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Review Article

Unmanned aerial systems for photogrammetry and remote sensing: A review

I. Colomina, P. Molina *

Centre Tecnològic de Telecomunicacions de Catalunya, Carl Friedrich Gauss 7, 08860 Castelldefels, Spain

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ABSTRACT

We discuss the evolution and state-of-the-art of the use of Unmanned Aerial Systems (UAS) in the field of Photogrammetry and Remote Sensing (PaRS). UAS, Remotely-Piloted Aerial Systems, Unmanned Aerial Vehicles or simply, drones are a hot topic comprising a diverse array of aspects including technology, privacy rights, safety and regulations, and even war and peace. Modern photogrammetry and remote sensing identified the potential of UAS-sourced imagery more than thirty years ago. In the last five years, these two sister disciplines have developed technology and methods that challenge the current aeronautical regulatory framework and their own traditional acquisition and processing methods. Navety and ingenuity have combined off-the-shelf, low-cost equipment with sophisticated computer vision, robotics and geomatic engineering. The results are cm-level resolution and accuracy products that can be generated even with cameras costing a few-hundred euros. In this review article, following a brief historic background and regulatory status analysis, we review the recent unmanned aircraft, sensing, navigation, orientation and general data processing developments for UAS photogrammetry and remote sensing with emphasis on the nano-micro-mini UAS segment.

1. Introduction

Let them fly and they will create a new market. Of course, we are referring to Unmanned Aerial Systems (UAS) and UAS-based aerial remote sensing and mapping. According to recent market research (MarketsandMarkets, 2013) the global unmanned aerial systems market revenue is worth 5400.0 M€ as of 2013 and expected to grow up to 6350.0 M€ by 2018. *Let them fly and they will create a new remote sensing market in your country* is the message this paper would like to send to local policy makers, regulatory bodies and mapping authorities all around the world. Entrepreneurship together with robotic, computer vision and geomatic technologies have established a new paradigm (Colomina et al., 2008) of aerial remote sensing and mapping that, for some years now, has been serving the needs of large-scale low-altitude imaging and geospatial information users and developing an industry of its own (Cho et al., 2013; Mayr, 2013; Petrie, 2013). The topic has become so important that the European national mapping agencies have organized working groups and begun to establish a common position (Cramer et al., 2013). Perhaps, we are standing right in front of the doors of the future, as suggested by the pioneering case of Trinidad and Tobago, where the government has already issued a tender for an UAS system "to provide colored map and imagery products to serve the identical purpose of conventional aerial survey and to satisfy the needs of a demanding spatial data market." GORTT (2013) Quite a forward looking decision. Yet, let us first explore what brought us here.

1.1. On names and acronyms

UAS are known under various different names and acronyms, such as "Unmanned Aerial Vehicle" (UAV), "aerial robot" or simply "drone," with "UAV" and "drone" being the most popular terms. The term UAS was adopted by the US Department of Defense (DOD) and the Civil Aviation Authority (CAA) of the UK. The International Civil Aviation Organization (ICAO) has introduced the concept of "Remotely-Piloted Aerial System" (RPAS), a particular class of UAS, in the ICAO Circular 328 (ICAO, 2011). This term is basically motivated by the fact that only RPAS will be able to integrate into the international civil aviation system. The aforementioned circular is a key reference in which the reader may find a comprehensive compilation of terms and definitions associated to UAS.

* Corresponding author. Tel.: +34 936452900.
E-mail addresses: ismael.colomina@cttc.es (I. Colomina), pere.molina@cttc.es (P. Molina).

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In this paper, we will refer to UAS for the system comprising an unmanned aircraft (UA), a ground control station (GCS) and a communications data link for the UA command and control (C2) from the GCS.

1.2. Pioneers

UAS were born (A.M. Low's "Aerial Target" of 1916; the Wright brothers Hewitt-Sperry Automatic airplane also in 1916) and raised (the Royal Navy used the Queen Bee drone for gunnery practice in 1933; USAF Firebees were used in North Vietnam and also by Israel against Egyptian targets in the Sinai during the 1973 October War) in the military context. Yet, the mapping potential of unmanned platforms was already understood by research groups in the late nineteen-seventies (Przybilla and Wester-Ebbinghaus, 1979; Wester-Ebbinghaus, 1980). Navigation and mapping sensors were integrated onto radio-controlled platforms to acquire low-altitude, high-resolution imagery. The idea did not find many enthusiasts in the academic community, as shown by the limited number of publications and conferences. However, visionary technology and service companies that were well aware of their user needs, and open-minded civil aviation authorities that anticipated the social and business benefits of unmanned aircraft, soon started to develop, apply and regulate the technology (Petrie, 2013). Remarkable examples of this can be found in Australia, Japan and the UK. But how far did those initial developments make it through the thick jungle of differing user requirements, inexistent regulations and constant technological evolution?

1.3. General evolution

We live in the information century, and Internet is one of its main drivers. This constitutes grounds for the following minor exercise. In September 2013, more than six million entries were found in Google when searching for the words "Unmanned Aerial Vehicles," and almost twelve million when searching for its acronym, UAV. Using Google Trends, one sees that Internet usage of the word UAV in 2013 has diminished to almost half of the amount registered in 2005. Yet, this might be partially explained by the new, popular term "drone." As a matter of fact, there has been a clear rise in the use of this word since 2009, reaching around ten times its 2005 level in 2013 (the maximum peak was achieved in December 2011, when the US government asked Iran to return a lost drone). This analysis is a simple, non-quantitative, yet fairly illustrative approximation to measuring the impact of UAS in current times.

In the attempt to quantify the evolution of UAS development and its penetration into current professional markets, it may be useful to analyze the number of inventoried UAS as a direct indicator of how their importance has grown. Table 1 details the number of UAS systems referenced in the 2013 annual inventory of UVS International (van Blyenburgh, 2013). This table is an extension of the review work presented in Everaerts (2009). UVS International represents manufacturers of Unmanned Vehicle Systems (UVS), subsystems and critical components for UVS and associated equipment, as well as companies supplying services with or for UVS, research organizations and academia. The annual reports are reference materials on UAS inventories, and will be further mentioned in our contribution.

Among the many interpretations that one may extract from the above table, an interesting trend is revealed: the number of developed UAS has multiplied by three from 2005 to present and, additionally, a relevant increase is observed in the civil/commercial type of platforms, especially in 2012 and 2013. Thus, it seems that PaRS UAS (clearly framed within that group) is cradled in a growing niche.

1.4. Literature evolution

Let us now focus on the scientific impact of UAS by screening the number of published papers at some of the most important PaRS conferences, for example the quadrennial International Society for Photogrammetry and Remote Sensing (ISPRS) congress. In 2004, the ISPRS congress in Istanbul hosted three UAS-related papers but did not feature any session specifically devoted to unmanned platforms. The trend changed in 2008, in Beijing, where 21 papers related to the use of UAS for PaRS and mapping purposes were presented in three different sessions. At the recent ISPRS congress in Melbourne in 2012, nine sessions related to UAS were held, featuring around 50 UAS-related papers. The international photogrammetric community has set up a dedicated biennial conference that began in 2011: the UAV-g (UAV-g 2011 in Zürich, Switzerland, UAV-g 2013 in Rostock, Germany and the upcoming UAV-g 2015 in Toronto, Canada). The increase in UAS-related publications at these conferences is clear, yet not exclusive. The IEEE Geoscience and Remote Sensing Society (IGARSS) has featured UAS-related papers at its annual symposiums since 2005. UAS-related papers have also been presented at the American Society for Photogrammetry and Remote Sensing (ASPRS) congresses, from 2005 in Baltimore up to present editions. Furthermore, the Multidisciplinary Digital Publishing Institute (MDPI) Open Access Journal of Remote Sensing published a special issue called "Unmanned Aerial Vehicles (UAVs) based Remote Sensing," closed in June 2012, with around 12 peer-reviewed papers. The IEEE Transactions on Geoscience and Remote Sensing journal also compiled seven papers on the use of UAS for Earth observation, published on 2009, and has been publishing UAS-related papers since 2007. The "Photogrammetrie, Fernerkundung und Geoinformation" (PFG) journal has featured five papers since 2007, with three in 2012.

A complete quantification of the UAS impact on current scientific disciplines should include a report on the number of papers in the conferences and journals of robotics and computer vision, like those sponsored by the IEEE Robotics and Automation Society (IEEE RAS) and the computer vision community respectively. These

Table 1
Number of referenced UAS, developmental initiatives and purpose, period 2005–2013.

Item	2005	2006	2007	2008	2009	2010	2011	2012	2013
Referenced UAS	544	603	789	974	1190	1244	1424	1581	1708
Producers/developers	207	252	312	369	422	500	511	478	540
Int'l teamed efforts	20	32	34	35	38	36	54	32	48
Producing countries	43	42	48	48	50	51	51	51	53
Devlopment purposes									
Civil/commercial	55	47	61	115	150	171	175	217	247
Military	397	413	491	578	683	631	674	548	564
Dual purpose	44	77	117	242	260	283	318	353	392
Research UAS	35	31	46	54	66	66	69	73	78
Developmental UAS	219	217	269	293	329	301	310	187	172

two disciplines have empowered UAS technologies and have come into the PaRS field with their own developments and ideas. The IEEE RAS organises and/or sponsors many UAS conferences. Among them, three ones deserve explicit mention: the IEEE International Conference on Robotics and Automation (ICRAS), the IEEE International Conference on Automation Science and Engineering (CASE) and the IEEE/Robotics Society of Japan (RSJ) International Conference on Intelligent Robots and Systems (IROS). As for IEEE journals, UAS technology can be found in the IEEE Transactions on Automation Science and Engineering (IEEE TASE), IEEE Transactions on Robotics (IEEE TR) and the IEEE Robotics and Automation Magazine (IEEE RAM). Far from being overlooked, its statistics are omitted here as the focus of the paper is PaRS.

1.5. Organization of the article

After providing an outline of how interest in UAS for PaRS has evolved, we introduce some history of the use of UAS in PaRS (Section 2), to later provide an overview of the current status of the main UAS technologies and regulations (Sections 3 and 4). In Section 5 we review the navigation, orientation and remote sensing payloads and in Section 6 we address UAS-sourced data post-processing. We conclude the article with a review of UAS geomatic applications and markets.

2. Early developments

Balloons are probably the oldest platforms for aerial observation. As a matter of fact, aerial photographs of Paris were already being captured in 1858 by Tournachon aboard a hot-air balloon. Later on, and thanks to the simplification of camera technology, other means such as kites (used by the English meteorologist E.D Archibald in 1882) and rockets (as used by the Swedish inventor Alfred Nobel in 1897) were used for aerial photography. Perhaps one of the most exciting early experiments was the use of small cameras mounted on the breasts of pigeons from the Bavarian Pigeon Corps, as proposed by J. Neubronner in 1903. Thus, Tournachon's adventures aside, one may conclude that the oldest form of aerial remote sensing was actually based on remotely-piloted vehicles. Yet, the reader would be right to harbor doubts about defining a pigeon as an "unmanned platform" or "remotely-piloted aircraft".

