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STRUCTURE FROM MOTION TECHNIQUE OF PROXIMAL SENSING AIRBORNE DATA FOR 3D RECONSTRUCTION OF EXTRACTION SITES

Emanuele TUFAROLO(*), Riccardo SALVINI(*), Marcello SEDDAIU(**), Chiara LANCIANO(*),
Stefano BERNARDINETTI(***), Francesco PETROLO(**), Luigi CARMIGNANI(*),
Giovanni MASSA(****) & Diego PIERUCCIONI(*****)

(*) University of Siena - Department of Environment, Earth and Physical Sciences and Centre of Geotechnologies CGT - Via Vetri Vecchi, 34 52027 San Giovanni Valdarno, Italy
(**) University of Siena - Centre of Geotechnologies CGT - Via Vetri Vecchi, 34 - 52027 San Giovanni Valdarno, Italy
(***) University of Cagliari - Department of Chemical and Geological Sciences and Centre of Geotechnologies CGT - Via Vetri Vecchi, 34 52027 San Giovanni Valdarno, Italy
(****) CGT Group, Strada Provinciale delle Miniere - Polo Industriale di Bomba - 52022 Cavriglia, Italy
(*****) University of Pisa - Department of Earth Science - Via Santa Maria, 53 - 56126 Pisa, Italy
Corresponding author: tufarolo@cgt-spinoff.it

EXTENDED ABSTRACT

I siti di estrazione mineraria spesso ricadono in aree non facilmente accessibili e sono contraddistinti da un'elevata complessità morfologica. A causa di tali caratteristiche, il loro rilievo e la loro modellazione, tramite tradizionali tecniche di indagine di tipo topografico, risultano essere operazioni particolarmente articolate ed estremamente costose. Nel presente articolo proponiamo un metodo di lavoro innovativo in grado di ridurre al minimo l'entità sia dei costi sia del lavoro sul campo. Si tratta dell'applicazione della fotogrammetria digitale basata su algoritmi di Structure from Motion (SfM), tecnica speditiva, economica ed efficace per il rilievo tridimensionale e la mappatura di vaste aree di particolare interesse geologico-geomorfologico. I prodotti derivati dal processing fotogrammetrico quali nuvole di punti tridimensionali, Modelli Digitali di Elevazione (DEM), ovvero Digital Surface Models (DSM) e Digital Terrain Models (DTM), ed ortofoto ad alta risoluzione, costituiscono una nuova frontiera nell'ambito dello studio e del monitoraggio del territorio e delle sue attività produttive.

Nel presente caso studio, ai fini della ricostruzione 3D dei siti di estrazione, si utilizzano immagini acquisite da sensori montati su un velivolo leggero, agile ed estremamente economico. L'aereomobile, denominato RadGyro (di proprietà del CGT Group, Università di Siena), è un velivolo sperimentale per misure multiparametriche airborne. Il velivolo è in grado di affrontare complessi piani di lavoro e di volare, quando necessario, a bassa quota, in modo tale da consentire un rilievo dettagliato delle caratteristiche desiderate anche in aree morfologicamente complesse. Un esempio di questa condizione è rappresentato dall'area di studio presentata in questo lavoro, situata nel comprensorio delle Alpi Apuane, il più grande e sfruttato bacino estrattivo marmifero d'Europa. A differenza delle tradizionali tecniche di indagine di tipo geologico, topografico e geo-meccanico, l'utilizzo di sensori aviotrasportati consente di realizzare il rilievo dei versanti rocciosi che costituiscono le cave in tutta la loro estensione.

Il RadGyro è attrezzato per acquisire serie di fotogrammi in modo indipendente, attraverso l'impiego di una coppia di fotocamere digitali non calibrate caratterizzate da un sensore full frame e ottica fissa da 35 mm. Inoltre, la presenza di cinque antenne GPS (Global Positioning System) e di un sistema di navigazione inerziale (INS, Inertial Navigation System) permette di associare a ciascun fotogramma la posizione e l'orientazione angolare della camera al momento di ciascun scatto. Volando ad un'altitudine variabile tra 100 m e 400 m AGL (Above Ground Level), le camere possono rilevare, rispettivamente, circa 50 e 200 km^2, con una risoluzione al suolo di 3.5 cm, nel primo caso, e 10.0 cm nel secondo.

L'orientamento esterno delle immagini può essere migliorato, se necessario, con l'acquisizione di punti di controllo a terra (Ground Control Points, GCPs) mediante tradizionali rilievi di tipo topografico.

Le informazioni di orientamento esterno associate ad ogni fotogramma sono quindi impiegate per portare a termine il processing fotogrammetrico attraverso l'utilizzo di appropriati software. L'applicazione di tecniche ed algoritmi SfM consente di individuare milioni di punti di legame (Tie Points) necessari per ottenere un accurato allineamento relativo dei fotogrammi. Il processing fotogrammetrico è quindi portato a conclusione mediante la realizzazione di DEM ed ortofoto caratterizzati da differenti risoluzioni e gradi di accuratezza a seconda dei parametri di survey, della qualità dei CGPs (cartografici o da rilievo topografico) e dei parametri di elaborazione. Ortofoto e DEM consentono, infine, di visualizzare un modello 3D dell'area test e restituirne le caratteristiche topografiche, geologiche e geomorfologiche fondamentali.

I risultati ottenuti confermano come gli algoritmi SfM implementati in software commerciali siano oggi di fondamentale ausilio nei processi di ricostruzione fotogrammetrica. Nello specifico, l'utilizzo di algoritmi SfM consente di sfruttare al meglio le potenzialità del RadGyro. Nei casi in cui il piano di volo fotogrammetrico standard non è applicabile, per cui si ricorre a voli non rigorosi dal punto di vista della presa, l'algoritmo è in grado di estrarre comunque milioni di tie points da fotogrammi obliqui (tramite tecniche di Computer Vision). Di conseguenza, risulta comunque possibile effettuare l'orientamento esterno senza interventi manuali da parte dell'operatore, contrariamente a quanto accade utilizzando le classiche stazioni fotografiche.

