software is used, otherwise IMU-GPS data need to be processed), positioning information can't be used for georeferencing the data. This doesn't affect the SfM reconstruction, but prevent from independently georeferencing the model, except if GCPs are measured on-site. Since the system is supposed to work remotely, this would not represent a solution. Today cameras are equipped with GPS providing geolocation data, but its accuracy it is too low, ranging from 1-2 meters to 30 meters, because the GPS signal is heavily influenced by the surrounding environment. Therefore, terrestrial models obtained with this methodology need a reference model to which they can be aligned (in our case, the UAV-derived model) to allow the georeferencing.

The alignment, which was also carried out in CloudCompare, is a time-consuming activity that can heavily affect the quality of the result: in the alignment step, the software rotates and translates the aligned model, as well as changes his scale factor, based on a number of couples of corresponding control points (a minimum of 3) picked on the aligned and on the reference model. The more couples of corresponding points are detected on the two models, the more accurate will be the alignment. In our case, a high number of control points was provided by several objects in the scene, like windows or doors corners, and we were able to effectively carry out this key step. A solution to this problem could be achieved by integrating the RGB module with a GPS unit and a timing GPS antenna to assign coordinate metadata to each image before the photogrammetric processing. This retroactive approach would be time-consuming too, but it would solve the problem and still be a low-cost solution.

Additional observations can be made, about the terrestrial mission planning choices, UGV acquisition parameters and terrestrial datasets. The speed directly influences the vehicle performance, depending on the ground surface characteristics: mission 3 was the most challenging, because of the ground material, slope and conformation. The average speed, set to 1 m/s along the acquisition path, guarantees an acceptable quality of the images if the object surface is at an appropriate distance from the camera. Based on previous tests, the minimum working distance was estimated to be 3 meters. Moreover, the speed is strictly connected to the number of images acquired: collecting data every 1.5 seconds with an average speed of 1 m/s could be considered an over-conservative choice. That leads to obtaining a huge number of images, a larger dataset, longer processing time even for a relatively short mission, unless an effective subsampling step is done. The dataset size depends on the geometric complexity of the mission: a longer and complex path, and a higher number of waypoints, determine an increase in the number of images collected

