UAV for 3D mapping applications: a review

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Keywords *UAV, photogrammetry, DSM, archaeology, agriculture, emergency, urban*

Abstract Unmanned Aerial Vehicle (UAV) platforms are nowadays a valuable source of data for inspection, surveillance, mapping and 3D modeling issues. As UAVs can be considered as a low-cost alternative to the classical manned aerial photogrammetry, new applications in the short- and close-range domain are introduced. Rotary or fixed wing UAVs, capable of performing the photogrammetric data acquisition with amateur or SLR digital cameras, can fly in manual, semi-automated and autonomous modes. Following a typical photogrammetric workflow, 3D results like Digital Surface or Terrain Models (DTM/DSM), contours, textured 3D models, vector information, etc. can be produced, even on large areas. The paper reports the state of the art of UAV for Geomatics applications, giving an overview of different UAV platforms, applications and case studies, showing also the latest developments of UAV image processing. New perspectives are also addressed.

Introduction

According to the UVS (Unmanned Vehicle System) International definition, an Unmanned Aerial Vehicle (UAV) is a generic aircraft design to operate with no human pilot onboard (http://www.uvs-international.org/). The simple term UAV is used commonly in the Geomatics community, but also other terms like Drone, Remotely Piloted Vehicle (RPV), Remotely Operated Aircraft (ROA), Micro Aerial Vehicles (MAV), Unmanned Combat Air Vehicle (UCAV), Small UAV (SUAV), Low Altitude Deep Penetration (LADP) UAV, Low Altitude Long Endurance (LALE) UAV, Medium Altitude Long Endurance (MALE) UAV, Remote Controlled (RC) Helicopter and Model Helicopter are often used, according to their propulsion system, altitude/endurance and the level of automation in the flight execution. The term UAS (Unmanned Aerial System) comprehends the whole system composed by the aerial vehicle/platform (UAV) and the Ground Control Station (GCS). [Sanna and Pralio, 2005] defines UAVs as Uninhabited Air Vehicles while [Von Blyenburg, 1999] defines UAVs as uninhabited and reusable motorized aerial vehicles.

In the past, the development of UAV systems and platforms was primarily motivated by military goals and applications. Unmanned inspection, surveillance, reconnaissance and mapping of inimical areas were the primary military aims. For Geomatics applications, the first experience was carried out three decades ago but only recently UAVs in the Geomatics field became a common platform for data acquisition. UAV photogrammetry (Colomina et al., 2008; Eisenbeiss, 2009) indeed opens various new applications in the close-range aerial domain, introducing a low-cost alternative to the classical manned aerial photogrammetry for large-scale topographic mapping or detailed 3D recording of ground information and being a valid complementary solution to terrestrial acquisitions (Fig.1). The latest UAV success and developments can be explained by the spreading of low-cost platforms combined with amateur or SRL digital cameras and GNSS/INS systems, necessary to navigate the platforms, predict the acquisition points and possibly perform direct geo-referencing. Although conventional airborne remote sensing has still some advantages and the tremendous improvements of very high-resolution satellite imagery are closing the gap between airborne and satellite mapping applications, UAV platforms are a very important alternative and solution for studying and exploring our environment, in particular for heritage locations or rapid response applications. Private companies are now investing and offering photogrammetric products (mainly DSM - and orthoimages) from UAV-based aerial images as the possibility of using flying unmanned platforms with variable dimensions, small weight and high ground resolution allow to carry out flight operations at lower costs compared to the ones required by traditional aircrafts. Problems and limitations are still existing, but UAVs are a really capable source of imaging data for a large variety of applications.

The paper reviews the most common UAV systems and applications in the Geomatics field, highlighting open problems and research issues related to regulations and data processing. The entire photogrammetric processing workflow is also reported with different examples and critical remarks.

UAV Platforms

The primary airframe types are fixed and rotary wings while the most common launch/take-off methods are, beside the autonomous mode, air-, hand-, car/track-, canister- or bungee cord launched. A typical UAV platform for Geomatics purposes can cost from 1000 Euro up to 50000 Euro, depending on the on-board instrumentation, payload, flight autonomy, type of platform and degree of automation needed for its specific applications. Low-cost solutions are not usually able to perform autonomous flights, but they always require human assistance in the take-off and landing phases. Low-cost and open-source platforms and toolkits were presented in [Bendea et al., 2008; Grenzdörffer et al., 2008; Meier et al., 2011; Neitzel et al., 2011; Stempfhuber et al., 2011]. Simple and hand-launched UAVs which perform flights autonomously using MEMS-based (Micro Electro-Mechanical Systems) or C/A code GPS for the auto-pilot are the most inexpensive systems (Vallet et al., 2011) although stability in case of windy areas might be a problem.

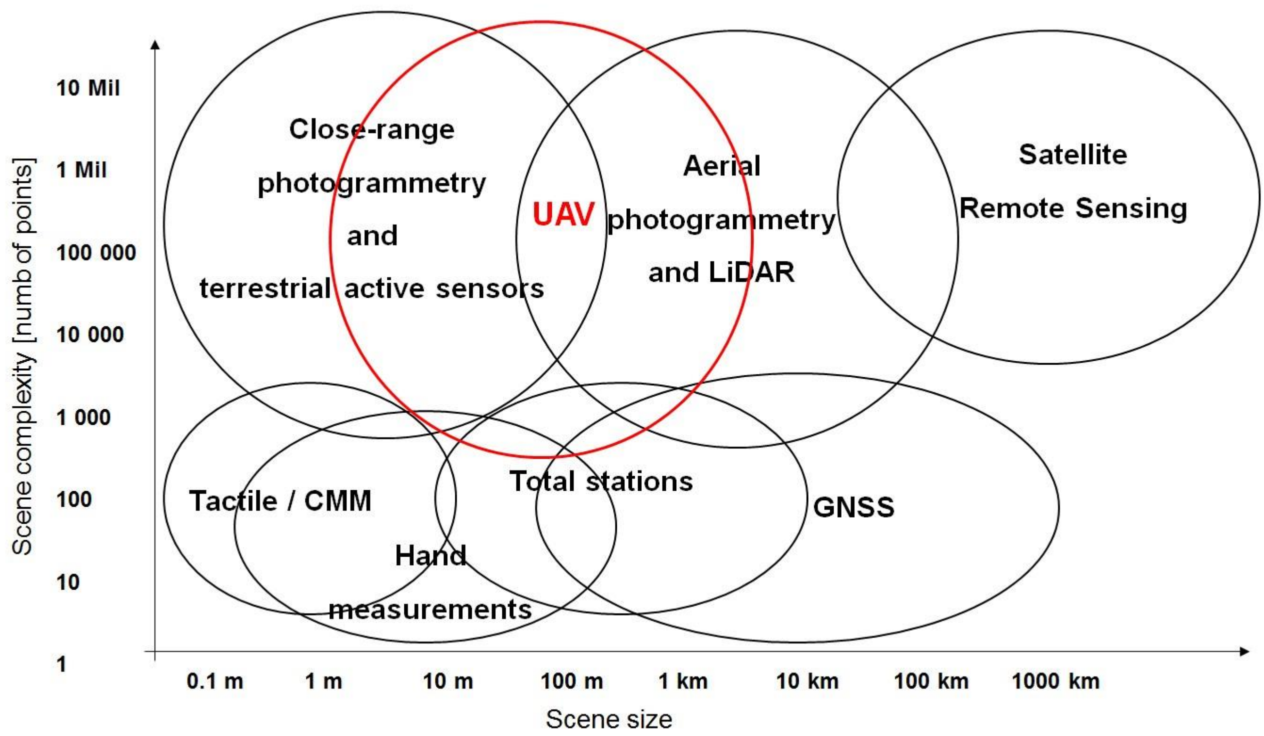

Fig. 1 Available Geomatics techniques, sensors and platforms for 3D recording purposes, according to the scene' dimensions and complexity.

More bigger and stable systems, generally based on an Internal Combustion Engine (ICE), have longer endurance with respect to electric engine UAVs and, thanks to the higher payload, they allow medium format (reflex) camera or LiDAR or SAR instruments on-board (Nagai et al., 2004; Vierling et al., 2006; Wang et al., 2009; Berni et al, 2009; Kohoutek and Eisenbeiss, 2012; Grenzdoffer et al. 2012).