ABSTRACT

Nowadays digital photogrammetry based on Structure from Motion (SfM) algorithms represents a low-cost and rapid technique for the tridimensional detection and mapping of large areas of particular geologic-geomorphologic and environmental interest.

In this case study, we use images captured from sensors mounted on a small and inexpensive aircraft for the 3D reconstruction of extraction sites. The aircraft, called RadGyro, is able to deal with morphologically complex zones, as the test area, located in the marble district of the Apuan Alps, the biggest and most exploited European extractive basin. The RadGyro is equipped with two digital cameras (full frame sensor and 35 mm fixed lens). Five GPS antennas and an Inertial Navigation System (INS) allow associating to each frame the camera position and its angular orientation. Ground Control Points (GCPs) acquired through traditional topographic surveys allow to improve the image exterior orientation as well as the SfM techniques allow detecting millions of tie points for an accurate alignment of photos. We finalize the photogrammetric processing by creating 3D point clouds, DSM, DTM and orthophotos. The results demonstrate how SfM algorithms, implemented in commercial software, emphasize the potentials of the RadGyro and are very useful in the photogrammetric processing.

***Key Words**: Structure from Motion, digital photogrammetry, airborne survey, proximal sensing, extraction sites.*

INTRODUCTION

Besides the use of the most modern terrestrial laser scanners, photogrammetry is one of the principal techniques for the modeling, study and topographic characterization of mining areas. Due to their morphological complexity and placement in areas of difficult access, the modeling of the marble quarries through the traditional terrestrial topographic methods is often very complex and expensive. At the same time, the areas in which the sites are located are difficult to detect by the use of conventional aircrafts and related classical photogrammetric payload.

In this paper, we present an innovative working approach that minimizes the work related to the on-site surveys. In fact, we acquire photogrammetric data using the prototype of an aircraft expressly created for multi-parametric surveys. The aircraft is able to fly at the low altitudes required to complete detailed investigations ensuring the aviator safety and minimizing the economic impact. SfM algorithms allow performing the photogrammetric processing of the images acquired by the sensors mounted on the aircraft. Such algorithms allow obtaining a high level of automation in the reconstruction of three-dimensional models. Despite the use of a few GCPs and not linear photogrammetric acquisition parameters, it is still possible to guarantee a good accuracy of the model reconstruction.

We describe some preliminary work done at the marble quarries of the Apuan Alps (Fig. 1), discussing about the results in terms of robustness of the reconstruction and data reliability and quality.

STRUCTURE FROM MOTION ALGORITHMS

Structure from Motion is a modern photogrammetric method for the creation of three-dimensional models (concerning the topography or other distinctive features of the observed territory) from sequences of two-dimensional images. A particular sensor, for example a photographic camera that moves either on the aircraft or on remotely piloted airborne system following a certain path (Rootwelt, 2014), can acquire the imagery. By overlapping 2D images, acquired from different locations and with different orientations, it is theoretically possible to reconstruct the 3D model of the photographed scene.

The SfM origins come from the fields of photogrammetry and computer vision (Spetsakis & Aloimonos, 1991; Boufama *et alii*, 1993; Szeliski & Kang, 1994).

Photogrammetry is a survey technique that, through geometric theories and optical, mechanical and electronic processes, allows realizing the graphical or analytical (digital) 2D or 3D reconstruction of an object characterized by known photographic perspectives. The aim of the traditional photogrammetry application (topographic photogrammetry) is to conduct aerial surveys and to product maps (Pappa *et alii*, 2001). The pioneers in this field (1840's) were Arago, Jordan, and Laussedat Stolze, who used the cameras to estimate the shape of a certain terrain from aerial and ground photographs, coining the name "photogrammetrie" (Maybank, 1993). After some time, the development of the airborne and spaceborne survey techniques led to an improvement in photogrammetry. In recent years, digital photogrammetry has become a powerful tool widely used for the three-dimensional modeling (Westoby *et alii*, 2012).

Computer Vision is a discipline that deals with the reconstruction, interpretation and understanding of a 3D scene starting from its 2D images in terms of properties of the structures situated on the scene (Sachdeva *et alii*, 2014). The aim of this discipline is to automate and integrate a wide range of processes and representations for the vision perception. Computer vision is closely linked to the artificial system theory, that allows extracting information from the images (Sachdeva *et alii*, 2014). Using the computer, in fact, it is possible to perform the numerical images analysis, in a way to understand the visual information contained in images and videos (Barrile *et alii*, 2015).

The SfM technique exists in various forms since 1979 (Ullman, 1979), but its applications were not common until the early 2000s (Snavely *et alii*, 2008). It is possible to apply SfM in some disciplines, from the geoscience (structural geology, tectonics, geomorphology, geodesy, mining) up to archeology, architecture and agriculture. In addition to orthorectified imagery,