Manned airborne aerial photographs came later (in 1909 W. Wright shot a motion picture aboard his home-made airplane), and rapidly became well-established tools in the military field, mainly for war purposes given the context of Europe at that time. It is out of the scope of this paper to comment on how photogrammetry was born and evolved, in the aerial or satellital platform context as well as the imaging sensor context.

Indeed, the evolution of integrated circuitry and radio-controlled systems in the late twentieth century was key in the advent of modern UAS for PaRS. In 1979, Przybilla and Wester-Ebbinghaus performed a test with a radio-controlled, fixed-wing UAS with a length of 3 m and equipped with an optical camera (Przybilla and Wester-Ebbinghaus, 1979). A second test was carried out in 1980 by the same team but using model helicopters carrying a medium-format Rolleiflex camera (Wester-Ebbinghaus, 1980). The prototype was used to aerially document an old steel construction, and it was first use of rotary-wing platforms for PaRS. From then until present times, the rotary- or fixed-wing, single- or multi-rotor, remotely- and/or auto-piloted platforms have been established in most of the UAS implementations for PaRS (those early experiments truly paved the way for future developments). The reader interested in the early stages of UAS-based PaRS is referred to the comprehensive literature review in Eisenbeiss (2009), and also to a comprehensive review of ancient and modern aviation history and unmanned flights in Dalamagkidis et al. (2009).

3. Unmanned aerial systems and unmanned aerial systems for PaRS

A UAS is a system of systems—that is, a set of complementary technologies brought together to fulfil a specific task—and, as such, there currently exists a wealth of different systems: it may be said that there is one for every combination of technologies. At the highest level of the UAS technology breakdown, three main UAS components are commonly identified, namely the *unmanned aerial vehicle*, the *ground control station* and the *communication data link*. Further down, other UAS components are considered critical, such as autopilots, navigation sensors, imaging sensors, mechanical servos, and wireless systems. In this paper, some of these UAS technologies with relevance within the PaRS field are presented and surveyed.

The categorization of the existing unmanned aircraft has been a constant and necessary exercise among the UAS community throughout its history "to bring order into chaos," quoting from the EuroSDR report of the project "NEWPLATFORMS" (Everaerts, 2009). As a result of this need, there is a myriad of classifications of UAS, according to the various characteristics of the aerial platform (size and weight, endurance, aerodynamics, etc.) or the system operation (mission range or flying altitude, nature of its application, etc.). We review some of current work on UAS classification hereafter.

The work presented in Eisenbeiss (2009) with respect to UAS categorization is noteworthy; it considers powered and non-powered, heavier- or lighter-than-air platforms and performs an assessment on range, endurance, weather and wind dependency, and maneuverability. It additionally defines a proprietary classification based on price and payload, including on-board navigation sensor grade and, thus, geo-referencing or real-time capabilities, and application accuracy requirements.

In van Blyenburgh (2013), a vast inventory of world-wide UAS, including categorizations based on size, weight, operating range and certification potential is provided. The classification based on size and operation range, depicted in Fig. 6, p. 169, with the corresponding number of inventorised platforms is of special interest. This table reveals three fairly well-distinguished UAS ecosystems: *nano-micro-mini* UAS, *close-short-medium-range* UAS, and the rest of UAS, which we will discuss hereafter.

From the last to the first, the Medium Range Endurance to Exo-Stratosferic UAS ecosystem groups the largest UAS with highest operating altitudes, which often consist of fine and complex avionics and are only allowed to fly under certain special regulations by certain specific teams, generally military units. Together, they total up to 179 referenced UAS. Secondly, *close-short-medium-range* UAS are characterized by an Maximum Take-Off Weight (MTOW) between 150 and 1250 kg and an operating range between 10 and 70 km. This group includes fixed- and rotary-wing developments from well-established companies (Raytheon, Northrop Grumman, Saab) generally equipped with remote sensing technologies, and total up to 546 developments. Finally, the *nano-micro-mini* UAS class is defined by low weights and payload sizes, low flying altitudes and quick operational deployments, and concentrates up to 728 developments. More specifically, *mini* UAS, which are defined by an operative range of less than 10 km, allowed to fly lower than national ceilings of segregated airspaces, feature less than two hours of endurance and less than thirty kilograms of MTOW (although the MTOW specification may vary from country to country), is the largest group, featuring 490 referenced systems. This UAS ecosystem seems to fit the PaRS community needs, in view of the existing PaRS UAS to be reviewed throughout this article.

At this point, a trade-off is evident: on the one hand, there is not a unique and universal classification of UAS but, on the other, it is necessary to distinguish among the myriad of platforms already existing in the world. In order to set a basis for our paper, we will use the following weight-based categorization: micro (less than 5 kg); mini (less than 30 kg); and tactical (less than 150 kg). With these categories, we aim at simplification and ease of reading, as well as covering the UAS portion of interest for the PaRS community. Additionally, based on our own experience, these names and definitions are fairly common among UAS professionals.

We will now review the crucial high-level components of a UAS, focusing on PaRS.

3.1. Unmanned aircraft

Conditioned by [the lack of] regulations and, to a certain degree, by the inherent complexity of large systems, a UAS PaRS mission has usually consisted of operating an aerial platform, most probably a fixed-wing or rotary-wing craft of less than 30 kg MTOW, within a range not greater than 10 km and flying below 300 m, carrying a small or medium-format optical camera (probably on the visible spectrum), and either remotely piloted by a human or automatically piloted by an autopilot based on two main navigation technologies, Global Navigation Satellite Systems (GNSS) (such as for example GPS) and Inertial Navigation Systems (INS), in a GNSS-only mode or INS/GNSS coupling. In our opinion, this is a representative picture of current unmanned aircraft for PaRS.

We believe that, in general, the geomatic community has finally taken positions on the *nano-micro-mini* UAS ecosystem. Yet, the history of UAS PaRS is marked by a heterogenous array of developments that sometimes departing from the previous ecosystem. Everaerts et al. (2004) presented a stratospheric UAS to offer high resolution aerial imagery in near real time for large-scale mapping and crisis monitoring, and presented recent updates in Everaerts and Lewyckyj (2011) with respect to the integration with local civil aviation authorities. More recently, Miraliakbari et al. (2012) reported on the use of gyrocopters as potential mapping platforms, focusing on the analysis of its vibrations, and Thamm (2011) presented a parachute-based remote-sensing system. In Kemper (2012), several non-conventional unmanned and manned platforms (balloons, blimps, trikes and paratrikes) are presented carrying remote-sensing payloads.

Everaerts (2009) features a comparative analysis of airborne platforms, satellite platforms, low-altitude and high-altitude UA, in relation to their main qualities for remote sensing missions, such as coverage, update rate, flexibility, quality, spatial resolution, positional accuracy, spectral resolution and accuracy, target applications and system economic cost. An update on the use of UAS for geomatics, covering market and legislation analysis, is provided in Haarbrink (2011).

In order to provide the reader with an idea of the current unmanned aircraft used for PaRS, and without attempting to provide a comprehensive list, a few systems are described in Appendix A. Table 10 compiles the main characteristics of micro and mini fixed-wing, rotary-wing and multi-rotor UAS for PaRS, respectively.

3.2. Ground control station

As per common understanding, Ground Control Stations (GCSs) are stationary or transportable hardware/software devices to monitor and command the unmanned aircraft. Although the word *ground* is inherent to the concept, a UA may actually be operated from the ground, sea or air. GCS are probably as important as the unmanned aircraft themselves, as they enable the interface with the "human intelligence"—any change in the route of the UAS, any eventual error on the aerial platform and/or any outcome of the payload sensors shall be sent to and seen within the GCS. As fundamental pieces in UAS, GCS have evolved over the past decades pushed by the parallel improvements in computer science and telecommunications. van Blyenburgh (2013) provides a compilation of referenced GCS, most of which are military.

Requirements in UA-GCS communication, commanding devices, the number of monitors and the crew members needed to command a UA are crucial variables to shape a particular GCS. From the Predators or GlobalHawks GCS, enabling simultaneous control of several platforms and command by up to six crew members, to small portable PC-based GCS such as that in the UX5, from Trimble, down to the software-only GCS, found in SwingletCAM, from SenseFly.

Even though, generally speaking, a commercial UAS such as any of those listed in Table 10 is a non-separable UA-GCS ensemble, there are some generic developments usable as stand-alone solutions, such as the Portable Ground Control Station, from UAV Factory.

3.3. Communication

UAS communication is critical in terms of mission requirements (that is, to command and control the aircraft and eventually screen the payload outcome) as well as safety, especially when it comes to UAS integration with Air Traffic Control (ATC) in non-segregated airspace.

The debate on UAS-related communication issues was present at the World Radiocommunication Conference (WRC-12), held in Geneva in February, 2012. As published on the International Telecommunication Union (ITU) website, the aim was to consider spectrum requirements and possible regulatory actions, including the identification of a globally harmonized spectrum, in order to support the safe operation of unmanned aircraft systems in the non-segregated airspace used by civil aviation (agenda item 1.3). Although unmanned aircraft systems have traditionally been used in segregated airspace where separation from other air traffic can be assured, administrations expect broad deployment of unmanned aircraft systems in non-segregated airspace alongside manned aircraft. The outcomes of the WRC-12, particularly focusing on agenda item 1.3, consisted of a new allocation to Aeronautical Mobile Satellite (Route) Service (AMS(R)S) in support of UAS, agreed to in the 5030–5091 MHz band, which is the core band for Microwave Landing Systems (MLS). The ITU Radiocommunication Sector was instructed to conduct studies to develop technical, regulatory and operational recommendations for the WRC in 2015. As agreed future actions, the ITU-R and WRC-15 will explore whether the Fixed Satellite Service (FSS) can be used to provide UAS command-and-control communications, consistent with the aeronautical safety of flight requirements, and highlighting the need for participation of aviation safety regulators and other aviation interests.

Indeed, when no integration with ATC is required (e.g. operation in segregated airspace[1]), communication links are only subject to standard frequency spectrum legislation. Thus, the responsibility for safety falls on the side of the particular radio-communication technology implemented on the UAS.

Many communication technologies are used in today's UAS, the most predominant of which in the Mini UAS category is Wi-Fi (usually around 2.4 GHz), as is used by some of the UAs in Table 10. Yet, other technologies have been considered, such as high-frequency satellite communication as in military systems (Predator, Global Hawk) or Worldwide Interoperability for Microwave Access (Wi-

[1] Note that the definition of segregated airspace is a national responsibility.