The developments and improvements at hardware and platform levels are done in the robotics, aeronautical and optical communities where breakthrough solutions are sought in order to miniaturize the optical systems, enhance the payload, achieve complete autonomous navigation and improve the flying performances (Huckridge and Ebert, 2008; Schafroth et al. 2009). Researches are also performed studies on flying invertebrates to understand their movement capabilities, obstacle avoidance or autonomous landing/takeoff capabilities (Franceschini et al. 2007; Moore et al., 2008). Based on size, weight, endurance, range and flying altitude, UVS International defines three main categories of UAVs:

- *Tactical UAVs* which include micro, mini, close-, short-, medium-range, medium-range endurance, low altitude deep penetration, low altitude long endurance, medium altitude long endurance systems. The mass varies from few kg up to 1,000 kg, the range from few km up to 500 km, the flight altitude from few hundreds meter to 5 km and the endurance from some minutes to 2-3 days.
- *Strategical UAVs*, including high altitude long endurance, stratospheric and exo-stratospheric systems which fly higher than 20,000 m altitude and have an endurance of 2-4 days.
- *Special tasks UAVs* like unmanned combat autonomous vehicles, lethal and decoys systems.

UAVs for Geomatics applications can be shortly classified according their engine/propulsion system in:

- unpowered platforms, e.g. balloon, kite, glider, paraglide;
- powered platforms, e.g. airship, glider, propeller, electric, combustion engine.

Alternatively, they could be classified according to the aerodynamic and “physical” features as:

- lighter-than-air, e.g. balloon, airship;
- rotary wing, either electric or with combustion engine, e.g. single-rotor, coaxial, quadrocopter, multi-rotor;
- fixed wing, either unpowered, electric or with internal combustion engine (ICE), e.g. glider or high wing.

Table 1. Evaluation of some UAV platforms employed for Geomatics applications, according to the literature and the authors' experience. The evaluation is from 1 (low) to 5 (high).

	Kite / Balloon	Fixed Wing		Rotary wings	
		electric	ICE engine	electric	ICE engine
Payload	3	3	4	2	4
Wind resistance	4	2	3	2	4
Minimum speed	4	2	2	4	4
Flying autonomy	-	3	5	2	4
Portability	3	2	2	3	3
Landing distance	4	3	2	4	4

In table 1, pros and cons of different UAV typologies are presented, according to the literature review and the authors' experience: rotor and fixed wing UAVs are compared to more traditional aerial low-cost kite and balloons.

UAV applications in Geomatics

Some UAVs civilian applications are mentioned in [Niranjan et al. 2007] while [Everaerts, 2008] reports on UAV projects, regulations, classifications and application in the mapping domain. The application fields where UAVs images and photogrammetrically derived DSM or orthoimages are generally employed include:

- Agriculture: producers can take reliable decisions to save money and time (e.g. precision farming), get quick and accurate record of damages or identify potential problems in the field (Newcombe, 2007).
- Forestry: assessments of woodlots, fires surveillance, vegetation monitoring, species identification, volume computation as well as silviculture can be accurately performed (Grenzdörffer, 2008; Martinez et al., 2006; Réstas, 2006; Berni et al., 2009).
- Archaeology and architecture: 3D surveying and mapping of sites and man-made structures can be performed with low-altitude image-based approaches (Çabuk, et al.,2007; Lambers et al., 2007; Oczipka et al., 2009; Verhoeven, 2009; Chiabrando et al., 2011; Rinaudo et al., 2012).
- Environment: quick and cheap regular flights allow the monitoring of land and water at multiple epochs (Thamm and Judex, 2006; Niethammer et al., 2010), road mapping (Zhang, 2008), cadastral mapping (Manyoky et al., 2011), thermal analyses (Hartmann et al., 2012), excavation

volume computation, volcano monitoring (Smith et al., 2009), coastline monitoting or natural resources documentations for geological analyses are also feasible.

- Emergency management: UAV are able to quickly acquire images for the early impact assessment and the rescue planning (Chou et al., 2010; Haarbrink and Koers, 2006; Molina et al., 2012). The flight can be performed over contaminated areas without any danger for operators or any long pre-flight operations.
- Traffic monitoring: surveillance, travel time estimation, trajectories, lane occupancies and incidence response are the most required information (Puri et al., 2007).

UAV images are also often used in combination with terrestrial surveying in order to close possible 3D modeling gaps and create orthoimages (Pueschel et al., 2008; Remondino et al., 2009). UAVs can be adopted for industrial applications too (i.e. air pollution monitoring, surveillance, surveying, etc.).

Historical framework and regulations

UAVs were originally developed for military applications, with flight recognition in enemy areas, without any risk for human pilots. The first experiences for civil and Geomatics applications were carried out at the end of the 70's (Przybilla et al, 1979) and their use greatly increased in the last decades thanks to the fast improvement of platforms, communication technologies and software as well as the growing number of possible applications. Thus the use of such flying platforms in civil applications imposed to increase the security of UAV flights in order to avoid dangers for human beings. The international community started to define the security criteria for UAV some years ago. In particular, NATO and EuroControl started their cooperation in 1999 in order to prepare regulations for UAV platforms and flights. This work did not lead to a common and international standard yet, especially for civil applications. But the great diffusion and commercialization of new UAV systems has pushed several national and international associations to analyse the operational safety of UAVs. Each country has one or more authorities involved in the UAV regulations, that operates independently. Due to the absence (at least in the past) of a cooperation between all these authorities, it is difficult to describe the specific aims of each of them without loss of generality. In table 2, a schematic summary of the already existing regulations in several countries is presented.

The elements of UAV regulations are mainly keen to increase the reliability of the platforms, underlining the need for safety certifications for each platform and ensuring the public safety. As they are conditioned by technical developments and safety standards, rules and certifications should be set equal to those currently applied to comparable manned aircraft, although the most important issue, being UAVs unmanned, it is the citizens security in case of an impact.

UAVs have currently different safety levels according to their dimension, weight and on board technology. For this reason, the rules applicable to each UAV could not be the same for all the platforms and categories. For example, in U.S., the safety is defined according to their use (public or civic), in some European countries according to the weight, as this parameter is directly connected to the damage they can produce when a crash occurs. Other restrictions are defined in terms of minimum and maximum altitude, maximum payload, area to be surveyed, GCS-vehicle connection (i.e. visual or radio), etc. The indirect control of a pilot from the GCS may lead to increased accidents due to human errors. For this reason, in several countries UAV operators need some training and qualifications.

Table 2. Regulations for UAS use in several countries.

	Regulation for civil use of UAS (laws and regulations)
Australia	CASA Circular, *Juli 2002*
Belgium	Certification Specification, Rev. 00, *24.01.07*
Canada	Approach to the Classification of Unmanned Aircraft, *19.10.10*
Denmark	Regulations on unmanned aircraft not weighing more than 25 kg-, Edition 3, *09.01.04*
France	Decree concerning the design of civil aircraft fly without anyone on board, *August 2010*
Great Britain	CAP 722, *06.04.10* u. Joint Doctrin 2/11, *30.3.11*
Norway	Operation of unmanned aircraft in Norway, *29.06.09*
Sweden	Flying with UAVs in airspace involving civil aviation activity, *25.03.03*
Switzerland	Verordnung des UVEK über Luftfahrtzeuge besonderer Kategorien, *01.04.11*
Czech	Czech aviation regulation L2 - Rules of the air, *25.08.11*
USA	UAS Certification Status, 18.08.08; Fact Sheet - Unmanned Aircraft Systems, 15.7.10 und NJO7210.766, 28.3.11, 8.2.12 und FAA Bill

Anyway, in the last few months the European Community has announced the beginning of three different "Roadmaps" in the field of R&D, complementary measures and safety regulations of the UAVs. This work will define common rules at EU level with the aim of defining a full integration of UAVs in the European Aviation system. This process is collecting the contributions of many stakeholders from several EU countries and consists of several steps and deliverables. The UAV flights will be divided in different categories according to the flying height and the strategy adopted to control the platform from the GCS (i.e. visual line-of-sight, radio line-of-sight, etc.) to define different regulations and technical prescriptions. The road maps, started in 2013, will be completed in 2028. For more information refer to (http://ec.europa.eu/enterprise/sectors/aerospace/uas/).