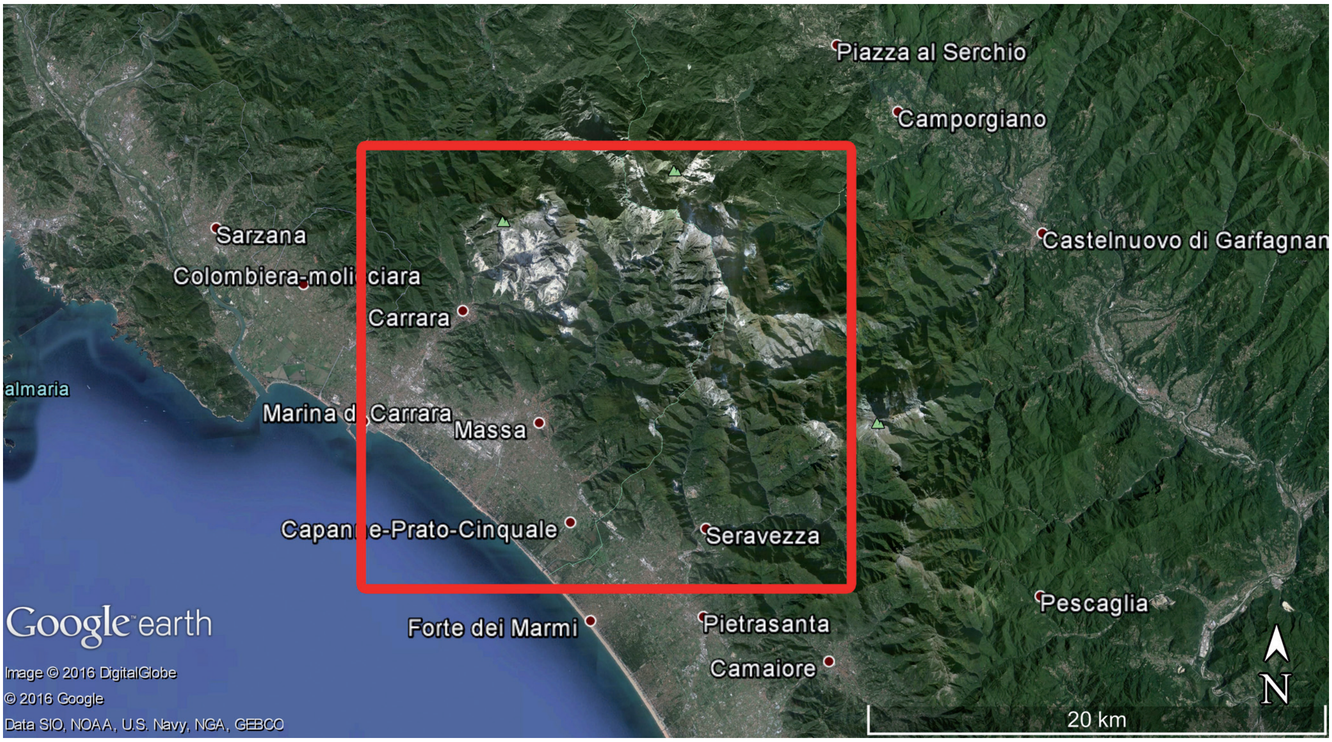

Fig. 1 - General view of the area including various test sites

SfM allows producing dense point clouds similar to those obtained using airborne surveys or terrestrial Lidar (Light Detection And Ranging, Shervais, 2015). SfM represents a low-cost method for high-resolution topographic reconstructions, suitable for low-budget researches in hardly accessible areas (Westoby *et alii*, 2012). The advantages of SfM procedure are the low cost (if compared, for example, to that of Lidar), the simplicity of use and a greatly limited operator supervision (Micheletti *et alii*, 2015). The equipment includes the cameras for the acquisition more computers and software for data processing. An aerial platform (aircraft, drone) can be useful for topographic mapping applications. The major limitation of the method is the processing time necessary for the alignment of images, which ranges from about ten minutes (for a few images) to days (for hundreds or thousands of photographs, Shervais, 2015).

Several authors describe the basic steps to implement a SfM process (Westoby *et alii*, 2012; James & Robson, 2014; Fonstad *et alii*, 2013; Micheletti *et alii*, 2014). The method is based on the fundamental principle of the stereoscopic photogrammetry, according to which it is possible to obtain the three-dimensional model from series of overlapping images (Westoby *et alii*, 2012). However, differently from the traditional photogrammetric methods, the software automatically solves the scene geometry, without the need to specify a priori targets or notable points in the acquired images (Westoby *et alii*, 2012). This technique is particularly cost-effective when a set of images, characterized by a high degree of overlap, is available, such as to allow a complete three-dimensional reconstruction of the acquired scene (Barrile *et alii*, 2015). The SfM software automatically identifies and resolves these points through the iterative procedure of *bundle adjustment*, based on a database of characteristics automatically extracted from a set of multiple overlapping images (Snavely, 2008). In particular, the bundle adjustment procedure implements the condition of collinearity to establish a mathematically rigorous relationship between the images and the object on the ground (Brown, 1971, 1976; Kenefick *et alii*, 1972; Granshaw, 1980). The algorithm works by minimizing a cost function related to a weighted sum of squared reprojection errors. In order to obtain a rapid convergence, it is usually used the Gauss-Newton iteration.

There are several steps to follow to obtain dense point clouds and three-dimensional models by the application of SfM techniques. The main issue is the determination of the tridimensional position of matching features in multiple photographs acquired from different angles and positions. To solve this matter it is necessary to recognize features in single images that can be used for the correspondence in other scenes (Westoby *et alii*, 2012).

In each image, the SIFT (Scale-Invariant Feature Transform) algorithm finds the significant points (Snavely, 2008; Barazzetti *et alii*, 2011). SIFT is a computer vision algorithm that allows detecting and describing the local characteristics of the images (Lowe & David, 1999). This algorithm detects, in each image, features that are invariant to the image scaling and rotation, and partially invariant to changes in illumination conditions and tridimensional camera viewpoints (Westoby *et alii*, 2012). The points of interest or *keypoints* are automatically identified in each image on all scales and in all positions. The number of keypoints found in a single image depends on the image texture and resolution: complex images at high resolutions usually provide the best results. Density, sharpness and resolution of the sequence of photographs influence the quality of the output data.