MAX), an interoperable implementation of the IEEE 802.16 wireless standard (Dusza and Wietfeld, 2010). A comprehensive overview of aspects related to command, control and communication technologies for small UAVs is provided in Barnard (2007). In addition, this presentation discusses aspects of the integration of UAS into non-segregated airspace and provides a comparison table of the frequencies used by some existing UAS, such as ScanEagle, FireScout or RMAX.

3.4. Mission planning

In the formal definition of UAS—aircraft, control station and data link—there is no explicit mention of mission preparation and execution. However, an essential component of UAS for geodata acquisition is the mission planning and management subsystem. Experience shows that a careful design of the aircraft trajectory (waypoints, strips, speed, attitude, etc.) and a flexible real-time mission management capacity (sensor configuration, triggering events, flying directions, etc.) are instrumental in achieving productive and safe acquisition missions (Mayr, 2011b).

Although the mission planning and real-time management component is usually an integrated part of commercial UAS (e.g., Micropilots Horizon or QGroundControl used by ArduPilot), there are open issues that still lead users to repeat acquisition campaigns simply because of flawed mission design or execution. Apparently, the "easy" operation of micro- and mini-UAS should mitigate this inconvenience However the aircraft of micro- and mini-UAS are tiny vehicles, sensitive to wind and wind bursts and of limited autonomy. A typical feature, for instance, of mission plans for UAS photogrammetry is the large forward (80%) and cross (60–80%) overlap to compensate for aircraft instability. A rare feature, for instance, of mission management is to accommodate flight plans to the actual wind conditions of the mission area at the time of mission execution. Mission planning and real-time mission management subsystems are the key to a competitive exploitation of UAS for photogrammetry and remote sensing.

An illustrative example of a real-time mission management subsystem is described in Stødle et al. (2013) where extreme operational conditions and long distances do not allow for mission failures. The system features real-time and off-line visualization of UAS-sourced images and therefore a quality-control tool on data completeness, etc. so the remote crew can take control of the unmanned aircraft and correct any possible deviations from the mission plan.

4. Regulatory bodies and regulations

The implementation of a harmonized regulatory panorama has been demanded by UAS stakeholders to drop the barriers for UAS certification and commercialization all over the world. Yet, this issue entails non-trivial technicalities and involves a large group of contributing agents. Based on the comprehensive list provided in Everaerts (2009), we present a summary of the main actors in UAS regulations and latest updates to date of publication.

The ICAO brings together states and key industry organizations to develop policies and standards on all aspects of civil aviation activity. In 2007, the Unmanned Aerial Systems Study Group (UASSG) was created to be the focal point and coordinator of all ICAO UAS-related work. As already mentioned in the first chapter of this article, the Circular 328 on UAS was released in 2011 by ICAO, being the first official ICAO document on the subject. Some relevant statements from this document can be highlighted, such as the fact that any UAS-related incident shall be investigated by the competent aviation bodies, and also the possibility to certify the aircraft and the ground station separately, which may be of high relevance to industrial stakeholders.

The European Aviation Safety Agency (EASA) is a European Union (EU) agency, gathering the civil aviation authorities of the member States, which developed a policy statement on "Airworthiness Certification of Unmanned Aircraft Systems (UAS)" in August, 2009. As published on its website, "this policy establishes general principles for type-certification (including environmental protection) of an Unmanned Aircraft System (UAS)."

The European Organisation for the Safety of Air Navigation, EUROCONTROL, is devoted to the creation of a uniform Air Traffic Management (ATM) system gathering civil and military users. In 2007, EUROCONTROL released the "Specifications for the Use of Military Remotely-Piloted Aircraft (RPA) as Operational Air Traffic outside Segregated Airspace" and has been updating it until the present time (the last update of this document is from February 2012).

On the defence and military side, other European actors contributing to regulations are the European Defence Agency (EDA), which aims to support the member states on improving European defence capabilities, and the North Atlantic Treaty Organization (NATO), responsible for the military regulations of most of the European countries. The EDA has been focusing on UAS air traffic insertion, frequency management and future UAS, and has funded several initiatives to its respect such as the AIR4ALL project (2008). On the other side, NATO has participated in a regulatory process through its Flight In Non-segregated Airspace (FINAS) group, although it clearly states they are not a regulatory body on this issue. The UAS-related work of NATO spans many aspects of UAS management, namely operator training, airworthiness, risk assessment, system architectures, etc., and has produced a wide collection of standards of best practices.

Additionally, there are a few noteworthy initiatives in the non-profit, user-driven category. First, the Association for Unmanned Vehicle Systems International (AUVSI), which is "the world's largest non-profit organization devoted exclusively to advancing the unmanned systems and robotics community" as stated on their website. Second, the European Organisation of Civil Aviation Equipment (EuroCAE), which deals exclusively with aviation standardisation (airborne and ground systems and equipment) and related documents as required for use in the regulation of aviation equipment and systems. The EuroCAE WG-73 deals with the analysis of key issues related to UAS operations in the context of European ATM and UAS terminology and definitions.

Some research companies' initiatives have helped clear a path for advancement in UAS regulations. The first noteworthy example is Everaerts and Lewyckyj (2011), in which the interaction with real air traffic control is studied in depth and carried out. Schulz (2011) also presents an effort to understand regulations for UAS, and the development of a certifiable UAS system admitting flexible scientific payloads.

Recent events and decisions are proof of the active work carried out by competent authorities on UAS regulation. For example, the US Federal Aviation Administration (FAA) was required to develop a "comprehensive plan for integrating UAS into the national airspace system no later than September 30, 2015" as stated in the 2012 FAA Reauthorization Act. In response to the mandate, the FAA recently published the "Integration of Civil Unmanned Aircraft Systems (UAS) in the National Airspace System (NAS) Roadmap" (Federal Aviation Administration, 2013). In the document, an initial "accommodation" phase and a final "integration" phase are described that, altogether, will last much longer than 2015. FAA conditions for the UAS being integrated into airspace is that they cannot reduce capacity, decrease safety, increase the risk (on air and on ground) and impact operations any more than other new technologies. Quoting (Federal Aviation Administration, 2013) "Integration efforts will focus on sequentially developing and implementing the UAS system requirements established by the

FAA as a result of Research and Development and test range outputs." For the latter purpose the FAA has already selected six test sites (Davis, 2013). For PaRS applications it is interesting to note that, among other general rules to abide by, the FAA Roadmap announces that "all UAS will require design and airworthiness certification to fly civil operations in the NAS" with the exception of "some special cases, such as small UAS (sUAS) with very limited operational range."

Last but not least, in the EU regional context, the European RPAS Steering group (ERSG) released (June 2013) the "Roadmap for the integration of civil Remotely-Piloted Aircraft Systems into the European Aviation System" a comprehensive report that proposes a plan spanning the period from 2013 to 2028 (ERSG, 2013). It includes detailed proposals and a schedule for a regulatory approach, a strategic research plan and a study on the societal impact of UAS. The ERSG is aware that most companies active in this business sector are small and medium enterprises (SMEs) which would be unable to cope with a disproportionate regulatory burden; and that, in addition, disproportionate regulation would considerably reduce the potential of UAS technology to develop a new market. In this respect, and in order to create a seamless EU UAS market, the ERSG report also proposes the transfer of national competences for UA under 150 kg to the EU by 2016. In the meantime (and this is of special interest for UAS PaRS applications since the majority of UAS commercial applications are undertaken with light UA), the development of regulations remains in the hands of the national CAAs. Up to now, fifteen EU countries have developed partial regulations for civil UAS operations and another five are in the process of doing so.

In Australia, as early as 2002, the Civil Aviation Safety Authority (CASA), passed Civil Aviation Safety Regulation 101 (CASR 101) (CASA, 2002), the first operational regulation for unmanned aircraft in the world. Now, thanks to CASR 101, anyone interested in becoming a UAS operator—those flying UAS for business in contrast to recreational and sport users—benefit from a regulatory framework that allows them to apply for a UAS operator's certificate. The certification covers a wide range of aspects including UAS controllers, UAS pilots, and medical, maintenance, and liability areas among others. At the time this paper was written, there were 40 certified UAS operators and of them 29 were certified for aerial survey operations (CASA website).

In the UK, the Civil Aviation Authority (CAA) has regulated UAS flights through the "Air Navigation: The Order and the Regulations" (CAP 393) and "Unmanned Aircraft System Operations in UK Airspace" (CAP 722) documents respectively (CAA, 2012a,b). A key asset to UAS operations is the Basic National UAS Certificate (BNUC), the CAA's accepted qualification for lightweight UAS pilots and crews. BNUCs are managed and awarded by the European Unmanned Systems Centre (EuroUSC) a UK organization that has been authorized by the CAA to asses the airworthiness of lightweight UAS of 150 kg and under. Of special interest for UAS-based photogrammetry and remote sensing is the BNUC-S, for the operation of UAS with a Maximum Take Off Mass (MTOM) of less than 20 kg that are used for "aerial work" under Visual Line of Sight (VLOS) or Extended VLOS (EVLOS) operational conditions.

In parallel, on a local and regional, partial, although encouraging steps, are being taken. In October 2012, the French Civil Aviation Authority, the DGAC, granted the first authorization ever issued to a UAS company in France to Delair-Tech, for a civil UAS to fly over 100 km in French airspace. This is of major relevance for power and pipe line surveys and, in general, any Beyond Visual Line of Sight (BVLOS) operation. In December 2012, COWI, the Danish photogrammetric and mapping company was the first private company in Denmark to be authorized to use UA for aerial surveys of disasters and other tasks that can benefit from aerial images in both urban and rural areas without further approval. At the time this article was written, there were a total of seven organizations authorized by the Danish Transport Authority (*Trafikstyrelsen*) to fly UA. If the survey area falls within a radius of five miles of an airport, the airport must be notified of the flight. In April 4, 2013, the company Aermatica conducted the first authorized UAS flight in non-segregated Italian airspace with its unmanned Anteos system. The authorization was granted by the Italian Civil Aviation Authority (*Ente Nazionale per l'Aviazione Civile*, ENAC) to perform an aerial survey of the *Basilica di S.M. di Collemaggio* in L'Aquila and other churches damaged during the L'Aquila earthquake.

In May 2013, the Brazilian National Civil Aviation Agency (*Agência Nacional de Aviação Civil*, ANAC) has recently authorized private operators to fly UA. Up to now, the Federal Police was the only non-military organization allowed to do so. X-Mobots (São Carlos, SP), the first private company to benefit from the decision, obtained its Certificate of Experimental Flight Authorization (*Certificado de Autorização de Voo Experimental*, CAVE) from the ANAC.