UAV data acquisition and processing

A typical image-based aerial surveying with an UAV platform requires a flight or mission planning and GCPs (Ground Control Points) measurement (if not already available) for geo-referencing purposes. After the acquisitions, images can be used for stitching and mosaicking purposes (Neitzel and Klonowski, 2009), or they can be the input of the photogrammetric process. In this case, camera calibration and image triangulation are initially performed, in order to generate successively a Digital Surface Model (DSM) or Digital Terrain Model (DTM). These products can be finally used for the production of ortho-images, 3D modelling applications or for the extraction of further metric information. In Fig. 2, the general workflow is shown: the input parameters are in green, while the single workflow steps are in yellow and they are discussed more in detail in the following sections.

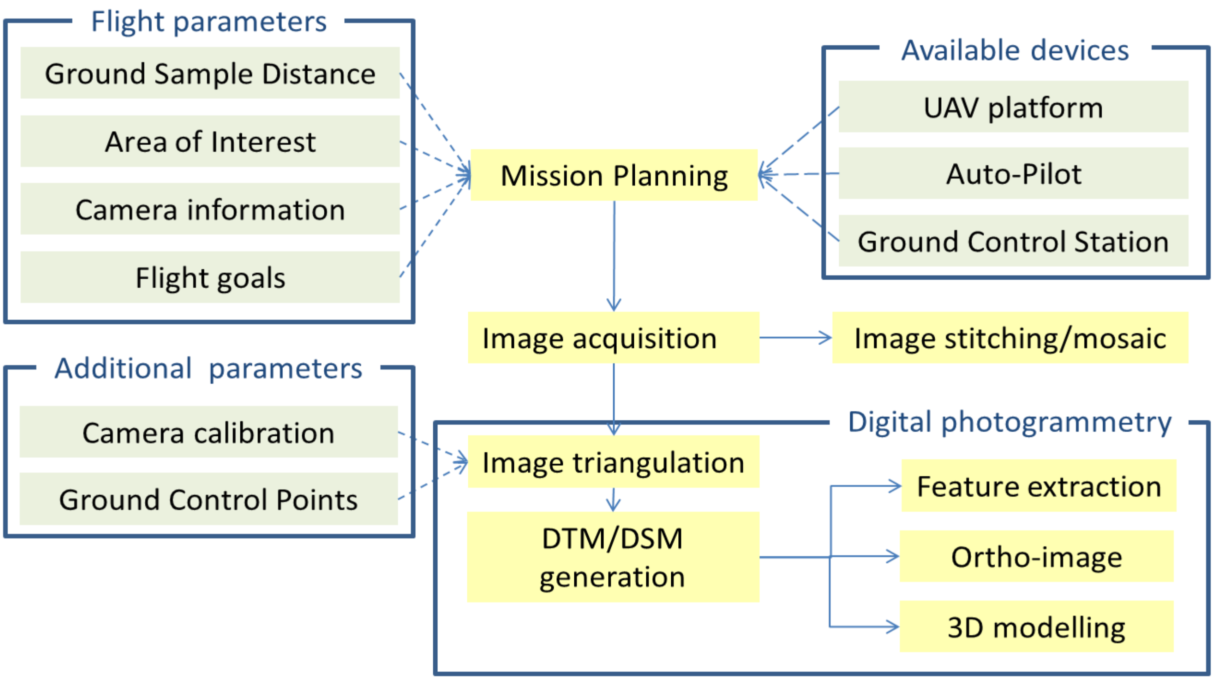

Fig. 2 Typical acquisition and processing pipeline for UAV images.

Flight planning and image acquisition

The mission (flight and data acquisition) is normally planned in the lab with dedicated software, starting from the knowledge of the area of interest (AOI), the required Ground Sample Distance (GSD) or footprint and the intrinsic parameters of the on-board digital camera. The desired image scale and used camera focal length are generally fixed in order to derive the mission flying height. The camera perspective centers (“waypoints”) are computed fixing the longitudinal and transversal overlap of the strips (e.g. 80%-60%). All these parameters vary according to the goal of the flight: missions for detailed 3D model generation usually request high overlaps and low altitude flights to achieve small GSDs, while quick flights for emergency surveying and management need wider areas to be recorded in few minutes, at a lower resolution.

The flight is normally done in manual, assisted or autonomous mode, according to the mission specifications, platform's type and environmental conditions. The presence onboard of GNSS/INS navigation devices is usually exploited for the autonomous flight (take-off, navigation and landing) and to guide the image acquisition. The image network quality is strongly influenced by the typology of the performed flight (Fig. 3): in the manual mode, the image overlap and the geometry of acquisition is usually very irregular, while the presence of GNSS/INS devices, together with a navigation system, can guide and improve the acquisition. The navigation system, generally called auto-pilot, is composed by both hardware (often in a miniaturize form) and software devices. An auto-pilot allows to perform a flight according the planning and communicate with the platform during the mission. The small size and the reduced payload of some UAV platforms is limiting the transportation of high quality navigation devices like those coupled to airborne cameras or LiDAR sensors. The cheapest solution relies on MEMS-based inertial sensors which feature a very reduced weight but accuracy not sufficient, to our knowledge, for direct geo-referencing (DeAgostino et al., 2010; Piras et al., 2010). More advanced and expensive sensors, maybe based on single/double frequency positioning mode or the use of RTK would improve the quality of positioning to a decimetre level, but they are still too expensive to be commonly used on low-cost solutions. During the flight, the autonomous platform is normally observed with a Ground Control Station (GCS) which shows real-time flight data such as position, speed, attitude and distances, GNSS observations, battery or fuel status, rotor speed, etc. On the opposite, remotely controlled systems are piloted by operator from the ground station. Most of the systems allow then image data acquisition following the computed waypoints while low-cost systems acquire images with a scheduled interval. The used devices (platform, auto-pilot and GCS) are fundamental for the quality and reliability of the final result: low-cost instruments can be sufficient for little extensions and low altitude flights, while more expensive devices must be used for long endurance flights over wide areas. Generally, in case of light weight and low-cost platforms, a regular overlap in the image block cannot be assured as there are strongly influenced by the presence of wind, piloting capabilities and GNSS/INS quality, all randomly affecting the attitude and location of the platforms during the flight. Thus higher overlaps, with respect to flights performed with manned vehicles or very expensive UAVs, are usually recommended to keep in count these problems.

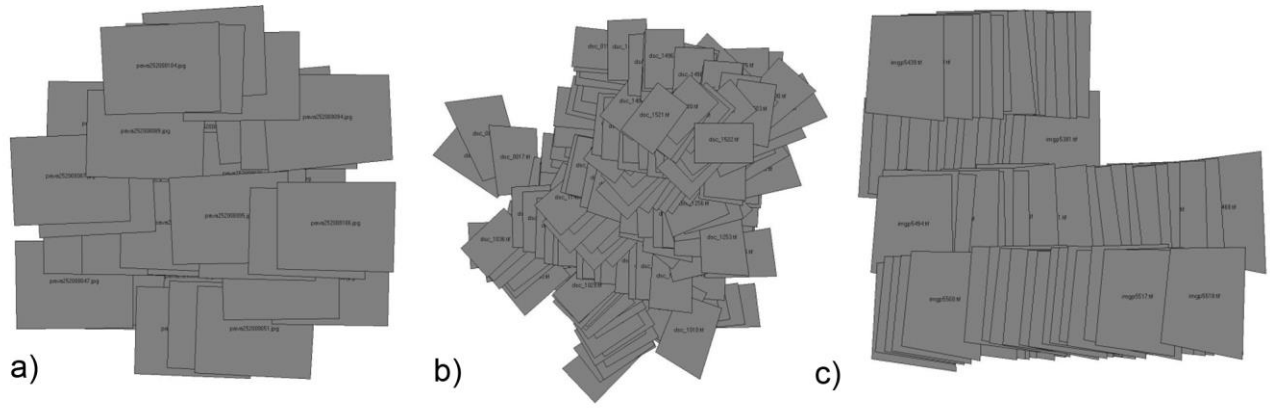

Fig. 3 Different modalities of the flight execution delivering different image block's quality: a) manual mode and image acquisition with a scheduled interval; b) low-cost navigation system with possible waypoints but irregular image overlap; c) automated flying and acquisition mode achieved with a high quality navigation system.