Decreasing the distance between the sensor and the characteristic of interest, thereby increasing the spatial resolution of the photo, it increases the spatial density and, consequently, the resolution of the final point cloud (Westoby *et alii*, 2012). To reconstruct the scene, the corresponding characteristics need to be visible in at least three photographs. However, it is recommended to acquire the greatest possible number of images, setting some geometrical constraints. In this way, it is possible to optimize both the maximum number of pairs of keypoints and the system redundancy. The epipolar geometry is fundamental to define the geometric constraints that link the homologous points recognized in the photographs representing the same scene (Barrile *et alii*, 2015). After the identification of keypoints, SIFT chooses the homologous points that deviate less from each other. After locating a point in the first scene, characterized by certain values of brightness, color, etc., the equivalent in the next scene appears to be the one that is closest to the analyzed point. The search of the homologous points is done within particular areas of the scene, angles or zones where elements of discontinuity appear to be more evident (Barrile *et alii*, 2015). For the model generation, it is necessary to define the internal orientation parameters of the photographic camera. This action is performed through the already determined correspondences (homologous points and epipolar geometry). In this phase, the control and limitation of the errors take place thanks to the already mentioned bundle adjustment.

The use of "dense image matching" algorithms allows producing the three-dimensional model. These algorithms are divided into two different types: the Area Based Matching (ABM) algorithms work on the statistical comparison of the gray intensity characterizing the different photographs and do not require the features extraction; the Feature Based Matching (FBM) algorithms that, conversely, search and extract the common features. Although it considerably lengthens the processing time, the combination of both types of algorithm guarantees optimal results (Barrile *et alii*, 2015).

The obtained three-dimensional point cloud is not georeferenced but represented in a local system. To move from a spatial coordinate system to an absolute coordinates system, it is necessary to recognize an appropriate number of GCPs, with known coordinates and detectable either in the photos or within the three-dimensional point cloud (Westoby *et alii*, 2012). The GCPs can be post-hoc derivate, identifying clearly visible features in the point cloud and on the field, and obtaining their coordinates through topographic surveys (GPS and/or Total Station). In many cases, before the images acquisition, it is necessary to identify physical targets characterized by a high contrast and clearly defined by a center of gravity on the field. This approach allows having a reliable and well-distributed network of targets throughout the area of interest and assessing possible non-linear structural errors in the SfM reconstruction (Westoby *et alii*, 2012).

SfM software typically falls into one of the two following categories: commercially available software, for which the workflow is more simplified but the software is a *black box*; open source software, for which the workflow is more complex. One of the main commercial software used for research in the field of geoscience and archeology is represented by Agisoft PhotoScan, available in the Standard and Professional editions. The Professional Edition is better for SfM technical applications in geology, as it allows using GCPs and the export of DEM and georeferenced orthophotomosaic. Although the Agisoft software is a sort of black box, it is based on the SIFT algorithm used in open source software (Verhoeven, 2011). The processing of the aerial photographs through the Agisoft PhotoScan Professional software includes the following main steps: loading photos; inspecting loaded images, removing unnecessary images, aligning photos, building dense point cloud, building mesh (3D polygonal model), generating texture, building tiled model, generating DEM, generating orthophotomosaic, exporting results.

RADGYRO: AN AIRCRAFT FOR MULTIPARAMETRIC SURVEY

The aircraft developed by our team, technically an aerodyne with rotary wing, called RadGyro, is a single prototype able to fly with more than 100 kg of scientific payload, totally independent from the operator during the acquisition phase.

The crew is reduced to a minimum and consists, in addition to the pilot, in two-three technicians on the ground in relation to the type of survey to be carried out. In only one flight day it is possible to survey up to 400 linear kilometers, with the possibility of taking off from any flight camp. The RadGyro turns out to be an agile, economical and safe vehicle. It allows flying at low altitude and at extremely low speed (less than 50 km/h in some cases). At the same time, it allows to execute complex flight plans, sometimes necessary for high-resolution survey in mountainous areas.The scientific payload (Fig. 2) can be subdivided into the main and the ancillary instrumentation. These instrumentations, thanks to their complete independence, may be used in relation to the target of interest.

The main sensors allow to survey the territory under different ranges of sensitivity in respect to the electromagnetic spectrum. In addition to cameras acquiring in visible spectrum (showed in this research paper), on board are installed (and are currently being optimized) additional systems capable of operating in the wavelengths of thermal infrared (7500-13000 nm), near infrared (by an hyperspectral scanner 400-1000 nm) and gamma rays (by AGRS system) (Fig. 3).

The photogrammetric system, based on a pair of digital cameras synchronized by 2.4 GHz radio frequency, is of fundamental importance for the three-dimensional modeling of the marble extraction sites of the Apuan Alps. The cameras are equipped with full-frame sensors in a mirror-less body, with the aim of maximizing the reliability by reducing to a minimum the mechanical moving parts, which would be extremely stressed during very complex flights. The cameras are combined with two high-quality lenses with a fixed focal length of about 35 mm.

The ancillary sensors provide information about the position of the aircraft in space and are of great use to the geometrically reconstruction of the models. Five GPS antennas in three different sub-systems and an inertial station (INS) allow to associate to each frame its spatial position (GPS WGS84 coordinates) and attitude (3D angular setting in terms of roll, pith and yaw). A radar system, combined with a barometer and a thermometer, allows to record the flight altitude (AGL) so as to compensate for any GPS signal cycle slip.