For further reading on UAS regulations and regulation roadmaps, in addition to the ERSG (ERSG, 2013) and FAA reports (Federal Aviation Administration, 2013), a comprehensive description on the most recent work is presented in van Blyenburgh (2013), including the ICAO circular 328, reports on the EuroCAE WG 73 on UAS and the experiences of different expert groups from several countries around the world.

5. Navigation, orientation and sensing payloads

For PaRS applications, two critical components of a UAS are the navigation-and-orientation payload and the remote-sensing payload.

In a typical UA, the "autopilot" loop repeatedly reads the aircraft's position, velocity and attitude (tPVA, with t standing for time) from the Navigation System (NS) and uses the tPVA parameters to feed the Flight Control System (FCS) to guide the aircraft (Elkaim et al., 2014). Specially in PaRS UAS, an Orientation System (OS) is also in place to estimate the same tPVA parameters but not necessarily in real-time e.g. to perform a posteriori sensor orientation for mapping. In an "ideally"-designed UA for PaRS, the NS sensors—inertial measurement unit (IMU), GNSS receiver, baroaltimeter, compass and possibly others—would be shared by the OS or the redundancy of the NS and OS sensors would be exploited. In practice, most times, the NS and OS are separated or the NS of the autopilot provides the tPVA solution to the OS. In the latter case the OS only has a trivial input/output function and its orientation parameters are not used as aerial control but as initial approximations for the automatic generation of tie points and their photogrammetric measurements. This is so because the NS is required to provide a real-time high-frequency (up to 1 kHz) tPVA solution of low to moderate accuracy as opposed to the OS that is required to provide a high accuracy tPVA solution although it is post-processed and at lower frequency. This chapter compiles information on available, commercial NS and OS suitable for UAS PaRS. Information supplied by the manufacturers' brochures and websites is presented in tables for both categories.

5.1. Autopilots and navigation systems

The components listed in Table 2 are just a few examples from the wide spectrum of UAS autopilots. Note that autopilot weights do not include GPS antennas (which may be the limiting weight factor for micro-UAS). Also note that the presented products may admit additional sensors and/or demonstrate different capabilities. AirWare, formerly Unmanned Innovation Inc. (USA), provides a range of autopilots from closed solutions to customized devices, featuring integrated INS/GPS navigation and flight control systems.

Table 2
Autopilot examples.

Product/company	Sensors	Weight (g)	Size (cm)	Platform	Price (kE)
osFlexPilot/Airware	INS/GPS/AS/MM	200	$11 \times 5.5 \times 2.8$	Fixed-wing, VTOL	$\leqslant$5.5
osFlexQuad/Airware	INS/GPS/AS/MM	32	$6.73 \times 6.73 \times 2$	Multi-rotor	$\leqslant$4
MP2128/MicroPilot	INS/GPS/BA/AS	24	$10 \times 4 \times 1.5$	Fixed-wing, VTOL	$\leqslant$4.4
MP2028/MicroPilot	INS/GPS/BA/AS	28	$10 \times 4 \times 1.5$	Fixed-wing, VTOL	$\leqslant$2.5
PiccoloNano/CloudCap Technologies	GPS/AS/BA	65	$4.6 \times 7.6 \times 2$	Small platforms	–
Piccolo II/CloudCap Technologies	INS/GPS/BA/AS	226	$14.2 \times 4.6 \times 6.2$	Fixed-wing, VTOL	–
VECTOR/UAV Navigation	INS/GPS/MM/BA/AS	180	–	Mini and Tactical	–
ArduPilot Mega 2.5/3DRobotics	INS/MM/BA	17	$6.7 \times 4 \times 1$	Fixed-wing, VTOL	0.12

AS: airspeed sensor; BA: baroaltimeter; MM: magnetometer; weigths do not include GPS antennas.
ArduPilot Mega 2.5 does not include GPS receiver, power module and telemetry module.

Table 3
Commercial Hybrid Measurement Units (HMU) and Hybrid Navigation Systems (HNS) for unmanned aircraft orientation.

Make	Model	Weight (kg)	GNSS Φ or ρ	σ_P (m)	Weight IMU (kg)	σ_a (μG/$\sqrt{\text{Hz}}$)	μ_a (μG)	σ_ω (deg/s/$\sqrt{\text{Hz}}$)	μ_ω (deg/h)	$\sigma_{\vartheta,\gamma}$ (deg)	σ_ψ (deg)
iMAR	VRU-FQ	1.750	Φ	0.05–0.30	1.750	50	100	0.0016	11	NA	NA
Applanix	AP LN-200 E	0.250	Φ	0.05–0.30	0.750	50	50	0.0008	0.5	0.008	0.025
Novatel	SPAN-IGM	0.515									
Adv. Nav.	Spatial-Dual	0.304	ρ	1.20–2.00	Included	246	35	0.009	4	0.15	0.10
Novatel	MIC ADIS-16488	0.124	Φ	0.01–0.02	0.048	67	100	0.005	6	0.04	0.22
Independent test										0.09	0.16
iMAR	iμVRU-01	0.050	ρ	1.20–2.00	Included	310	2000	0.005	10	0.20	<1
Adv. Nav.	Spatial	0.025	Φ	0.01–0.02	Included	400	60	0.005	18	0.40	0.80
Independent test			ρ	0.22–0.77						0.07	0.30
SBG	IG500-E (box)	0.049	Φ,ρ	0.05–0.30	Included	250	60	0.05	20	0.50	0.50
SBG	IG500-E (OEM)	0.010	Φ,ρ	0.05–0.30	Included	250	60	0.05	20	0.50	0.50

Φ: phase measurements; ρ: code measurements; σ_P: positional precision; σ_P: positional precision; σ_a: linear accelerations' noise (PSD level); μ_a: linear accelerations' in-run bias stability (PSD level); σ_ω: angular rates' noise (PSD level); μ_ω: angular rates' in-run bias stability (PSD level); $\sigma_{\vartheta,\gamma}$: roll and pitch precision (whole spectrum); σ_ψ: heading precision (whole spectrum); NA: not available.

MicroPilot (Canada) has been producing a wide range of products since 1995, which have been used by companies or institutions such as SRS Technologies (USA), BlueBird Aerosystems (Israel), INTA (Spain) and several branches of NASA. Prices range from 2000 to 8000 US dollars, multiplying the on-board computational capabilities by fifty times (in higher-end models). Piccolo, by CloudCap Technologies (USA), provides a solution including the core autopilot, flight sensors, navigation, wireless communication and payload interfaces, and has been used for PaRS (Schinstock et al., 2009; Cosentino, 2008). UAV Navigation describe themselves as providers of "high performance navigation and autopilot solutions used by many Tier1 aerospace companies in a wide range of UAS such as high-performance tactical unmanned planes, targets, mini UAS, helicopter and quadcopter aerial vehicles," and has also been used by PaRS groups (Zarco-Tejada and Berni, 2012). For additional information, a survey of UAS autopilots can be found in Chao et al. (2010) and a comprehensive compilation of the main brands of UAS autopilots is provided in UAVMarketSpace (2012). Finally, van Blyenburgh (2013) compiles a list of 201 inventorised autopilots.

Several open-source frameworks exist to tackle auto-piloting in UAS. Meier et al. (2011) and Mészáros (2011) present reviews of available open-source hardware and software for both UAS and UGVs, in addition to actual results based on in–house developments. Some noteworthy developments are the Paparazzi project (Brissset and Drouin, 2004), defined as "a free and open-source hardware and software project intended to create a powerful and versatile autopilot system for fixed-wing and multi-copter platforms," and already used in aerial imaging missions (Jensen et al., 2008, 2009). Other initiatives are the OpenPilot project (http://www.openpilot.org/about/), a community-driven open-source project combining software and hardware-plus-sensor solutions for fixed- and rotary-wing platforms, or ArduPilot (http://www.diydrones.com/notes/ArduPilot), created within the DIYDrones community, developing a family of open source autopilots based on the Arduino platform. The ArduPilot product family, manufactured by 3DRobotics, is quite popular among micro UAS users and also radio-control model aircraft developers, as it provides small and affordable products for guidance and control.

In addition, Unmanned Ground Vehicles (UGV) have both benefited and contributed to the advent of autopilot technology. Early developments such as CLARAty, by the NASA's Jet Propulsion Laboratory, preceded the recent Robot Operating System (ROS) (www.ros.org), which has been also adopted by aerial vehicles (Singh et al., 2012)

5.2. Orientation systems

Today's level of miniaturization of computer boards, GNSS receivers and antennas, IMUs and, in general, sensors allows for the integration of hybrid measurement units (HMU) for light unmanned aircraft whose measurements can be processed—in real-time, in a hybrid navigation system (HNS) or in post-processing, in a hybrid orientation system (HOS)—to deliver position orientation parameters at the cm-level (Rehak et al., 2013). These results are dominated by the quality of the GNSS receiver and, to an even larger extent, the quality of the GNSS receiver's antenna (van Diggelen, 2010). The accuracy of the attitude part of orientation is highly dependent on the IMU quality and flight dynamics, and it varies within the interval $[0.015, 0.2]$ deg for $\sigma_{\vartheta,\gamma}$ (roll and pitch) and within $[0.03, 0.5]$ deg for σ_ψ (heading). Therefore, the figures given in the next paragraph are simply indicative as they include general specifications and specific test results of different trajectories. To summarize the current capabilities of HMU and HOS, considering the critical role of the payload weight, we review a representative, though noncomprehensive, set of commercial systems with weights from around 1 kg down to 0.01 kg.

A 0.9–1.5 kg HMU (0.25 kg for its GNSS multiple-frequency antenna, 0.25 kg for its control unit including a GNSS multiple-frequency phase receiver and 0.4–1.0 kg for its IMU) guarantees a geodetic-grade tPVA post-processed solution (P: $\sigma_{e,n,u} < 0.05$ m, V: $\sigma_{ve,vn,vu} < 0.005$ m/s, A: $\sigma_{\vartheta,\gamma} < 0.015$ deg, $\sigma_{\psi} < 0.030$ deg). This category of HMUs and HNSs is represented by the Appanix (Trimble) AP family (AP20 and AP40) and Novatel's MEMS Interface Card (MIC) with tactical-grade or higher grade IMUs like the Northrop-Grumman LN200 or the KVH 1750. iMAR's iVRU-FQ belongs to this category although its weight (1.8 kg) is significantly higher. The performance of this technology is well-known and the figures above are repeatable.