Camera calibration and image orientation

Camera calibration and image orientation are two fundamental prerequisites for any metric reconstruction from images. In metrological applications, the separation of both tasks in two different steps should be preferred (Remondino and Fraser, 2006). Indeed, they require different block geometries, which can be better optimized if they are treated in separated stages. On the other hand, in many applications where lower accuracy is required, calibration and orientation can be computed at the same time by solving a self-calibrating bundle adjustment. In case of aerial cameras, the camera calibration is generally performed in the lab although in-flight calibration are also performed (Colomina et al., 2007), possibly with strips at different flying heights. Camera calibration and image orientation tasks require the extraction of common features visible in as many images as possible (tie points) followed by a bundle adjustment, i.e. a non-linear optimization procedure in order to minimize an appropriate cost function (Brown, 1976; Triggs et al., 2000; Gruen and Beyer, 2001). Procedure based on the manual identification of tie points by an expert operator or based on signalized coded markers are well assessed and used today. Recently fully automated procedures for the extraction of a consistent and redundant sets of tie points from markerless close-range images have been developed for photogrammetric applications (Barazzetti et al., 2011; Pierrot-Deseilligny and Clery, 2011). Some efficient commercial solutions have also appeared on the market (e.g. PhotoModeler Scanner, Eos Inc; PhotoScan, Agisoft) while commercial software for aerial applications still need some user interaction or the availability of GNSS/INS data for automated tie points extraction. In Computer Vision, the simultaneous determination of camera (interior and exterior) parameters and 3D structure is normally called "Structure from Motion" (Hartley and Zisserman, 2004; Snavely et al., 2008; Robertson and Cipolla, 2009). Some free web-based approaches (e.g. Photosynth, 123DCatch, etc.) and open source solutions (VisualSfM (Wu, 2011) Bundler (Snavely et al., 2007), etc.) are also available although generally not reliable and accurate enough in case of large and complex image blocks with variable baselines and image scale. The employed bundle adjustment algorithm must be reliable, able to handle possible outliers and provide statistical outputs to validate the results. The collected GNSS/INS data, if available, can help for the automated tie point extraction and can allow the direct geo-referencing of the captured images. In applications with low metric quality requirements, e.g. for fast data acquisition and mapping during emergency response, the accuracy of direct GNSS/INS observation can be enough (Pfeifer et al., 2009; Zhou, 2009).

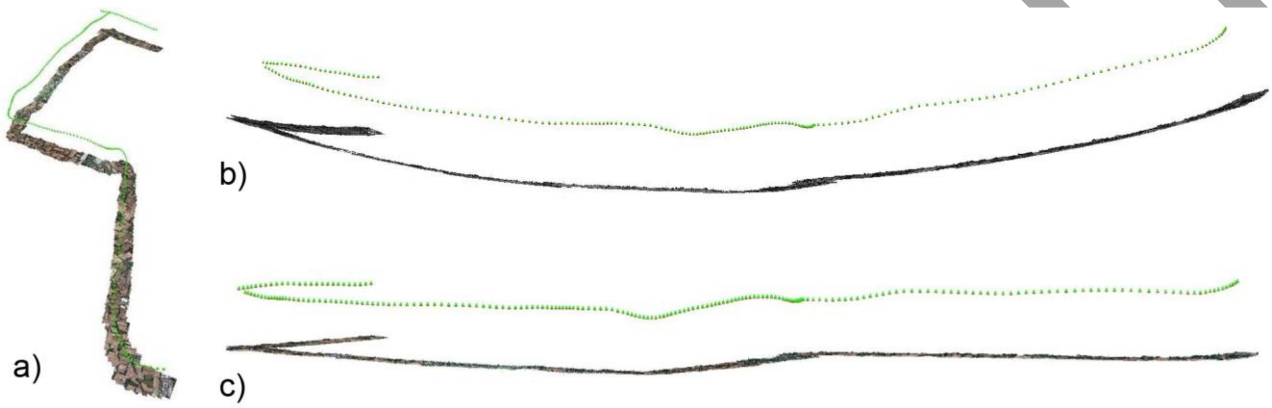

Fig. 4 Orientation results of an aerial block over a flat area of ca 2 km (a). The derived camera poses are shown in red/green, while color dots are the 3D object points on the ground. The absence of ground constraint (b) can led to a wrong solution of the computed 3D shape (i.e. ground deformation). The more rigorous approach, based on GCPs used as observations in the bundle solution (c), deliver the correct 3D shape of the surveyed scene, i.e. a flat terrain.

If the navigation positioning system cannot be directly used (even for autonomous flight) as the signal is strongly degraded or not available (downtowns, rainforest areas, etc.), the orientation phase must rely only on a pure image-based approach (Eugster, H.; Nebiker, , 2008; Wang et al., 2008; Barazzetti et al., 2010; Anai et al., 2012) thus requiring GCPs for scaling and geo-referencing. These two latter steps are very important in order to get metric results. To perform indirect geo-referencing, there are basically two ways to proceed:

1) import at least three GCPs in the bundle adjustment solution, treating them as weighted observations inside the least squares minimization. This approach is the most rigorous as (i) it minimizes the possible image block deformations and possible systematic errors, (ii) it avoids instability of the bundle solution (convergence to a wrong solution) and (iii) it helps in the determination of the correct 3D shape of the surveyed scene.

2) use a free-network approach in the bundle adjustment (Granshaw, 1980; Dermanis, 1994) and apply only at the end of the bundle a similarity (Helmert) transformation in order to bring the image

network results into a desired reference coordinate system. This approach is not rigorous: the solution is sought minimizing the trace of the covariance matrix, introducing the necessary datum with some initial approximations. As no external constraint is introduced, if the bundle solution cannot determine the right 3D shape of the surveyed scene, the successive similarity transformation (from the initial relative orientation to the external one) would not improve the result. The two approaches, in theory, are thus not equivalent and they can lead to totally different results (Fig. 4): in the first approach, the quality of the bundle is only influenced by the redundant control information and, moreover, additional check points can be used to derive some statistics of the adjustment. On the other, the second approach has no external shape constraints in the bundle adjustment thus the solution is only based on the integrity and quality of the multi-ray relative orientation. The fundamental requirement is thus to have a good image network in order to achieve correct results in terms of computed object coordinates and scene's 3D shape.

Surface reconstruction and orthoimage generation

Once a set of images has been oriented, the following steps in the 3D reconstruction and modeling workflow are the surface measurement, orthophoto creation and feature extraction. Starting from the known camera orientation parameters, a scene can be digitally reconstructed by means of interactive procedures or automated dense image matching techniques. The output is normally a sparse or a dense point cloud, describing the salient corners and features in the former case or the entire surface's shape of the surveyed scene in the latter case. Dense image matching algorithms should be able to extract dense point clouds to define the object's surface and its main geometric discontinuities.

Therefore the point density must be adaptively tuned to preserve edges and, possibly, avoid too many points in flat areas. At the same time, a correct matching result must be guaranteed also in regions with poor textures. The actual state-of-the-art is the multi-image matching technique (Seitz et al., 2006; Vu et al., 2009; Zhu et al., 2010) based on semi-global matching algorithms (Gerke et al., 2010; Hirschmüller, 2008), patch-based methods (Furukawa, 2010) or optimal flow algorithms (Pierrot-Deseilligny and Paparoditis, 2006). The last two methods has been implemented into open source packages named, respectively, PMVS and MicMac.