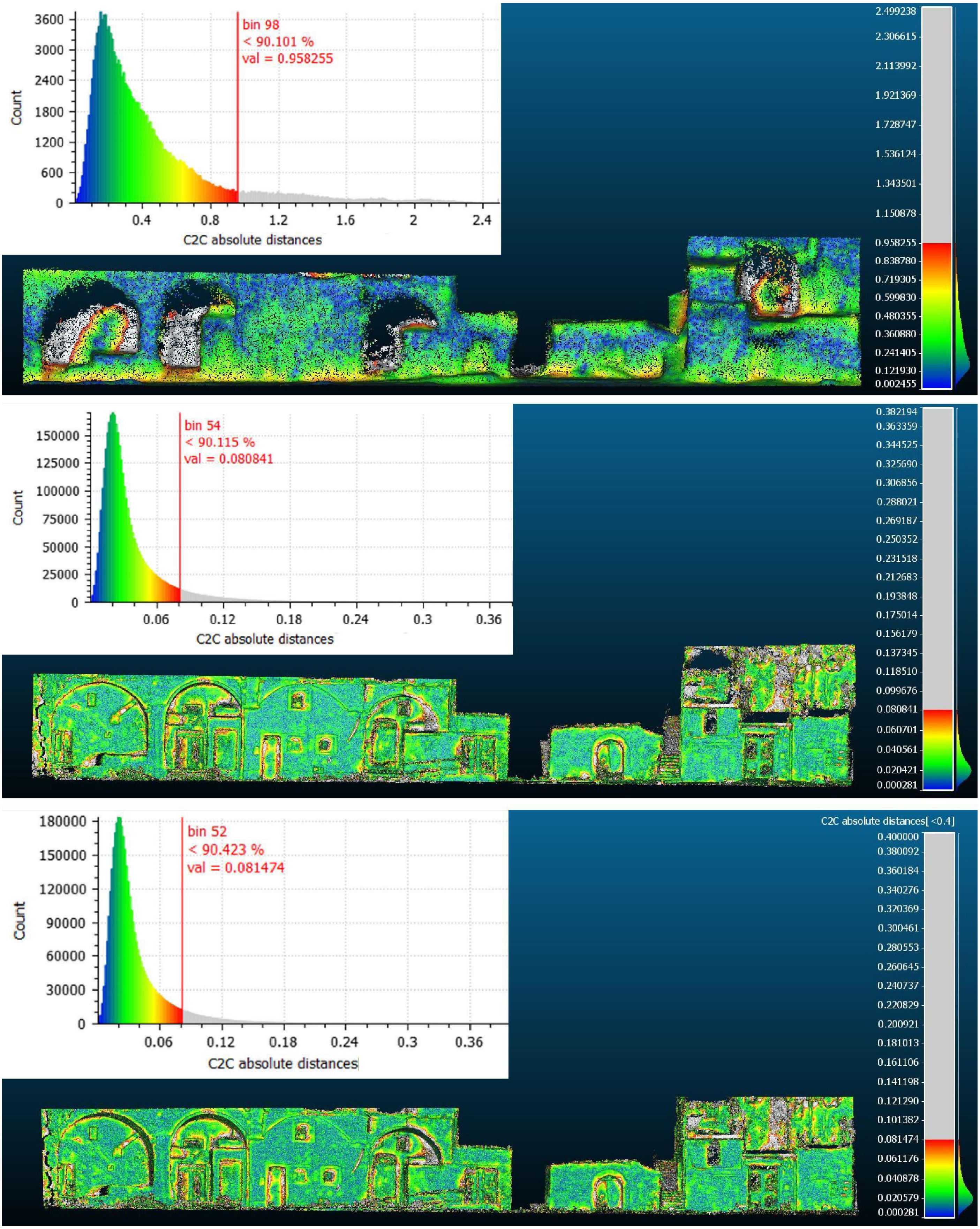

Fig. 4 - C2C comparison results in CloudCompare. Scalar field hosted by the aerial point cloud and computed distance distribution (a); scalar field hosted by the terrestrial point cloud and computed distance distribution (b); scalar field hosted by the merged point cloud and computed distance distribution (c).

compared to the number of images expected. This can be observed considering the number of images obtained and expected for each mission. The increase seems to be bigger for a higher number of waypoints and a longer path. This should be taken into account when mission planning is made, in order to balance the path design with the sampling time in connection with the path length and the resolution needed, avoiding excessive data redundancy. Large datasets processing is a relevant topic in this research field and this limitation is likely to be overcome with the next advances. In fact, many studies are focusing on decreasing computing resources and processing time required by a large amount of data: some methodologies are being developed, exploiting the cloud computing environment, using virtual machines, HPC (High-Performance Computing) and multi-processor parallel computing to decrease the processing time and storage needed.

Furthermore, considering the number of images discarded during the quality check, it seems that data redundancy itself helps to guarantee the minimum overlap between consecutive images, needed for the SfM processing. This applies in particular to complex paths: about 6% of the images collected from mobile photogrammetry was discarded in the quality check before processing.

Moreover, in our case, UGV missions were planned based on a UAV survey that provided local knowledge about the scenario. All of this information (distances, presence of obstacles, slopes, ground characteristics) are useful and often necessary to design a safe and proper survey, taking into account the vehicles specifications such as camera FOV, battery life or ground clearance. Lighting conditions are also very important: low light or intense contrast can lead to low-quality images which are useless for the processing software.

According to our study, mobile photogrammetry using the developed UGV displays the following benefits and disadvantages:

- Remote sensing: the photogrammetric survey can be carried out in remote mode; therefore, hazardous scenarios can be safely investigated and reconstructed;
- Accuracy: the processed models represent a remarkable improvement in the reconstruction of vertical and sub-vertical surfaces, such as buildings facades, and can be complementary to UAV models.
- Data integration: the lack of an accurate sensor positioning system leads to the need for a reference model, such as a UAV model, for the georeferencing of terrestrial data. This can be achieved with a time-consuming procedure and its accuracy depends on the number of control points detected in the scene.
- Acquisition settings: the main UGV mission parameters are speed, working distance and sampling time: they need to be properly set in order to achieve an acceptable compromise between the image overlap/ resolution needed and data redundancy.
- Field factors: Slopes, obstacles, lighting conditions should be taken into account. A preliminary brief knowledge of the scenario is recommended to be aware of potential limitations and optimize the mission design.

CONCLUSIONS

An accuracy assessment was carried out comparing aerial and terrestrial models, derived from UAV and UGV photogrammetry, to a reference model obtained from a stationary ground survey. The comparison resulted in a higher reliability of the terrestrial model with a mean error of 4.6 cm. The computed error for the terrestrial model is lower than 9 cm for 91% of the points, which represent an acceptable value, about ten times smaller than the error computed for the aerial model. Moreover, the terrestrial model provides higher quality information and details of the surfaces. It must be taken into account that some differences between models can be traced back to georeferencing and alignment errors, which are influenced by the number and distribution of the control points measured.

The mission planning parameters have a key role in the building of UGV datasets: path, speed and sampling time settings must be accurately evaluated to avoid high redundancy or lack of data, also taking into account ground conformation and field factors. Local knowledge about the environment, which can for example be provided by a UAV flight, seems to be necessary to obtain useful information for the design of UGV missions and surveys. The main open issue is represented by the alignment and georeferencing of the aerial and terrestrial model in a common reference system. The survey was proved to be achieved with proper accuracy but also to be a time-consuming step, as a large number of control points is needed in order to obtain a good quality result. Despite that, the adopted workflow represents an effective low-cost methodology for the complementary mapping of dangerous scenarios in remote mode.

When searching for the causes of landslides, a co-occurrence of factors contributes to increase cutting forces decreasing the shear strength of the material. In this case, the urban context in which the landslide took place must be taken into account, therefore all the resulting anthropogenic factors that contribute to the phenomenon. The anthropogenic activities on the slope seems to be decisive at a first analysis, both in terms of lack of an effective drainage system for the surface runoff of water, as well as water leaks coming from the wastewater network.

The adopted methodology can be still improved but seems to represent a low-cost solution for safe disaster scenario mapping activities, resulting in consistent products which can be used for documenting the damages or employed for spatial analyses. In particular, terrestrial mobile photogrammetry using the UGV provides additional high-resolution data of objects which are not accurately mapped using a UAV, such as buildings facades, providing an accurate reconstruction of the surfaces.

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