PHOTOGRAMMETRIC SUB-SYSTEM

Hardware

In detail, the photogrammetric sub-system uses a pair of commercial mirror-less Sony A7 digital cameras, equipped with a CMOS (Complementary Metal-Oxide Semiconductor) sensor with a diagonal length of about 35 mm composed by 24 million

Fig. 2 - Radgyro and the scientific payload during a ground phase

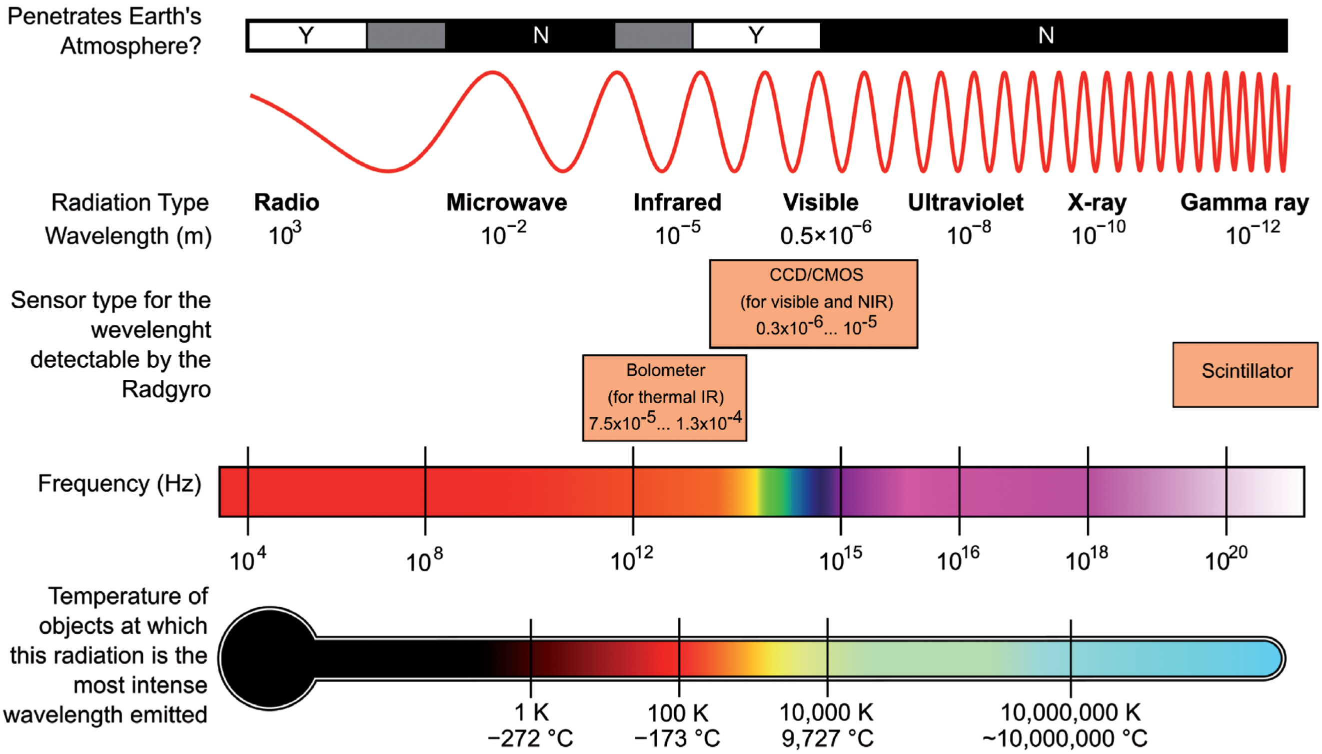

Fig. 3 - Wavelengths detectable by the sensors mounted on the RadGyro

pixels. This sensor, coupled to a Zeiss 35mm lens, is able to acquire frames with extremely high resolution, while maintaining a strong incisiveness also in the edges. The flight plan is executed in security-conditions thanks to the redundancy of the shots (the two cameras are in fact independent but synchronized) and the possibility of use an acquisition interval of only 1 Hz.

The system is appropriately pre-calibrated in order to obtain the maximum internal orientation accuracy.

The cameras are placed in aerodynamic pods located in the sides of RadGyro; in the same pods the inertial system is also positioned and fixed to steel brackets solidal to the cameras and to the main structure of the aircraft (Fig. 4)

The frame storage takes place directly in the internal memory card. This distinctive feature, along with the redundancy, provides a high safety factor relatively to the completion of the survey, even in case of complete collapse of the airborne computer system and part of the on board stabilized power supply.

Software

During the acquisition phase, the inertial system is driven by a software (MT Manager, xSense) able to record a database with data related to the various elementary sensors that make up the system (gyroscopes, magnetometers, accelerometers), in addition to the position information recorded by the integrated GPS. The software, in post-processing, is able to export a high-frequency inertial data in an ASCII file by applying suitable filtering to data to make them usable for the photogrammetric workflow (Fig. 5).

Based on the “time” variable, this information is synchronized with the images, while, simultaneously, the same information is used to populate a database that for each second shows the name of the frame according to the “aaammgghhmmss_DX/SX[1]” nomenclature, relative frame coordinates, camera positions and