The derived unstructured point clouds need to be afterwards structured and interpolated, maybe simplified and finally textured for photo-realistic visualization. Dense point clouds are generally preferred in case of terrain/surface reconstruction (e.g. archaeological excavation, forestry area, etc.) while sparse clouds which are afterward turned into simple polygonal information can be preferred when modeling man-made scenes like buildings. For the creation of orthoimages, a dense point cloud is mandatory in order to achieve precise ortho-rectification and for a complete removal of terrain distortions. On the other hand, in case of low-accuracy applications (e.g. rapid response, disaster assessment, etc.) a simple image rectification method (without the need of dense image matching) can be applied followed by a stitching operation (Neitzel and Klonowski, 2011).

Case Studies

As already mentioned, images acquired flying UAV platforms give useful information for different applications, such as archaeological documentation, geological studies and monitoring, urban area modeling and monitoring, emergency assessment and so on. The typical required products are dense point clouds, polygonal models or orthoimages which are afterwards used for mapping, volume computation, displacement analyses, visualization, city modeling, map generation, etc.. In the following sections an overview of some applications is given and the achieved results are shown. The data presented in the following case studies were acquired by the authors or by some project partners and they were processed by the authors using the Apero (Pierrot-Deseilligny and Clery, 2011) and Mic-Mac (Pierrot-Deseilligny and Paparoditis, 2006) open-source tools customized for specific UAV applications.

Archaeological site 3D recoding and modeling

The availability of accurate 3D information is very important during excavation in order to define the state of works/excavations at a particular epoch or to digitally reconstruct the findings that had been discovered for documentation, digital preservation and visualization purposes. An example of such application is given in Fig. 5, where the Neptune Temple in the archaeological area of Paestum (Italy) is shown. Given the shape, complexity and dimensions of the monument, a combination of terrestrial and UAV (vertical and oblique) images was employed in order to guarantee the completeness of the 3D surveying work. The employed UAV is a 4-rotors MD4-1000 Microdrone system, entirely of carbon fibre which can carry up to 1,0 kg instruments with an endurance longer than 45 minutes. For the nadir images, the UAV mounted an Olympus E-P1 camera (12 Megapixels, 4.3 µm pixel size) with 17 mm focal length while for the oblique images it was used an Olympus XZ-1 (10 Megapixels, 2 µm pixel size) with 6 mm focal length. For both flights, the average GSD of the images is ca 3 cm. The auto-pilot system allowed to perform two complete flights in autonomous mode, but the stored coordinates of the projection centres were not sufficient for direct geo-referencing. For this reason, a set of reliable GCPs (measured with total station on corners and features of the temple) was necessary to derive scaled and geo-referenced 3D results. The orientation procedure was finally completed adding terrestrial to UAV images (ca 190) and orienting the whole dataset simultaneously in order to bring all the data in the same coordinate system. After the recovery of the camera poses, a DSM was produced for documentation and visualization purposes (Fiorillo et al., 2012).

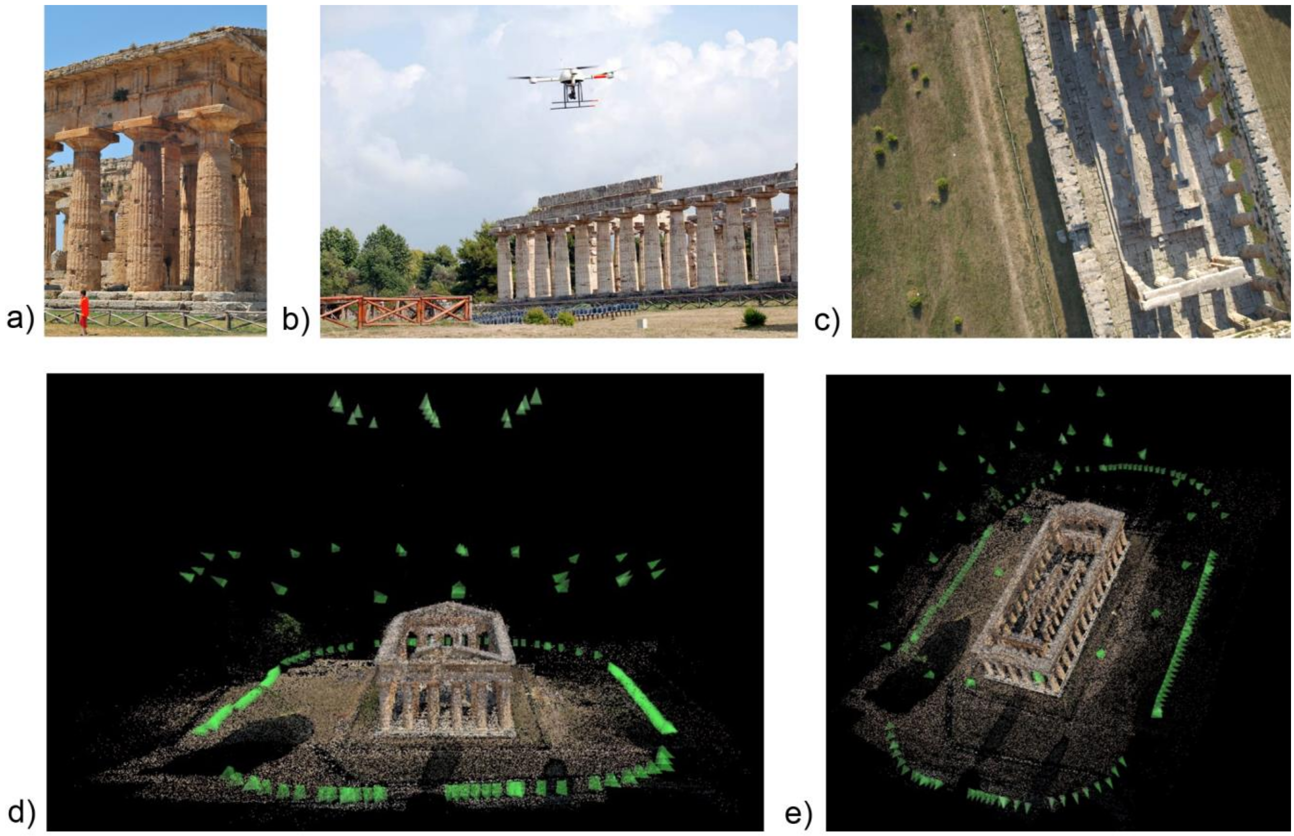

Fig. 5 Integration of terrestrial images (a) with oblique (b) and vertical (c) UAV acquisitions for the surveying and modeling of the complex Neptune temple in Paestum, Italy. The integrated adjustment for the derivation of the camera poses of all the images (d, e) in a unique reference system.