For frame photographic cameras, the above precision performance is compatible with direct sensor orientation (DiSO)—a.k.a. direct georeferencing—for altitudes up to 50 m above ground and ground sampling distances (GSD) of 2 cm or larger. The heading precision requirement is dependent on the camera "size" (number of pixels) and shape (number of rows and columns) and for a consumer-grade camera of about 14 Mpx, for the mentioned height and GSD, a heading error precision of $\sigma_{\psi} < 0.06$ deg would be sufficient. These are precision figures, which do not take into account the remaining INS/GNSS inaccuracies. For mapping applications, they assume that the camera is calibrated down to the 0.5 px ($1-\sigma$ level) precision and accuracy. Therefore, although the performance is promising for DiSO, it is better suited to the Fast AT (Blázquez and Colomina, 2012a) and integrated sensor orientation (ISO) (Blázquez and Colomina, 2012b) procedures. Note that for DiSO, it is not just precision that counts but also accuracy; i.e., absence of systematic errors.

Advanced Navigation's Spatial-Dual HMU and HNS (0.304 kg without its two GNSS antennas, despite being in a shockproof case) implements an interesting concept: two GNSS geodetic-grade receivers featuring a triple-frequency capability, enabled for GPS, GLONASS, Galileo and BeiDou signals.

The double antenna design guarantees 0.1 deg heading accuracy regardless of the vehicle dynamics for 1 m or longer antenna-to-antenna distances. The HMU includes baroaltimeters, magnetometers, a MEMS IMU and optional odometers and pressure sensors for terrestrial and underwater navigation respectively. Based on a high-frequency IMU output rate, the Spatial-Dual can generate a tPVA solution up to 1 kHz making it ideal for both navigation and orientation systems in high-dynamic motion. According to the manufacturer, the Spatial-Dual can deliver positions at the cm level as provided by GNSS phase measurements, velocities better than 1 cm/s and attitudes at the 0.15 deg, 0.1 deg levels for $\sigma_{\vartheta,\gamma}$ and σ_{ψ} respectively.

These results allow for block adjustment with a reduced set of ground control points (due to the positional precision of aerial control). For very wide angle objectives and/or low resolution images—instantaneous field of view (IFOV) of 0.2 deg,—they are consistent with DiSO and sufficient for Fast AT. They also allow for fast automatic tie point identification and measurement.

MEMS-based, lighter HMUs at the 0.1 kg level, are represented by Novatel's combination of the MIC and the ADIS-16488 IMU from Analog Devices (0.08 kg without GPS antenna and protective box), iMAR's iIMU-01 and iVRU-01 units (0.05 kg without GPS antenna), Advanced Navigation's Spatial (0.025 kg without GPS antenna) and SBG's IG500-E (0.049 kg without GPS antenna, 0.01 kg without protective box for OEM integration). In Novatel (2013) the combination of Novatel's MIC and the ADIS-16488 IMU, is related to performances $\sigma_{e,n} \approx 0.01$ m, $\sigma_u \approx 0.02$ m, $\sigma_{\gamma,\vartheta} \approx 0.04$ deg, and $\sigma_{\psi} \approx 0.22$ deg that are consistent with an independent evaluation of the same IMU (Goodall et al., 2012) that delivered $\sigma_{\gamma,\vartheta} \approx 0.09$ deg, and $\sigma_{\psi} \approx 0.16$ deg. Advanced Navigation (2012) reports accuracies of $\sigma_{e,n} \approx 0.2$ m, $\sigma_u \approx 0.8$ m, $\sigma_{\gamma} \approx 0.05$ deg, $\sigma_{\vartheta} \approx 0.08$ deg and $\sigma_{\psi} \approx 0.3$ deg for its Spatial HNS in a terrestrial kinematic test (with odometer). However, the company is rather conservative in its navigation performance specifications ($\sigma_{\gamma,\vartheta} \approx 0.4$ deg, $\sigma_{\psi} \approx 0.8$ deg).

As with the Advanced Navigation's Spatial-Dual, cm-level positional precision for aerial control allows for reduced to minimal ground control configurations in integrated sensor orientation (ISO, block adjustment with position or position/attitude aerial control). This given, IMU quality and trajectory dynamics make the difference between just ISO or Fast AT and DiSO. dm-level positional accuracy can be exploited depending on GSDs and project requirements. Even in the poor accuracy case (m-level positioning, deg-level attitude), these orientation systems facilitate digital aerial triangulation as image connections through tie points can be rapidly derived from the known geometry between images.

Whether or not a low-cost OS whose results cannot be exploited as aerial control measurements is of interest is an open question. From a technical point of view it brings us back to the pre-GPS days of classical aerial triangulation. From a business point of view, achievement of sufficient productivity very much depends on local infrastructure (ground control point databases) and logistics (cost of ground surveys).

We conclude this section by quoting (Gakstatter, 2010): *as soon as 2014 and at latest by 2020, centimeter level accuracy will be in the hands of anyone with a few hundred dollars to spend*, which is consistent with the discussions and results in van Diggelen et al. (2011) and Rehak et al. (2013). Therefore, sooner than later, cm-level accuracies for exterior orientation parameters of images acquired with micro-unmanned aircraft and heavier aircraft will be an inexpensive, achievable goal. Geodetic-grade attitude precisions ($\sigma_{\vartheta,\gamma} < 0.015$ deg, $\sigma_{\psi} < 0.030$ deg) compatible with DiSO can be achieved with the traditional, "heavy" tactical-grade IMUs. Results of airborne missions combining geodetic-grade multi-constellation GNSS receivers with MEMS tactical-grade, light IMUs are not yet available. However, with weights of around 0.05 kg, large-scale production behind them, and the possibility to use redundant IMU setups we can expect significant progress towards DiSO precisions with 0.01 kg-level, INS/GNSS-based orientation systems in coming years.

5.3. Sensing payloads

UAS-based PaRS is a particular case of airborne PaRS and, as such, once the application requirements are set, the optimal combination of carrier—the UA—and sensing payload has to be found. In practice, it is often the case that the UA is predefined and, therefore, the UAS developer or operator faces the problem of fitting a remote sensing payload into the given UA volume, weight and power specifications, beside serving the specific application requirements (sensing bandwidth, accuracy, resolution, etc.) Finding the right balance is not only difficult but also complex, as the range of available systems is vast, ranging from low-cost mass-market, amateur and professional, to systems specifically designed for PaRS ones (including those designed for UAS and general systems).

A recent in-depth survey on optical remote sensing instruments, for terrestrial static, terrestrial kinematic, airborne and space image acquisition systems, can be found in Remondino (2011). Specifically for UAS, van Blyenburgh (2013) identifies 406 imaging and ranging instruments including active and passive systems, optical—from the visible band, to the Near Infrared (NIR) up to the Thermal Infrared (TIR) and microwave systems.

This section concentrates on remote sensing instruments which might be suitable for micro, mini and tactical UA payloads, particularly distinguishing between visible-band, near-infrared, multispectral, hyperspectral, thermal, laser scanners and synthetic aperture radar. Tables 4–9 describe fundamental characteristics of some common and/or representative sensors, and aim to complement sensor integrators' knowledge on available systems.

5.3.1. Visible-band, near-infrared and multi-spectral cameras

The photogrammetric and remote sensing community have benefited from the mass-market and other professional markets' strength by leveraging these to design remote sensing instruments with high resolution.

Some developments consisting of multiple-head RGB cameras have been performed and results have been recently published. Xie et al. (2012) presents a wide-angle camera based on four single cameras Canon EOS 5D Mark II, including its calibration process and results. Grenzdörffer et al. (2012) describes the integration of five cameras (Crevis MV-CS27U USB) and its geometric and radiometric calibration procedures. Kohoutek and Eisenbeiss (2012)

Table 4
Common and/or representative small format (SF) and medium format (MF) visible band cameras.

Manufacturer and model	Format type	Resolution (MPx)	Size (mm^2)	Pixel size (μm)	Weight (kg)	Frame rate (fps)	Speed (s^{-1})
Phase One iXA 180	MF	CCD 80	53.7 ×40.4	5.2	1.70	0.7	4000 (fp) 1600 (ls)
Trimble IQ180	MF	CCD 80	53.7 ×40.4	5.2	1.50	–	1000 (ls)
Hasselblad H4D-60	MF	CCD 60	53.7 ×40.2	6.0	1.80	0.7	800 (ls)
Sony NEX-7	SF MILC	CMOS 24.3	23.5 ×15.6	3.9	0.35	2.3	4000 (fp)
Ricoh GXR A16	SF IUC	CMOS 16.2	23.6 ×15.7	4.8	0.35	3	3200 (fp)

fp: focal plane shutter, ls: leaf shutter.

Table 5
Common and/or representative multispectral cameras for UAS.

Manufacturer and model	Resolution (Mpx)	Size (mm^2)	Pixel size (μm)	Weight (kg)	Spectral range (nm)
Tertracam MiniMCA-6	CMOS 1.3	6.66 ×5.32	5.2 ×5.2	0.7	450–1050
Quest Innovations Condor-5 UAV-285	CCD 1.4	10.2 ×8.3	7.5 ×8.1	0.8	400–1000

Specifications on the MiniMCA-6 hold for each of the 6 sensors.

Table 6
Common and/or representative hyperspectral cameras for UAS.

Manufacturer and model	Resolution (Mpx)	Size (mm^2)	Pixel size (μm)	Weight (kg)	Spectral range (nm)	Spectral bands and resolution
Rikola Ltd. Hyperspectral Camera	CMOS	5.6 ×5.6	5.5	0.6	500–900	40 10 nm
Headwall Photonics Micro-Hyperspec X-series NIR	InGaAs	9.6 ×9.6	30	1.025	900–1700	62 12.9 nm

Table 7
Common and/or representative thermal cameras for UAS.

Manufacturer and model	Resolution (Mpx)	Size (mm^2)	Pixel size (μm)	Weight (kg)	Spectral range (μm)	Thermal sensitivity (mK)
FLIR TAU 2 640	Uncooled VOx Microbolometer 640 × 512	10.8 ×8.7	17	0.07	7.5–13.5	⩽50
Thermoteknix Systems Ltd. Miricle 307K-25	Amorphous Silicon 640 × 480	16 ×12.8	25	0.105	8–12	⩽50

Table 8
Common and/or representative laser scanners for UAS.

Manufacturer and model	Scanning pattern	Range (m)	Weight (kg)	Angular res. (deg)	FOV (deg)	Laser class and λ (nm)	Frequency (kp/s)	Application
ibeo Automotive Systems IBEO LUX	4 Scanning Parallel lines	200	1	(H) 0.125 (V) 0.8	(H) 110 (V) 3.2	Class A 905	22	A
Velodyne HDL-32E	32 Laser/detector Pairs	100	2	(H) – (V) 1.33	(H) 360 (V) 41	Class A 905	700	MM
RIEGL VQ-820-GU	1 Scanning Line	⩾1000	–	(H) 0.01 (V) N/A	(H) 60 (V) N/A	Class 3B 532	200	H

A: automotive; MM: terrestrial mobile mapping; H: hydrography.

Table 9
Common and/or representative synthetic aperture radars for UAS.