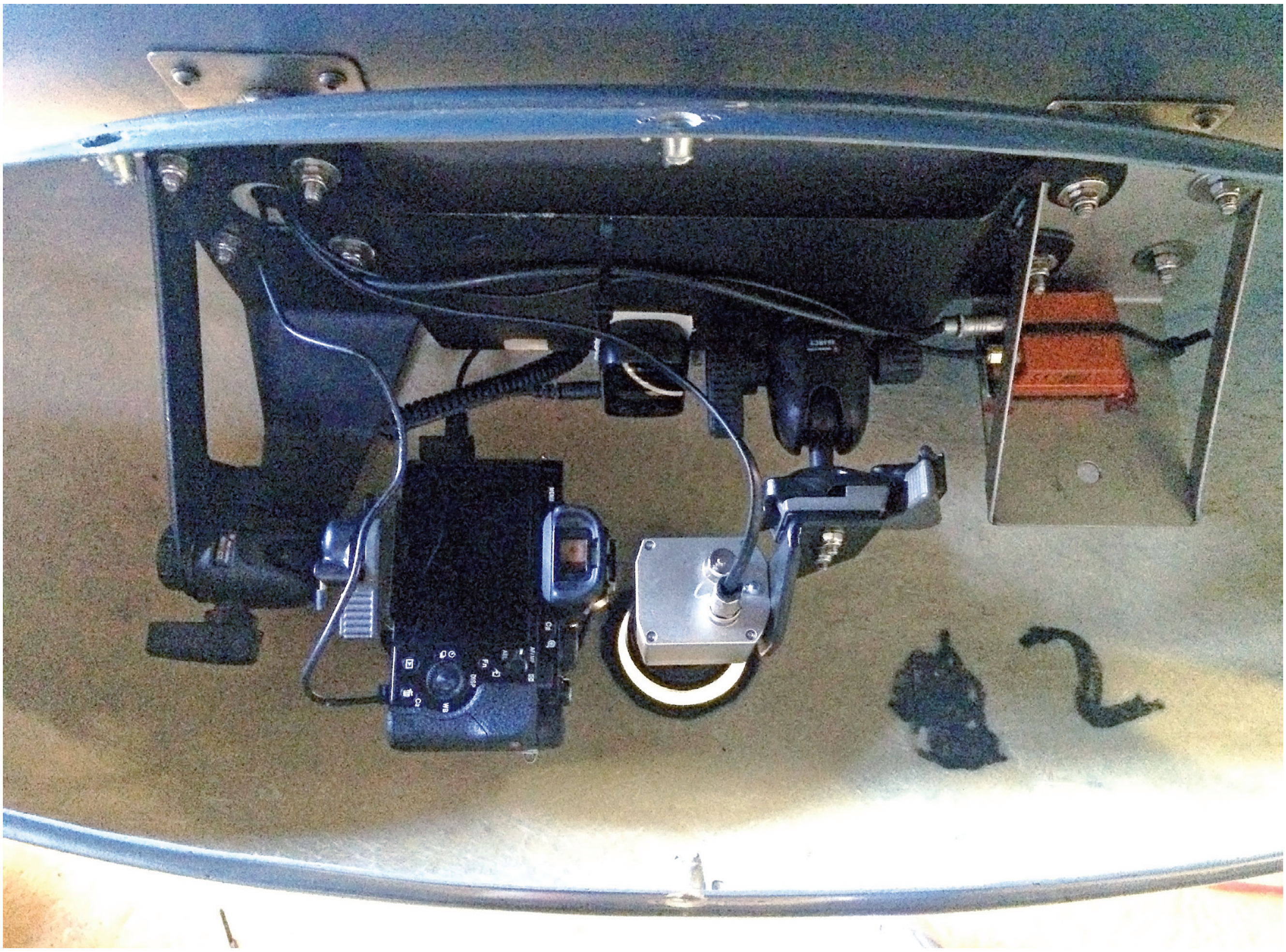

Fig. 4 - Photographic detail of the lateral pod with sensors: thermal camera (center), photogrammetric camera sensor (left)and inertial system (right)

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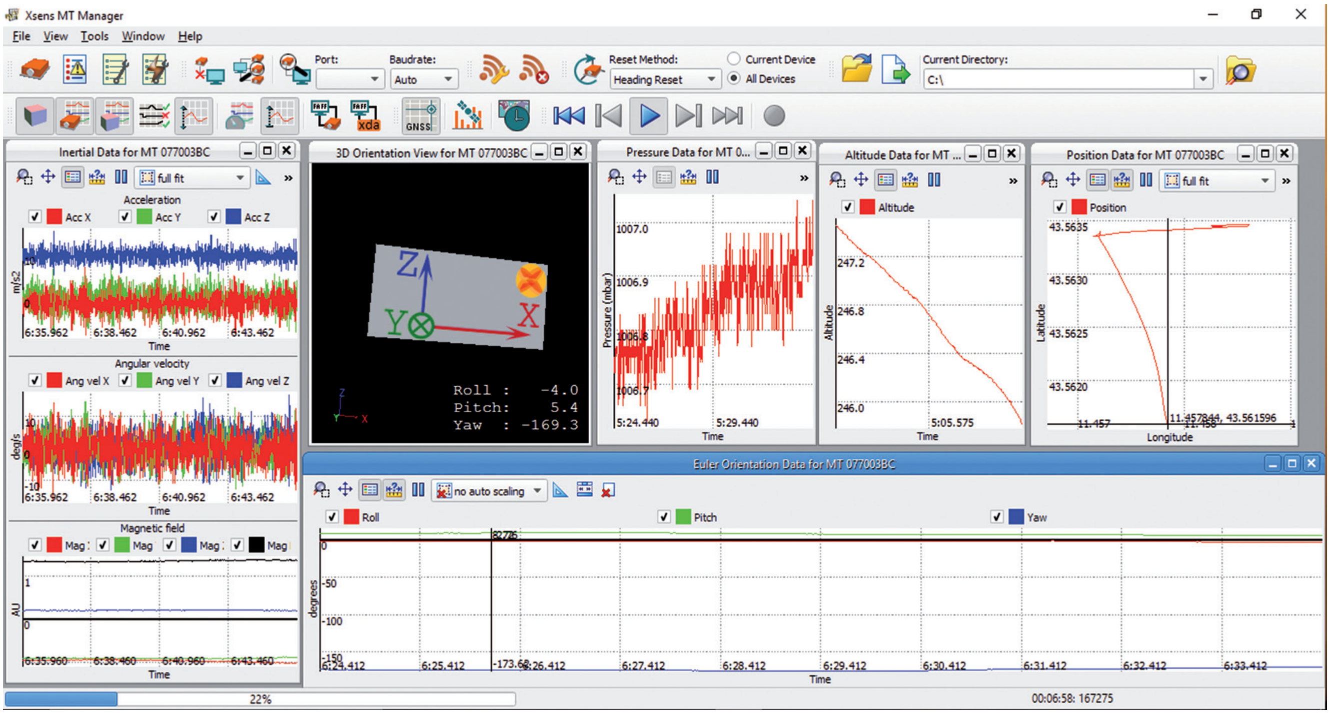
[1] *The frames are renamed by day and date format, plus a suffix for identifying the cameras. Ex: a shot acquired with DX camera in April 12, 2015 at 13h 34m 06s is renamed as 20150412133406_DX. DX stays for right hand side, SX for left hand side*



Xsens MT Manager

Baudrate: Auto

Reset Method: Heading Reset

○ Current Device

● All Devices

Current Directory: C:\

Roll : -4.0
Pitch: 5.4
Yaw : -169.3

22%

00:06:58: 167275

Fig. 5 - Screenshot of the software used for control and processing of data from the inertial navigation system

angular variations. The database is exportable to GIS (Geographic Information System) and WebGIS software in order to view the true path followed by the aircraft during the fly and all the acquired photos.