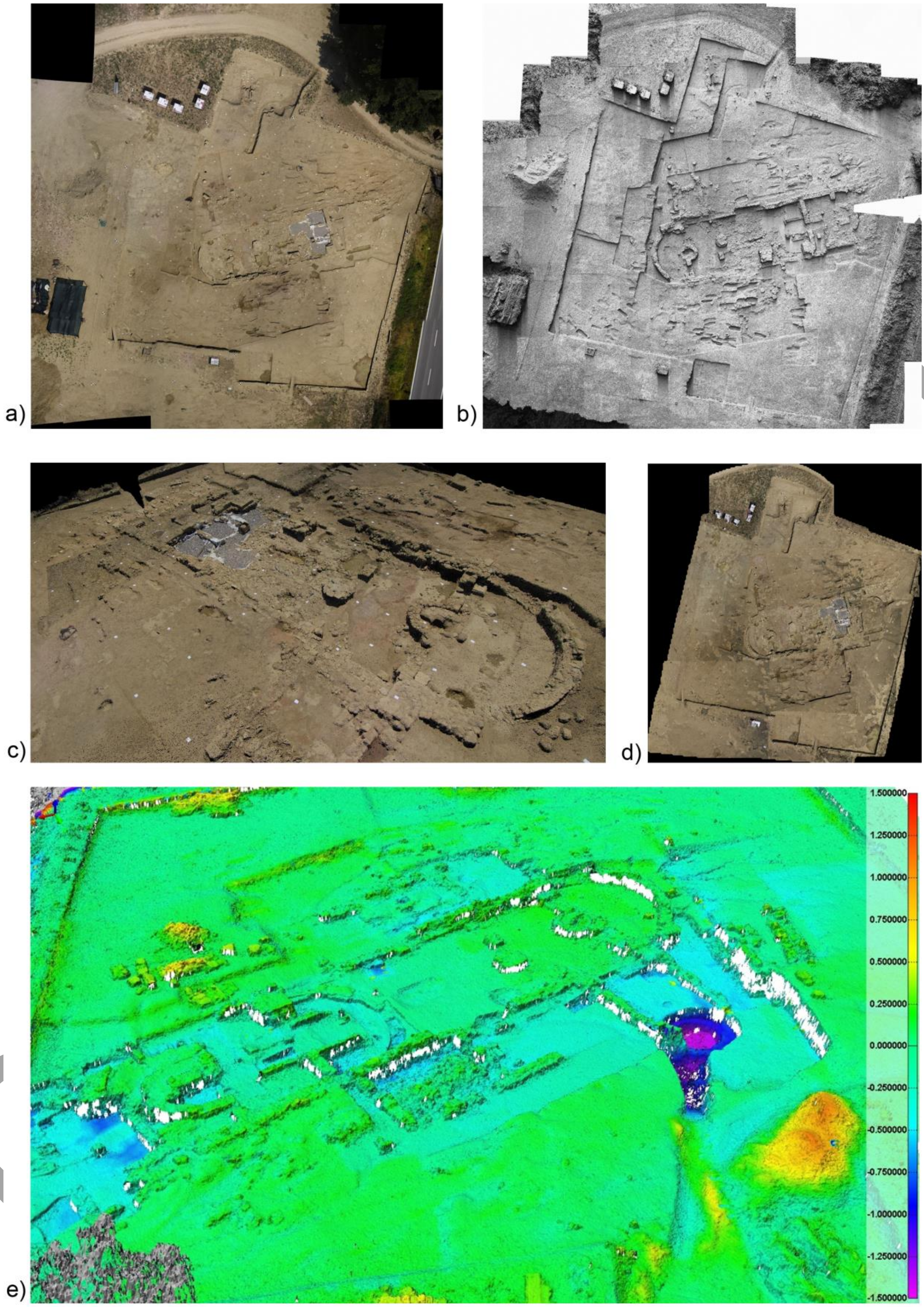

Fig. 6 A mosaic view of the excavation area in Pava (Siena, Italy) surveyed with UAV images for volume excavation computation and GIS applications (a). The derived DSM shown as shaded (b) and textured mode (c) and the produced ortho-image (d) (Remondino et al., 2011). If multi-temporal images are available, DSM differences can be computed for volume exaction estimation (e).

A second example is reported in Fig. 6, showing the archaeological area of Pava (ca 60 x 50 m) surveyed every year at the beginning and end of the excavation period to monitor the advances of the work, compute the exaction volume and produce multi-temporal orthoimages of the area. The flights (35 m height) were performed with a Microdrone MD4-200 in 2010 and 2011. The heritage area is quite windy, so an electric platform was probably not the most suited one. For each session, using multiple shootings for each waypoint, a reliable set of images (ca 40) was acquired, with an average GSD of 1 cm.

In order to evaluate the quality of the image triangulation procedure, some circular targets, measured with a total station, are used as ground control (GCP) and other as check points (CK). After the orientation step, the RMSE on the CK resulted 0.037 m in planimetry and 0.023 m in height for the 2010 flight: very similar results were achieved in the second flight. The derived DSMs (Fig. 6b,c) were used within the Pava's GIS to produce vector layers, ortho-images (Fg.6d) and to check the advances in the excavation or the excavation volumes (Fig.6e).

Geological and mining studies

UAVs can give reliable information in the geological monitoring of different areas, in particular for those sites with can be better surveyed using vertical flights. Dense point clouds generated over areas of interest can give information about the shape of rock surfaces, their stability, slopes and volumes.

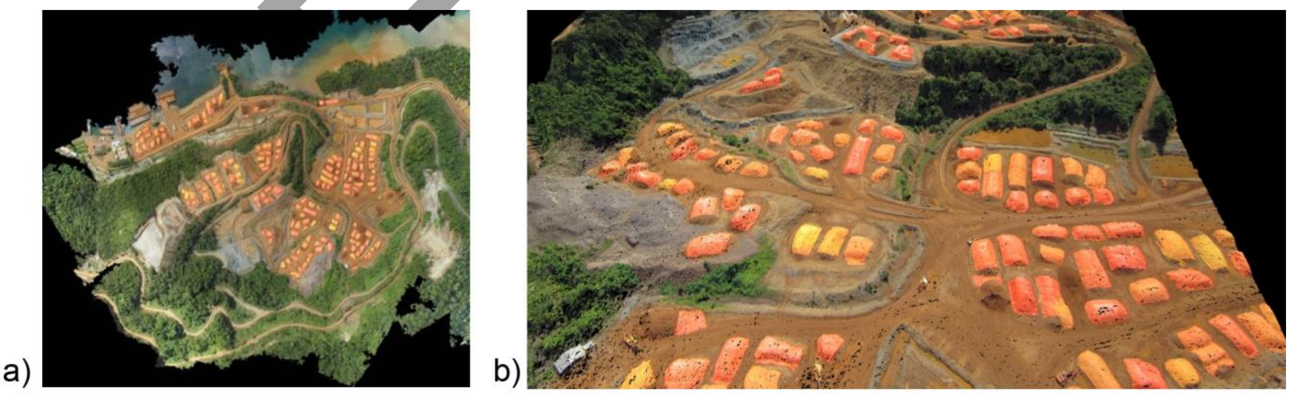

Fig. 7 Mosaic of ca 50 UAV images over a nickel quarry area in Indonesia (a) and produced DSM for volume computation (b).

UAVs can be thus a powerful, quick, cheap and reliable alternative to terrestrial laser scanners for monitoring the excavation material in mine areas or quarries. The generated DSM (e.g. Fig. 7 and 8) allows quick multi-temporal volumes estimations, without problems of occlusion that can be faced by using terrestrial acquisitions.

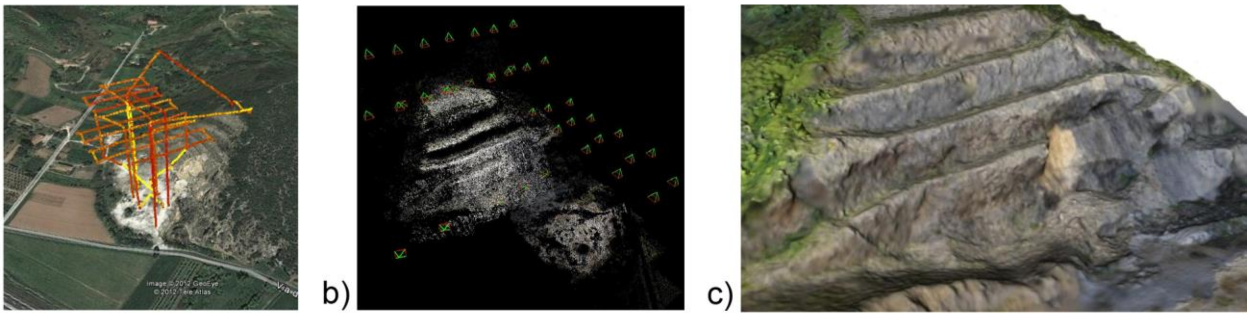

Fig. 8 The flight plan for an UAV surveying of the rock quarry visualized in GoogleEarth (a). The image orientation results, showing different strips composed of oblique and nadir images (b). Produced photogrammetric DSM for excavation monitoring and volume computation (c).

Urban areas

An UAV platform can be used to survey small urban areas, when national regulation allows doing it, for cartographic, mapping and cadastral applications. These images have very high resolution if flights are performed at 100-200 m height over the ground. Very high overlaps are recommended in order to reduce occluded areas and achieve more complete and detailed DSM. A sufficient number of GCPs is mandatory in order to geo-reference the processed images within the bundle adjustment and derive point clouds: the number of GCPs varies according to the image block dimensions and the complexity of the surveyed area. The quality of achieved point clouds is usually very high (up to few centimetres) and this data can thus be used for further analysis and feature extraction.