Manufacturer and model	Spectral bands	Weight (kg)	Transmitted power (W)	Resolution (m)
IMSAR NanoSAR B	X and Ku	1.58	1	between 0.3 and 5
Fraunhofer FHR MIRANDA	W	–	0.1	0.15
NASA JPL UAVSAR	L	200	2000	2
SELEX Galileo PicoSAR	X	10	–	1

NanoSAR B weight does not account for antenna and IMU.

describes the use of a range-imaging (RIM) camera on a UAS, based on the time-of-flight (ToF) measurement principle, to measure distances to structures.

The maturation of visible-spectrum cameras has impacted several side-technologies, for example, mobile phones. Current smartphones come equipped with high-quality cameras at a reasonably low-cost. Yun et al. (2012) reports on a fixed-wing UAS equipped with Samsung Galaxy S and S2 smartphones to produce a digital elevation model (DEM) of a construction area in South Korea. More recently, the French company Lehman Aviation presented the LA300 UAS, featuring an on-board 41 megapixel Nokia Lumia 1020 optical camera.

Moving to the upper portion of the spectrum, several small, commercial multi-spectral cameras exist and have already been used in UAS for PaRS. This is the case of the mini-MCA series, from Tetracam, which is available in three configurations to capture four, six and twelve channels (Tetracam, 2012). They are able to discriminate spectral reflectance which is an important indicator in applications related to vegetation health. Bendig et al. (2012) and Lucieer et al. (2012) describe developments using mini-MCA cameras and Kelcey and Lucieer (2012) reports on the geometric and radiometric calibration of a mini-MCA.

Table 4 summarizes common and/or representative RGB cameras suitable for UAS PaRS, as reported in several experiements. Bäumker and Przybilla (2011) report on the Ricoh GXR using the A16 lens, featuring 16.2 Mpx and variable focal length (24–85 mm), and Küng et al. (2011) report on the use of the Sony NEX-5. In the same product family, the Sony NEX-7 is present in commercial systems such as Falcon 8, from Ascending Technologies, or the Aeromapper, from Aeromao. In addition, some sensors are described as potential candidates in view of their specifications. For ease of comparison, we follow the same structure as in Remondino (2011) for the visible-band cameras.

Finally, Table 5 describes some of the most common developments in the field of multi-spectral sensing for UAS.

5.3.2. Hyperspectral cameras

Remote sensing with hyperspectral cameras deals with imaging narrow spectral bands over a continuous spectral range, producing the spectra of all pixels in the scene. In contrast, multispectral remote sensing produces discrete bands and usually has a lower spectral resolution. Hyperspectral sensors, therefore, extract more detailed information than multispectral sensors because an entire spectrum is acquired at each pixel. Contrary to the visible-spectrum camera developments, which have reached a weights of hundreds of grams and resolutions of tens of megapixels, the miniaturization process of multi- and hyper-spectral cameras is challenging in terms of optics and sensor calibration.

A combination of two commercial products has been announced for the first quarter of 2013, the fixed-wing UAS BRAMOR gHY, by C-Astral (Slovenia), and a small and light-weight hyperspectral camera developed by Rikola Ltd. Rikola (2012).

In Rufino and Moccia (2005), a set of diverse sensors is presented in a UAS integration, consisting of a thermal camera, a three-band multispectral camera operating in the visible spectrum, and two hyperspectral sensors operating in the visible and NIR bands.

Table 6 provides information on recent relevant developments on hyperspectral sensors for UAS.

5.3.3. Thermal imaging

There has been noticeable progress in thermal imaging miniaturization in recent years. Low-weight, small-size imagers, such as those developed by FLIR, were first used in the military context for remote reconnaissance (Kostrzewa et al., 2003) and are becoming more common in applications such as forest fire monitoring (Rufino and Moccia, 2005; Scholtz et al., 2011). Aero-triangulation studies have also been carried out using thermal images (Hartmann et al., 2012).

Table 7 compiles some existing products in the family of thermal sensors, suitable for light UAS.

5.3.4. Laser scanners

While the use of laser scanners (or LiDAR, indistinctively) together with medium-large format cameras, is now common in traditional photogrammetry, their application to UAS for PaRS remains challenging, either due to the trade-off between performance and the size or cost of LiDAR, or the effect of flight dynamics on the measurement process (Zhou et al., 2012; Wallace et al., 2012). Despite such difficulties, one of the first UA-borne LiDAR and camera integrations was presented a few years ago (Nagai et al., 2004). Other early integrations that followed them featured development for rapid mapping in emergency situations (Choi et al., 2009), and a compact and lightweight airborne laser scanner LMS-Q160 from Riegl mounted on a rotary wing Scout B1-100 (Imbach and Erk, 2009).

Short-range laser scanners (for example, from manufacturers such as FARO, SICK and Hokuyo) have already been integrated in UAS, but not for PaRS missions. In these cases, obstacle detection and avoidance (Scherer et al., 2008) or short-range mapping have been reported.

Table 8 presents recent LiDAR sensors which have been recently integrated with UAS. Recent integrations include the TerraLuma octocopter, which is equipped with an Ibeo LUX automotive LiDAR system (Wallace et al., 2012), or the premature 3D flash LiDAR described in Zhou et al. (2012), optimized in size and weight for UAS, presenting results for simulated flights at 300 m' altitude. In addition, the Velodynes HDL-32E has been successfully integrated on a Phoenix AL-2 multicopter UAS, from Phoenix Aerial Systems, and the RIEGL VQ-820-GU hydrographic scanner, integrated in a Schiebel CAMCOPTER S-100.

5.3.5. Synthetic aperture radar

As for laser scanners, Synthetic Aperture Radar (SAR) technology has come a long way in traditional remote sensing. Yet its adaption to UAS (miniaturization versus performance) has still not been solved. However, there is some literature on the use of this technology, and few integration efforts into UAS have been reported world-wide. Indeed, the good performance of SAR despite adverse weather conditions is a very interesting feature not just for military groups, which have traditionally endorsed SAR technology, but also in PaRS.

Remy et al. (2012) describes a novel system for UAS, based on the combination of radar P- and X-bands for generation of digital terrain and elevation models in forested areas. In Essen et al. (2012), a development based on the W-band (millimeter-wave) is integrated within the NEO S300 helicopter-type UAS, to observe small-scale features and resolving up to 15 cm. In Schulz (2011), a platform development based on the SwissUAV NEO S-350 is presented along with the integration of a millimeter-wave SAR.

Table SAR compiles current SAR sensors integrated in UAS. The UAVSAR concept, developed by the NASA JPL (details in the table were extracted from Rosen et al. (2006)), is currently being integrated on Global Hawk UAS. More details on this integration were provided at the UAS Payloads Conference in Washington DC, June 19, 2012. The SELEX Galileo's PicoSAR has also been integragted into an Integrator UAS, from InSitu.

6. Processing

As in traditional airborne PaRS, the processing of the data and measurements collected in a UAS mission is a key step in the development of UAS PaRS services. In principle, one would expect UAS PaRS to yield exactly the same type of products as airborne PaRS and that the corresponding production line paradigm—the "basic operations" (Dowman, 2012)—would be similar with some influences from close-range photogrammetry (Haala et al., 2011; Remondino et al., 2011; Mayr, 2013). After all, it is a question of blocks of aerial images with some influences from close-range photogrammetry and also a question of close-range photogrammetry going aerial. Indeed, today, this is the case for a subset of the traditional PaRS products: orthophotos and elevation/surface models (assuming that the previous image orientation and camera calibration data are available). The tendency indicates that, in the near future, this will be the case for most of PaRS products since, once images are oriented and cameras calibrated, automatic, assisted or manual image interpretation (semantic feature extraction) to produce 3D models of various levels of detail can be conducted (Qin et al., 2013). (Deviation from parallelism of the image planes and possibly scale differences of overlapping images due to rotational and translational high frequency UA motion may hinder the stereoscopic capacity and visual comfort of human operators. However, convergent images can be rectified to the stereoscopic normal case and to a common scale.)

We note that the "old" photogrammetric community wishing to benefit from the next technological wave is reluctant to let a newcomer into the *santum sanctorum* of data processing without scrutinizing its performance and is prone to keep on using known software and methods "updated" for UAS (Cramer, 2013b; Mayr, 2013). This translates into more informative software outputs, more intermediate quality-control checks and more interactive editing tools. On the other hand, the "new" mapping community is less sensitive to and in lesser need of self-diagnosis tools and intermediate quality control checks and therefore more prone to the use of fully automated implementations of the same paradigm. There seems to be room for everyone, updated classics and newcomers.

On one hand, that UAS acqusition technologies, from platforms to sensors, are "lighter, smaller and simpler" does not necessarily translate into simpler processing software systems. In fact, in general, more sophisticated processing is required to compensate for the necessarily limited performance of small, lightweight platforms and acquisition systems. This situation is described well in Qin et al. (2013), a realistic paper where the challenges of processing—orientating and calibrating—a block of about 900 images are described. In a way, it could be said that photogrammetry and computer vision had to join forces to accurately and automatically process UAS-sourced images. On the other hand, "lighter, smaller and simpler" does not necessarily translate into second class results because the circumstances of UAS PaRS are different—and even more favorable—from those of traditional airborne PaRS: UAS PaRS can leverage the huge investment in mass-market navigation and imaging technologies, benefit from overall miniaturization trends and take advantage of its usually GSD.

6.1. Image orientation and camera calibration

An autopilot usually includes its own low-cost, light navigation system (NS). An orientation system (OS), depending on the orientation requirements, usually includes a mapping-grade or geodetic-grade set of sensors. In the former case, the NS time–Position–Velocity–Attitude (tPVA) solution can hardly be used as aerial control and therefore neither direct sensor orientation (DiSO) nor integrated sensor orientation (ISO) make much sense, and we have to go back to pure aerial triangulation or indirect sensor orientation (InSO). In this case, the orientation parameters provided by the NS simplify the automatic generation of tie points, their photogrammetric measurements and initial approximations to their coordinates. As a result, in practice, the orientation of unsorted sets of images by InSO is more of an academic exercise than a real issue in outdoor applications. In the latter case (Rehak et al., 2013) show that cm-level positioning can be achieved and both DiSO and ISO are possible.

Thus we arrive at the first question: InSO versus ISO. Advocates of a pure photogrammetric approach, that is InSO, argue that in small areas a dense set of Ground Control Points (GCPs) is easy and cheap to establish and, in general, obtain from existing orthophotomaps. Further, they claim that the fewer navigation and orientation sensors, the less MTOW and longer the autonomy. Those in favor of INS/GNSS (for their use in DiSO and ISO) argue that with less than 100 g (Table 3) cm- to dm-level positioning is feasible as proven by (Rehak et al., 2013). At the time this report was written, the vast majority of UAS imagery for mapping is being processed with the InSO method; i.e., deriving orientation and calibration parameters solely from photogrammetric measurements and GCPs. (In fact, while there are end-to-end commercial solutions for InSO, there are no comparable solutions for ISO yet.)