Then, all the frames and the ASCII files generated from the database are imported into photogrammetry software such as Agisoft PhotoScan Professional for processing and 3D point clouds, DEMs and orthophotomosaic production.

THE PHOTOGRAMMETRIC AIRBORNE SURVEY

Two different approaches are applied for the test areas described in this paper: a traditional flight plan with parallel strips and, for the most morphologically complex areas, a non-geometrically rigorous flights in which the sensitivity of the pilot has been entrusted to complete the acquisition. The path is created in vector format in a way that the pilot is able to follow the flight plan and cover the areas of interest through an aeronautical navigator.

While the classic photogrammetric approach with parallel strips (Fig. 6a) has not presented particular difficulties during processing, the "non-rigorous" approach (Fig. 6b) needed some measures such as the increase of overlapping scenes. This redundancy helped to limit the risk of any holes in the 3D model due to the imperfect nadirality of the cameras and for the not equal distance between adjacent passes (although we provided indicative values to the pilot, in this case we cannot call them strips).

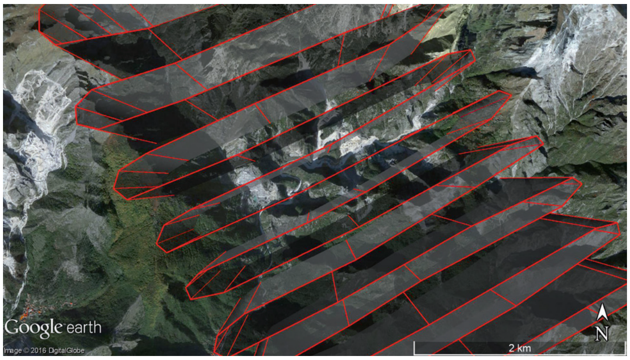


Fig. 6a - Standard photogrammetric test area with parallel strips

Fig. 6b - Test area of "non-rigorous" flight paths

Camera characteristics of SONY A7	
Length of the sensor (X)	*35.8 mm*
Length of the sensor (Y)	*23.9 mm*
# pixels (X)	*6024*
# pixels (Y)	*4024*
Pixel Size	*5.9 µm*
Uncalibrated Focal Lenght	*35 mm*

Tab. 1 - SONY A7 digital camera characteristics

In the following tables we present the information related to the sensor (Tab. 1), together with the designed flight parameters and the theoretical resolutions expected for the test areas. Table 2 shows the information associated to the factual path followed by the pilot.

The planned flights allowed acquiring a dataset of more than ten thousand frames, that underwent automatic and manual selection in order to thin up the dataset to several thousand images. Furthermore, the frames involved in the reconstruction of the final 3D model are only those of the left hand side digital camera (according to the aircraft direction of flight).

FRAME PROCESSING AND PRODUCTS VISUALIZATION

The selected frames, used in the reconstruction of the test areas, for the creation of DEMs and orthophotos, leading to achieve different resolutions and accuracy depending on the survey parameters, the source of CGPs (from cartography or topographic survey) and processing parameters (strongly influenced by computing power available). The processing parameters adopted in this work and their qualitative and

PARAMETERS	**Area ID**				
	#1	**#2**	**#3**	**#4**	**#5**
Expected flight lenght*	-	~90 km	-	-	-
Expected ground coverage	~12 sqkm	~13.75 sqkm	~ 9.5 sqkm	~0.45 sqkm	~0.45 sqkm
AGL calculated height	400 m	400 m	400 m	150 m	150 m
Calculated distance of shots**	109 m	109 m	109 m	46 m	46 m
Calculated distance of flight strips**	204 m	204 m	204 m	77 m	77 m
Calculated distance of shots **	3.9 sec	3.9 sec	3.9 sec	1.6 sec	1.6 sec
Aircraft velocity	100 km/h	100 km/h	100 km/h	90 km/h	90 km/h
GSD	6.7 cm	6.7 cm	6.7 cm	2.5 cm	2.5 cm
Frame scale	~1:11500	~1:11500	~1:11500	~1:4300	~1:4300
Expected survey geometry**	NR (*Non-rigorous"*)	SPS (*Standard Photogrammetry Strips)*	NR	-	-
Real survey geometry ***	NR	SPS (90° compared to planned)	NR (more take-off to complete)	NR	NR

The information refers to sidelap and overlap of respectively 50% and 60%.

* The flight lenght is shown only on the standard photogrammetric plan, given the impossibility of a priori knowledge of the linear km of non-stringent flights.

** Data refer to the calculated minimum parameters; thanks to the system characteristics, it was possible to acquire the images in a safely way bringing to 1hz the shooting frequency and approximating by defect the other parameters.

*** Notes of the areas #2 and #3 refer to the actions of contrasting for the changing metereological conditions, typical of the test areas.