In Fig. 9, a dense urban area in Bandung (Indonesia) is shown: the area was surveyed with an electric fixed-wing RPV platform at an average height of about 150 m. Due to weather conditions (quite strong wing) and the absence of an auto-pilot onboard, the acquired images (ca 270, average GSD is about 5 cm) are not perfectly aligned in strips (Fig.9b). After the bundle block adjustment, a dense DSM was created for the estimation of the population in the surveyed area and map production.

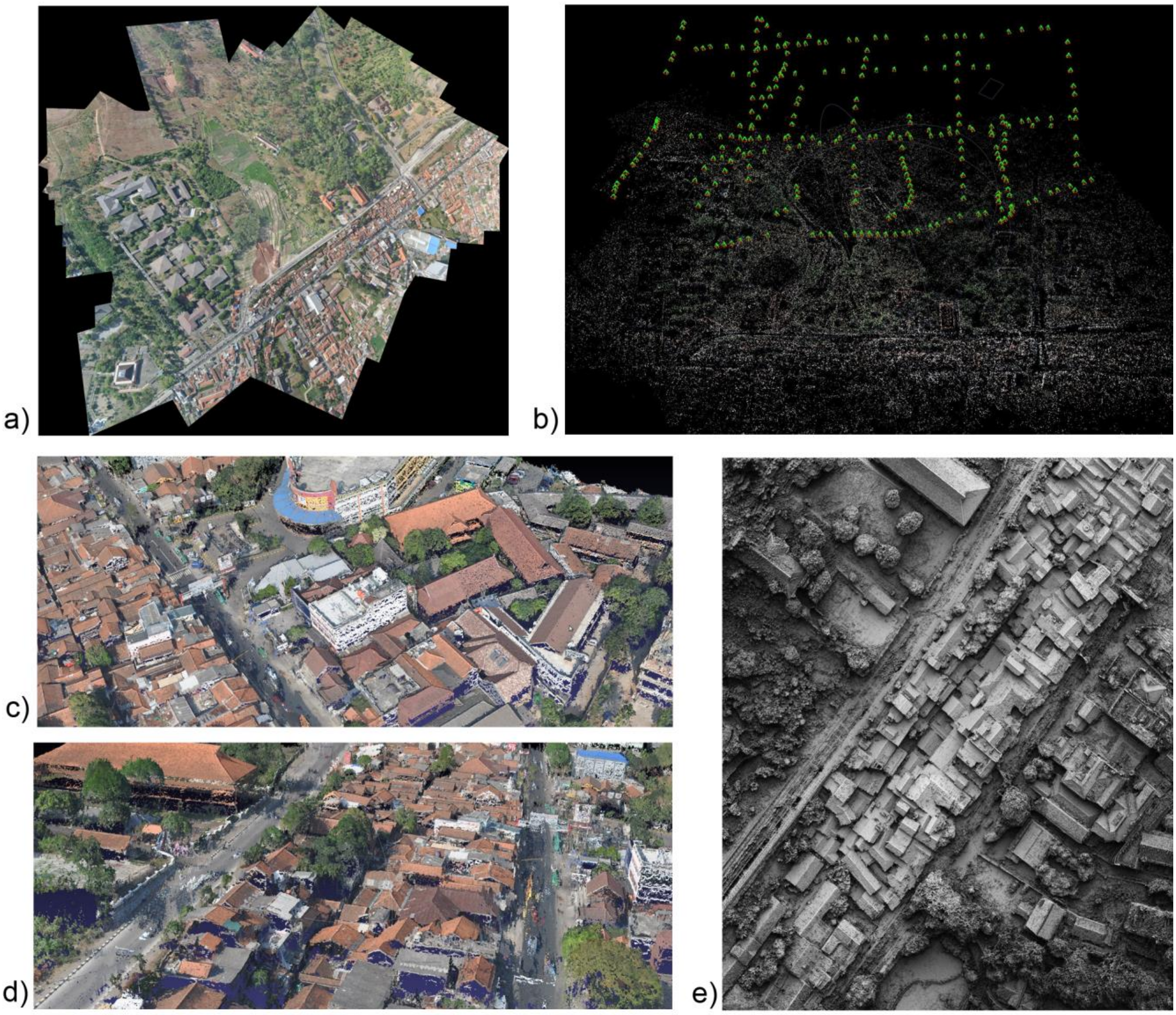

Fig. 9 A mosaic over an urban area in Bandung, Indonesia (a). Visualization of the bundle adjustment results (b) of the large UAV block (ca 270 images) and a close view of the produced DSM over the urban area, shown as point cloud (c, d) and shaded mode (e).

A second example is an UAV flight over the area of Povo (Trento, Italy). Images were acquired at 100-125 m height using a Microdrone MD4-200 with a Pentax Optio A40 camera (8 mm focal length) onboard. The average GSD is about 3 cm and the degree of detail is very high over the whole area. The image overlap was about 80% along track and 40% across track. The image block (four parallel strips plus one higher and orthogonal) allowed the generation of a very detailed and dense DSM (Fig. 10). The generated DSM was finally used for the building footprint extraction, the cadastral updating of the area, photovoltaic potential computation or 3D building modeling.

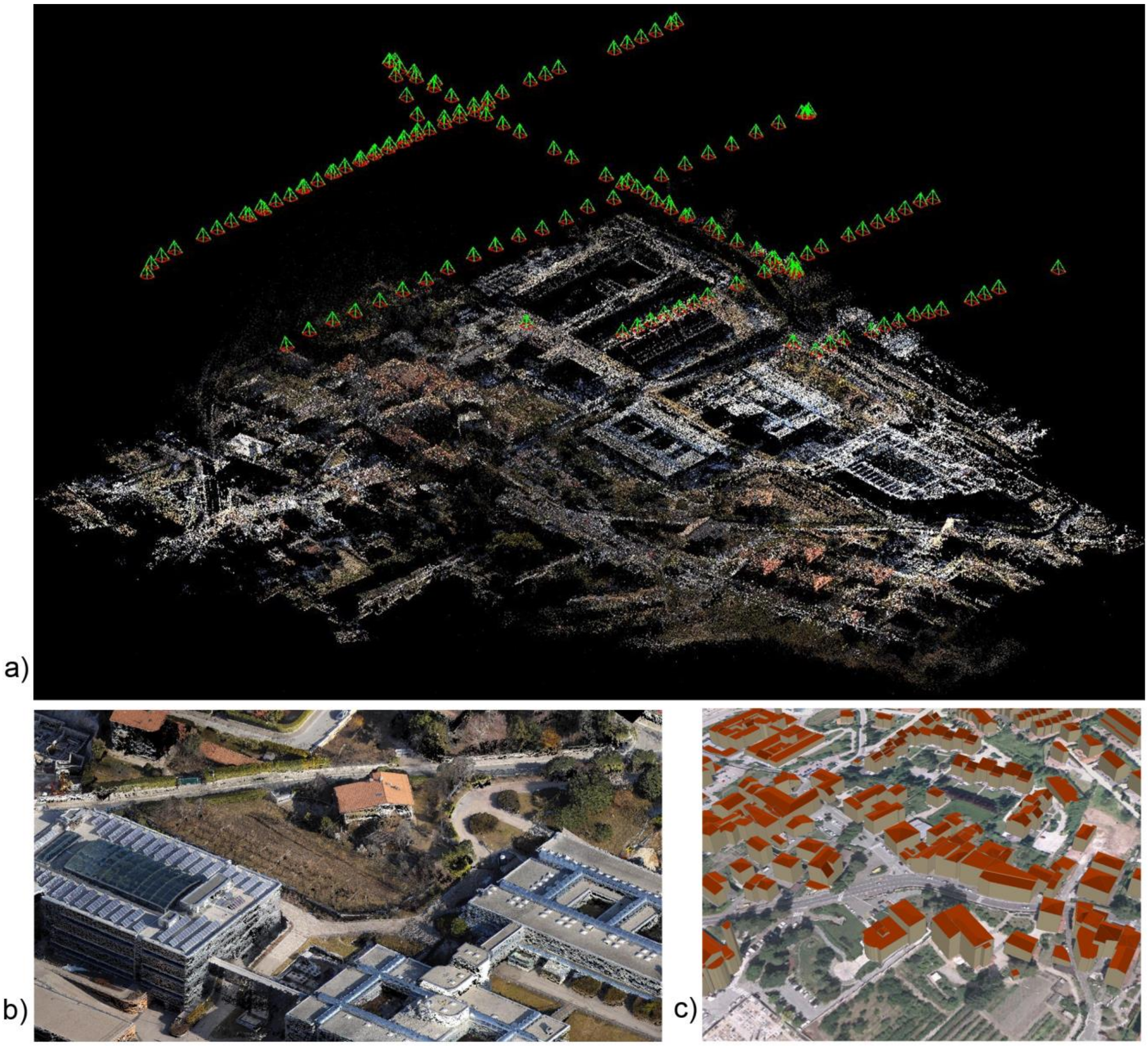

Fig. 10 Visualization of the image triangulation results of the UAV block (a). A close view of the produced dense point cloud of the urban area (b) and the derived 3D building models (LOD2) of the surveyed area (c).