Within the InSO realm, there are three calibration sub-strategies. One option is to calibrate the camera shortly before or after the mission but previously to the bundle adjustment in a separate process as recommended in Remondino et al. (2011) where varying distances to object and convergent images guarantee the determinability of calibration parameters. We will refer to this as pre-calibration. (pre-calibration is also required for DiSO) A second option is to apply self-calibration as done, for instance, in the Pix4D software—with the Conrady-Brown (CB) (Brown, 1971) and interior orientation (IO) models—as reported in Cramer (2013b). The third option is to combine both, also as reported in Cramer (2013a) and suggested in Colomina et al. (2007). There are not many comparative analyses on the performance of the three strategies. In Cramer (2013b), both pre-calibration and self-calibration yield comparable results and, interestingly, the combination of pre-calibration and self-calibration does not bring any significant improvement. The risks of self-calibration with the CB and IO models in aerial bundle adjustment are known and well-illustrated in Vallet et al. (2011) and Rosnell and Honkavaara (2012) where, for the same UAS image data set, rather different interior orientation parameters are recovered. On the other hand, the instability of some calibration parameters in the CB and IO calibration models explains why self-calibration with those parameters: (a) works well and that their value has a more contextual than absolute sense and (b) dominates over other self-calibration models.

Whatever the camera calibration strategy is, modern InSO is based on the automatic detection and image measurement of tie points. In traditional photogrammetry, this task has been solved since the beginning of the 1990s (Tsingas, 1992) and is known as automatic aerial triangulation (AAT). However, fifteen years later, the traditional, long established and proven photogrammetric AAT software was not able to process UAS blocks (Qin et al., 2013). In fact, there is nothing wrong with AAT. It was simply designed under completely different assumptions: interior orientation, radial and decentering distortions were assumed to be stable and therefore amenable for infrequent pre-calibration; block structure was assumed regular (almost nadir images, approximate constant scale, overlap and, within strips, attitude); and geometric and radiometric variations were known to be moderate.

On the contrary, the irregularity of UAS blocks was no obstacle to automatic image matching and bundle adjustment software originated in the computer vision community for more general purposes—the so-called Structure from Motion (SfM) approach (Snavely et al., 2008; Agarwal et al., 2009),—or specifically for UAS flights (Küng et al., 2011), or in more recent photogrammetric AAT software like PhotoScan from AgiSoft as reported, for instance, in Gini et al. (2013). Computer vision techniques for automatic tie point generation are based on point detectors and descriptors of the SIFT type (Lowe, 2004) and its many variations or redesigns like SURF (Bay et al., 2008), ASIFT (Morel and Yu, 2009), BRIEF (Calonder et al., 2010) and LDAHash (Strecha et al., 2012). The tie point candidates are obtained image-wise with the point detectors. In a block of n images, in order to avoid the combinatorial computational explosion of $n \times (n-1)/2$ potential image overlaps, efficient algorithms, using more or less external information, have been derived to identify tie points in a reasonable time period. Some of these algorithms and related software packages have resorted to parallel processing; either through multi-core or through Graphical Processing Unit (GPU) computing.

Abdel-Wahab et al. (2012), Cramer (2013b) and Qin et al. (2013) show how to combine SfM and photogrammetric techniques and, in particular, initialize Inpho's MATCH-AT and Leica's AAT with SfM tie points respectively. A similar approach is used in Rosnell and Honkavaara (2012) to initialize BAE's Socet Set software. Cramer (2013b) reports on the empirical point determination accuracy of two UAS flights with consumer-grade cameras, a Canon Ixus 100 IS and a Ricoh GXR Mount A12 with a Carl Zeiss Biogon objective, processed with a combined SfM and AAT approach. With it, horizontal accuracy is at the half GSD level (μ_E = 0.5 GSD, μ_N = 0.4 GSD) and vertical accuracy somewhat worse, μ_h = 0.7 GSD. The same image data set processed with the Pix4D software (Strecha, 2011; Strecha et al., 2012) yields a remarkable $\mu_E = \mu_N$ = 0.25 GSD and μ_h = 1.0 GSD.

An early review of the classical photogrammetric software packages in the context of UAS photogrammetry is given in Eisenbeiss (2009). From the five principal packages identified in Dowman (2012), at least two have announced new versions supporting UAS-sourced images. In contrast, photogrammetric software from younger companies like AgiSoft, SimActive, ICAROS, Menci Software, RACURS or Orbit GT seem to be better prepared to re-engineer their software rapidly and accept UAS-sourced images. Thus, Gini et al. (2013), for instance, compare the orientation and calibration performance of Pix4D with AgiSoft's PhotoScan and, for the latter, report empirical point determination accuracies of μ_E = 1.1 GSD, μ_N = 0.4 GSD and μ_h = 1.2 GSD; or, in terms of flying height (FH), $\mu_E = 3.8 \times 10^{-4}$ FH, $\mu_N = 1.4 \times 10^{-4}$ FH and $\mu_h = 4.2 \times 10^{-4}$ FH. Remondino et al. (2012) analyze the performance of low-cost, free web service and open-source systems for the automatic orientation of UAS images in a close-range application (AgiSoft's PhotoScan, Microsoft's Photosynth, Microsoft and University of Washington's Bundler, IGN's APERO, and Google and University of Washington's VisualSfM). All software packages were able to deliver correct results as long as the network geometry was strong. However, they conclude that for large and complex data sets, the pure SfM approach is not free from reliability and repeatability problems. Note that APERO (Pierrot-Deseilligny and Cléry, 2011) is an open source tool that integrates computer vision and photogrammetric techniques.

Since INS/GNSS navigation in GNSS-denied or challenged environments may require the so-called "visual aiding"—i.e., the inclusion of tie features measurements in the navigation filter and the implicit or explicit use of the corresponding images' exterior orientation—we mention the related pioneering work in Grün (1985) on real-time bundle adjustment and the Simultaneous Localization and Mapping (SLAM) concept originated in the robotics community (Smith et al., 1986; Leonard and Durrant Whyte, 1991). In a typical SLAM problem, measurements are modelled with stochastic differential equations (SDE) and stochastic equations (SE). The SDEs account for dynamic modelling e.g. the inertial mechanization equations that model the IMU measurements. Their integration yields the "prediction" step of the various SLAM estimation techniques. The SE—the "observation equations" in the geodetic language—are used to model measurements like GNSS ranges and image measurements, yielding the "update" step. The most popular related estimation technique of SLAM is the Kalman filter (Kalman, 1960), a closely related technique to sequential least-squares estimation. In some navigation problems, even in the absence of a dynamic model—i.e., an SDE,—the Kalman filter (KF) is used by the introduction of a trivial dynamic model like $\dot{x} = 0 + v$ with low weights. A recent departure from the classical KF known as incremental Smoothing and Mapping (iSAM) is given in Kaess et al. (2008), based on incremental bundle adjustment closely related to the work of Grün (1985). The literature of INS/GNSS, GNSS and INS navigation with optical sensor aiding for UAS is vast. The reader can consult the comprehensive survey in Kendoul (2012) or examples from the robotics (Dusha and Mejías, 2012) and photogrammetric community (Wang et al., 2008) respectively. Of particular interest for UAS applications is Visual SLAM where the primary instrument of navigation is an optical sensor. An interesting example of Visual SLAM is given in Strasdat et al. (2012) where the relevance of closing trajectory loops—i.e., tie and control features—is demonstrated.

Last, we note that, in the context of Kalman filtering and smoothing (KFS), a real-time solution (forward prediction-filtering step) is, in general, sub-optimal as compared to a post-processed solution (forward and backward prediction-filtering steps and final smoothing). Further, a real-time or even post-processed solution with KFS is, in general, sub-optimal as compared to a post-processed solution with least-squares network adjustment like a bundle adjustment because, in general, it cannot benefit from the tie point geometric constraints between strips.

6.2. Surface reconstruction

Digital surface models (DSM) and orthophotos are the two main mapping products of UAS PaRS. In principle, once images are oriented and, possibly, calibrated, deriving DSM and orthophotos are routine tasks that have already been automated in PaRS since more than 20 years ago (Krzystek, 1991). However, few questions (with still open answers) arise when dealing with UAS-based measurements, namely how conventional software for surface reconstruction perform with UAS images; in case of success, what is the quality (metric accuracy and morphological fidelity) of the obtained solutions; and what is the performance of the new generation software and techniques for DSM production. This section reviews literature regarding this issues.

Rosnell and Honkavaara (2012) investigated point cloud generation from UAS image sequences collected with two different camera setups, and studied the post-processing results using two software pieces, BAE systems' SocetSet, a traditional photogrammetric software, and Microsoft's Photosynth, an Internet-based service designed for photo-collection. Their conclusions indicate that aerial photogrammetric processing with the latter software is possible yet provides sparse point clouds and non-negligible distortions on the final surface model (vertical accuracy Root Mean Square (RMS) was estimated to oscillate between $\mu_h = 40$ GSD and $\mu_h = 120$ GSD). Moreover, the traditional post-processing software produced a point cloud almost as dense and accurate as the reference point cloud provided by a large-format photogrammetric camera (RMS height differences of $\mu_h = 6$ GSD). Yet, the authors observe problems (failed matching) in low altitude and large three-dimensional image sets, suggesting that conventional processing software might not still be flexible enough for UAS-like scenarios (close-range and oblique imagery).

Haala et al. (2013) present the results of processing aerial images from two different cameras using an in-house software development, named SURE. The paper assesses the empirical accuracy of the obtained DSM by measuring distances from points to planar patches extracted from a reference DSM. For a set of 33 patches extracted on two different areas, a Canon Ixus 100 IS yielded a vertical accuracy RMS of $\mu_h = 0.5$ GSD and $\mu_h = 0.53$ GSD, respectively, whilst a Ricoh GXR yielded a vertical accuracy RMS of $\mu_h = 0.33$ GSD and $\mu_h = 0.28$ GSD (the latter camera features a better signal-to-noise ratio due a bigger pixel size).

Harwin and Lucieer (2012) present a comprehensive compilation of the state-of-the-art techniques and their results for UAS-based point cloud generation, and present an accuracy study for the multi-view stereopsis technique. The authors estimate seven-parameter Helmert transformations for point cloud georeferencing—this analysis goes beyond just one-dimensional height accuracy analysis. The study presents results for a set of different testing scenarios: variable GCP measurement methods (Total Station or Real-Time Kinematic GPS), different GCP distributions, number of GCPs used in the adjustment, or even types of GCP targets. As a summarizing result, the authors state that vertical accuracy between $\mu_h = 2.5$ GSD and $\mu_h = 4$ GSD can be achieved when flying between 40 and 50 m above ground, provided sufficient, clearly visible and evenly-distributed GCPs, and between 70% and 95% of overlap between images.