Tab. 2 - Planned flight parameters and theoretical spatial resolutions expected for the test areas

Parameters	Area ID				
	#1	#2	#3	#4	#5
Real survey geometry	NR	SPS (90° compared to planned)	NR (more take-off to complete)	NR	NR
GCP from topographic survey	Not	N	N	Yes	Y
GCP number	/	/	/	24	27
Number of images	4400	2280	4600	156	205
Average flight altitude	230 m	650 m	340 m	443 m	140 m
GSD	4 cm	10 cm	5 cm	2 cm	1.8 cm
Coverage area	10 sqkm	26 sqkm	20 sqkm	0.44 sqkm	0.43 sqkm
Alignment accuracy	High	High	High	High	High
Average camera position error	32 m	47 m	27 m	16 m	16 m
GCP error	/	/	/	0.096 m	0.10 m
Point cloud quality	Low	Medium	Low	Medium	Medium
Point cloud density	280 millions of points	70 millions of points	180 millions of points	50 millions of points	40 millions of points
DEM resolution	0.30 m	0.80 m	0.40 m	0.10 m	0.10 m
Orthophotomosaic spatial resolution	0.1 m	0.1 m	0.1 m	0.10 m	0.10 m

Tab. 3 - Photogrammetric processing parameters and results

quantitative results are summarized in the Table 3.

The acquired data are then imported and processed within the Agisoft PhotoScan software that, through the identification of hundreds or thousands of tie points, is used to align the images and thus to solve the interior and exterior orientation of frames. In this stage it is also possible to associate to each frame the coordinates and attitudes of camera centers of acquisition that were recorded during the flight: this data allows to georeference the entire photogrammetric model with low accuracies typical of GPS receivers operating in single frequency as the ones mounted on the aircraft INS.

Nevertheless, the accuracy of the model can be improved by utilizing a sufficient number of well-spatially distributed GCPs recognizable in the photographs and measured on-site through topographic instruments (GPS and/or Total Station). Some of these points from field measurements can be used as Check Points for testing the accuracy of the model.

The 3D alignment of photos is followed by the extraction of a dense cloud constituted by tens of millions of points. DEM is produced from this cloud and high-resolution orthophotomosaics are created. The creation of the dense point cloud involves a considerable amount of hardware resources, especially when thousands of photos are processed: in the absence of enormous computing power, it is necessary a considerable lowering of the resolution of the dense cloud.

Orthophotos and DEM are used to visualize the 3D model within ESRI ArcGIS Pro software, at the moment the only software tested for coupling the digital model of the terrain, the orthoimages and the geologic data derived from the fieldwork. This code can be used for the 3D restitution and the geological photo-interpretation of the natural territory and quarries; in fact, in the 3D models it is possible to characterize with high detail the main geologic features, both of ductile and brittle origin like faults, folds and lithological boundaries, with the benefit of a three-dimensional visualization form several points of view.

The restituted data, being geo-referenced, can be inserted in a topographic and/or structural-geological map. Moreover, it is possible to upload in a 2D window geological maps, topographic maps, aerial and/or satellite high-resolution images, infrared images, while in a 3D window can be load the DEM on which it is possible to "drape" the different types of georeferenced images loaded in 2D window. From the direct comparison between two-dimensional and three-dimensional views, it is possible to edit and draw lines or polygons, improving, in many cases, the accuracy and reliability of the geological photo-interpreted data.

CONSIDERATIONS ON THE ACHIEVED RESULTS AND FUTURE DEVELOPMENTS

Acquired data and reconstructed 3D models show how SfM algorithms, implemented in commercial software, are today optimal in the photogrammetric reconstruction of extremely morphologically complex areas typical of mining basins like the marble quarries of the Apuan Alps in Italy. The complete coverage of the areas of interest was guaranteed in this work by the use of RadGyro thanks to its ability of flying at low altitudes with extreme agility, even following complex flight plan lines (impossible with a normal airplane and at prohibitive costs using helicopters).

The SfM algorithms allowed taking advantage of the characteristics of the aircraft. When the standard photogrammetric flight plan did not have the chance to be executed, and a not rigorous flight plan was performed, the ability of these algorithms to extract millions of tie points from "pseudo-random" frames, using computer vision techniques, allowed to execute the exterior orientation even in impossible conditions for the classical photogrammetric stations that require, without the certainty of success, the operator manual intervention.

The quality of the result is proved by the sub-metric resolutions obtained in the extraction of digital elevation models from the 3D point clouds and the creation of orthophotos with centimeter and decimeter spatial resolution.

The mean square error calculated on the GCP coordinates, as well as the error calculated on the camera positions provided as input data, can be used as a preliminary quantitative index of data quality. In particular, the latter show errors with magnitude comparable to the accuracy of the instrument used to acquired their coordinates; the error on the absolute geo-referencing of camera positions lies between 15 and 50 m, which is the order of magnitude that can be expectable from a single GPS antenna, low cost and single frequency, without using info from topographic survey. The absolute geo-referencing error decreases dramatically in areas with GCP detected by topographical GPS survey, where the mean square error on GCPs decreases until the decimeter. These results can give a first positive response to the question on the reliability of the workflow followed for the reconstruction of areas with complex morphology. The reliability of outputs is confirmed also by the qualitative inspection, resulting in a satisfactory internal reconstruction of the model, in compliance with the real geometries and the overall readability of the orthorectified images. Importantly, in the case of applications where high accuracy in absolute georeferencing is required, it is necessary to executed a topographic fieldwork for the acquisition of GCPs; the topographic survey can be estimated in few working days for surfaces with extension comparable to the presented test areas.

The acquired data and the reconstructed models with this methodology can allow realizing various typology of products such as photo-interpreted maps with structural-geological contents, map of joints, etc.. The high precision of restituion and the 3D information, can allow to improve the existing geologic cartography or to plan the extractive activities to medium and long term. Another application of this methodology could be the computation of the extracted material volumes in a quarry, in a precise time spam, by applying a mathematical difference between the two high-resolution multi-temporal DEMs.

The Authors plan to increase, necessarily, the test areas and the extension of the topographic survey in such a way to obtain a sufficiently large dataset for the statistical evaluation of the different airborne surveys in different conditions and their comparison with other survey techniques. We also plan to evaluate in detail the economic sustainability of the process and the positive impact on the environmental sustainability of the extraction sites, expected from the research activity based on data acquired in these type of airborne surveys.

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