Conclusions and future developments

The article presented an overview of existing UAV systems, problems and applications with particular attention to the Geomatics field. The examples reported in the paper show the current state-of-the-art of photogrammetric UAV technology in different application domains. Although automation is not always demanded, the reported achievements demonstrate the high level of autonomous photogrammetric processing. UAVs have recently received a lot of attention, since they are fairly inexpensive platforms, with navigation/control devices and recording sensors for quick digital data production. The great advantage of actual UAV systems is the ability to quickly deliver high temporal and spatial resolution information and to allow a rapid response in a number of critical situations where immediate access to 3D geo-information is crucial. Indeed they feature real-time capability for fast data acquisition, transmission and, possibly, processing. UAVs can be used in high risk situations and inaccessible areas although they still have some limitations in particular for the payload, insurance and stability. Rotary wing UAV platforms can even take-off and land vertically, thus no runway area is required, while fixed wing UAVs can cover wider areas in few minutes. For some applications, not demanding very accurate 3D results, complete remote sensing solutions, based on open hardware and software are also available. And in case of small scale applications, UAVs can be a complement or replacement of terrestrial acquisition (images or range data). The derived high-resolution images (GSD generally in the centimetre level) can be used, beside very dense point cloud generation, for texture mapping purposes on existing 3D data, for orthophoto production, map and drawing generation or 3D building modelling. If compared to traditional airborne platforms, UAVs decrease the operational costs and reduce the risk of access in harsh environments, still keeping high accuracy potential. But the small or medium format cameras which are generally employed, in particular on low-cost and small payload systems, enforce the acquisition of a higher number of images in order to achieve the same image coverage at a comparable resolution. In these conditions, automated and reliable orientation software are strictly recommended to reduce the processing time. Some reliable solution are nowadays available, even in the low-cost open-source sector.

The stability of low-cost and light platforms is generally an important issue, in particular in windy areas, although camera and platform stabilizers can reduce the weather dependency. Generally the stability issue is solved shooting many images (continuous acquisition or multiple shots from the predefined waypoints) and using, during the processing phase, only the best image. High altitude surveying can affect gasoline and turbine engines while the payload limitation enforce the use of low weight GNSS/IMU thus denying direct geo-referencing solutions. New reliable navigation systems are nowadays available, but the cost has limited their use until now to very few examples. A drawback is thus the system manoeuvre and transportation that generally requires at least two persons.

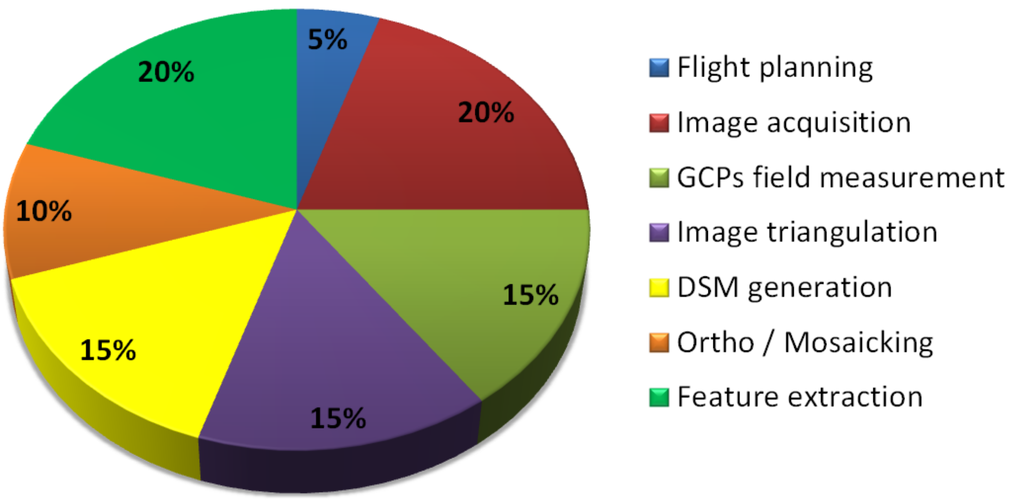

Fig. 11 Approximate time effort in a typical UAV-based photogrammetric workflow.

UAV regulations are under development in several countries all around the world, in order to propose some technical specifications and areas where these devices can be used (e.g. over urban settlements), increasing the range of their applications. At the moment, the lack of precise rule frameworks and the tedious requests for flight permissions, represent the biggest limitation for UAV applications. Hopefully the incoming rules will regulate UAV applications for surveying issues.

Considering an entire UAV-based field campaign (Fig. 11) and based on the authors' experience, we can safely say that, although automation has reached satisfactory level of performances for automated tie point extraction and DSM generation, an high percentage of the time is absorbed by the image orientation and GCPs measurements, in particular if direct geo-referencing cannot be performed. The time requested for the feature extraction depends on the typology of feature to be extracted and is generally a time-consuming phase too.

The GCPs measurement step represents an important issue with UAV image blocks. As the accuracy of the topographic network is influencing the image triangulation accuracy and the GSD of the images is often reaching the centimetre level, there might be problems in reaching sub-pixel accuracies at the end of the image triangulation process. So far, in the literature, RMSEs of 2-3 pixels are normally reported, also due to the camera performances, image network quality, un-modelled errors, etc.

In the near future, the most feasible improvement should be related to payload, autonomy and stability issues as well as faster (or even real-time) data processing thanks to GPU programming (Wendel et al., 2012). High-end navigation sensors, like DGPS and inexpensive INS would allow direct geo-referencing with accurate results. In case of low-end navigation systems, real-time image orientation could be achieved with onboard advanced SLAM (Simultaneous Localisation And

Mapping) methods (Konolige et al., 2008; Nuechter et al., 2007; Strasdat et al., 2010). Lab post-processing will be most probably always mandatory for applications requiring high accuracy results.

On the other hand, the acquisition of image blocks with a suitable geometry for photogrammetric process is still a critical task, especially in case of large scale projects and non-flat objects (e.g. buildings, towers, rock faces, etc.). While the planning of image acquisition is quite simple when using nadir images, the same task becomes much more complex in the case of 3D objects requiring convergent images.

Two or more flights can be necessary over large areas, when UAV with reduced endurance limits are used, leading to images with illumination changes due to the different acquisition time that may affect the DSM generation and orthoimage quality. Future research has also to be addressed to develop tools for simplifying this task. Other hot research issues tied to UAV applications are related to the use of new sensors on-board like thermal, multispectral (Bolten and Bareth, 2012) or range imaging cameras (Lange et al., 2011), just to cite some of them.

Acknowledgements

The work was partly supported by the 3M and CIEM project (co-founded Marie-Curie Actions 7th F.P. - PCOFOUND- GA-2008-226070, acronym “Trentino Project”). The authors are really thankful to Zenit (http://www.zenit-sa.com), Dr Deni Suwardhi (ITB Bandung, Indonesia), Dr Catur Aries Rokhmana (Gadjah Mada University, Indonesia) and Prof. Juan José Fernández Martin (Valladolid University, Spain) for providing some datasets presented in the article and useful discussions on the UAV topic.

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