To our best knowledge there are no analyses concerning the morphological fidelity of elevation models obtained with UAS photogrammetry, an indication that contour lines are usually not derived from these type of point clouds.

In Fritz et al. (2013), a study is carried on to compare UAS-based point clouds using an frame camera and Terrestrial Laser Scanner (TLS) point clouds for tree stem reconstruction. No direct results on the point cloud generation are provided—rather, the study focuses tree detection and radius estimation. In these metrics, results point that reconstruction was less accurate and less dense than with TLS.

Besides frame cameras, LiDAR technology has played a major role in point cloud generation in conventional PaRS. Although extensively used for DSM generation via aerial or terrestrial acquisition, the use of LiDAR in UAS platforms has been (and still is) limited as already discussed in Section 5.3. Indeed, optical frame cameras have concentrated the focus of UAS commercial developments (see Table 10 as a compilation example), mainly pushed by a feasible miniaturization and cost-effectiveness of technology as already discussed. This circumstance, in combination with the integration of the computer vision research into UAS, has brought into scene state-of-the-art approaches for point cloud generation and/or densification using optical cameras in UAS, such as Structure-from-Motion (Hudzietz and Saripalli, 2011), Multi-View Stereopsis (Wefelscheid et al., 2011; Harwin and Lucieer, 2012) and optimal flow (Pierrot-Deseilligny and Cléry, 2011). The last two methods are already implemented into the open-source packages PMVS and Micmac, respectively (Remondino et al., 2011).

Particularly, the introduction of Semi-Global Matching (SGM) (Hirschmüller, 2005) has been key in using optical cameras as a stand-alone solution for dense DSM production, and this is also reflected in UAS literature (Bulatov et al., 2011; Küng et al., 2011; Haala et al., 2013). A comparative analysis of SGM and LiDAR is presented in Gehrke et al. (2010) under the "controversial" question of whether SGM would take the lead over LiDAR for DSM generation. In this analysis, the SGM accuracy is described as "typically 0.5 GSD horizontally and 1.5 GSD vertically," and further testing with real images and LiDAR measurements show a vertical RMS difference of $\mu_h = 1$ GSD between SGM-based and LiDAR-based DSM, showing a remarkable coherence between the two products.

As opposed to old, comfortable times when manned flights shared similar patterns, the geometry of UAS-sourced photogrammetry is much more variable; and therefore, the extrapolation of the presented results to other UAS flights with different base-to-height ratios has to be made with caution.

7. UAS PaRS applications and geomatic markets

The European Commission carried out a comprehensive study to monitor the uses of UAS in Europe, aiming to identify strengths and weaknesses in comparison with international developments (European Comission, 2007). In this study, a list of potential applications for civil and commercial UAS is provided consisting of *Non-Military Governmental* (Civil Security, Border Security, Coastguard); *Fire-fighting and Emergency Services* (forest fire spotting and co-ordination, major incident response co-ordination, emergency rescue), *Energy Sector and Communication Networks* (Oil and Gas industry distribution infrastructure, electricity grids, railway network monitoring), *Agricultural Forestry and Fisheries* (environmental monitoring, crop dusting, resource optimization); *Earth Observation and Remote sensing* (climate monitoring, aerial photography, mapping and surveying, seismic monitoring, pollution monitoring), and *Communications and Broadcasting* (VHALE platforms as proxy-satellites, MALE UAS for communication coverage, camera platforms). Modulated to the scope of our paper, this chapter provides a review of the state-of-the-art initiatives regarding just a few of the applications featured in the previous list (the names of the applications may be also modified for convenience).

7.1. Agricultural and environmental applications

Remote sensing is a well-known art for agriculture and environment analysis. Vegetation and/or biodiversity control has been traditionally performed using aerial and/or satellite imagery, resulting in high expenses when fine resolution is requested. UAS have successfully introduced the *smaller, cheaper-to-operate* platform paradigm among the remote-sensing community. The range of available sensors is widening as a natural attempt to adapt to smaller platforms, in which weight and dimension restrictions hold as opposite to manned aerial platforms, and also to adapt to user and application needs.

Several researchers and/or companies have balanced the requirements of the payload and aerial platform to enable the operation of small, fast and easily deployable systems and cover small or medium-size areas. For example, Rufino and Moccia (2005) used a radio-controlled fixed-wing model to fly a thermal imager and a hyperspectral sensor in visible-NIR bands targeting forest fire monitoring. Another example is Zarco-Tejada and Berni (2012), in which a miniaturized hyperspectral camera mounted on a fixed-wing auto-piloted platform of 6 kg MTOW is described. In Bendig et al. (2012) a mini-UAS MK-Okto by HiSystems GmbH equipped with either a NEC F30 IS thermal imaging system or a tetracam Mini MCA-4 is described for successful Normalized Difference Vegetation Index (NDVI) computation. Gini et al. (2012) describes the use of a Pentax Optio A40 for RGB photos and a Sigma DP1 modified to acquire the NIR band, on-board a Microdrones md4-200, for tree classification based on different vegetation indices. Agüera et al. (2011) describes the use of the same platform, equipped with an ADC Lite Tetracam, to compare aerial and ground measurements and vegetation indices. Lucieer et al. (2012) uses an Oktokopter with optical and hyperspectral cameras to analyze the Antarctic moss beds, and Jensen et al. (2012) presents an RGB, NIR and thermal-vision concept to monitor stream termperatures. Costa et al. (2012) presents a combination of UAS and a ground wireless sensor network to proceed with crop fertilizing missions. In it, the UAS route is modified depending on the inputs from the ground network, which can measure the amount of fertilizer applied. In Grenzdörffer and Niemeyer (2011), the use of UAS for Bidirectional Reflectance Distribution Function (BRDF) measurements is proposed as an alternative to costly and cumbersome field goniometer measurement campaigns, in the context of agricultural applications.

An example of environmental application is presented in Wich and Koh (2012), in which small fixed-wing UAS carrying photo- or video-cameras are used in missions in Switzerland, the Netherlands, Indonesia, Malaysia and Nepal, to perform detection of several species such as orangutans, elephants or rhinos and provide information on density and circulation of animals. The use of small UAS to detect animals is also the motivation behind (Israel, 2011), in which a thermal camera Tau640 from FLIR is flown on-board a Falcon 8 from Ascending Technologies GmbH to detect small fawns in meadows before mowing machines could harm them. Grenzdörffer (2013) reports on the use of UAS for bird counts.

In the geological field, Eisenbeiss (2009) reports on the use of a rotary-wing Copter 1B equipped with a Nikon D2Xs to perform oblique-view mapping of the mountainous area of Randa, Switzerland. Its mission is to analyze tectonic fractures. In Delacourt et al. (2009), a coastal management application, related to the quantification of morphosedimentary changes of the coastal fringe, is carried out with a rotary-wing platform carrying a commercial digital reflex camera to generate a DEM for hydrodynamics numerical modelling. Eck and Imbach (2011) reports on the use of a high-resolution 3-axis magnetic sensor, mounted on an autonomous Scout B1-100 helicopter to generate detailed magnetic maps.

Cox et al. (2006) is a report performed in 2006 by the NASA's Civil UAV Team, in which a list of NASA-funded science mission experiences since 1995 are compiled, such as clear air radiation measurements, cumulus electrification measurements, harvest optimization, coastal mapping, atmospheric chemistry and many others. It also provides an assessment of Earth science, Land Management and Homeland versus their required capabilities (access to regulated airspace, long endurance, quick deployment, etc.).

7.2. Intelligence, surveillance, and reconnaissance

Aerial observation by unmanned platforms has been powered basically in the military context. Indeed, small, especially handheld or hand launched, UAS can provide an "over-the-hill" point of view to an army's ground troops, in order to avoid unseen potiential dangers. In larger UAS categories, large unmanned aircraft provide broad-area surveillance i.e. border control and restricted area surveillance. UAS have also been used as communications relays to increase battlefield awareness, or as decoys to fool enemy's radars. Close to the military segment, search-and-rescue or disaster management missions share many objectives with the previously specified (basically, providing quick imagery from an area where no supporting structures can be assumed), and thus can somehow be classified as Intelligence, Surveillance, and Reconnaissance (ISR) missions. We note that tactical UAS (or bigger) is usually preferred for ISR as they implement real-time image or video downloads easier than mini or micro UAS.

As illustrative examples of military-related UAS, two developments are described. Insitu, a Boeing company, has developed the ScanEagle, a 20 kg MTOW fixed-wing with a wingspan of 3 m, used by the U.S. Navy and Marine Corps. This system delivers imagery enabling tactical commanders to develop a clearer picture of the battlefield. As standard payload, it carries either an inertially stabilized electro-optical or an infrared camera. The gimbaled camera allows the operator to easily track both stationary and moving targets, providing real-time intelligence. Another development by Insitu is the Integrator, which has approximately the same dimensions but of larger MTOW, as it is designed to provide high payload capacity and modularity to include different sensors for each mission. The Integrators baseline sensor package includes inertially stabilized electro-optic, long-wave infrared and mid-wave infrared cameras, with infrared marker and laser rangefinder.

Hereafter, some scientific work is compiled in relation the ISR UAS. Molina et al. (2012) report on the use of a rotary-wing UA equipped with video and thermal cameras to detect lost persons in difficult-to-access situations, that is, to add value in the search component of search-and-rescue, and (van Persie et al., 2011) describes a similar development, using a video camera on a rotary-wing platform, to support fire brigades in real-time crisis management. Another rotary-wing development is presented in Choi and Lee (2011) for rapid disaster management, carrying two optical cameras and a LiDAR, and presenting results including the geo-referenced LiDAR point cloud.

7.3. Aerial monitoring in engineering

Again, the "above-the-head" privileged point of view that UAS provide is the main motivation for using them in civil engineering or, in general, in any engineering requiring infrastructure monitoring. Some of the actual infrastructures of interest for inspection are high and medium voltage lines, oil and gas pipe lines, roads, railways, etc.

Merz and Chapman (2011) presents the design of a helicopter-type UAS targeting infrastructure inspections and crop monitoring missions using an RGB camera and convenient filters. The use of a Commercial-Off-The-Shelf (COTS) 2D LiDAR on-board to enable terrain-based navigation, and thus to ensure beyond line-of-sight operation in a priori unknown areas, is noteworthy.

When combined with the suitable remote sensing tools, UAS can be also powerful resources for energy efficiency and wealth management. Jensen et al. (2009) describes an approach using multiple swinglet-type UAS to perform distributed wind measurement, which is of interest for meteorologists and also wind farms. Matsuoka et al. (2012) reports on an experiment conducted in order to investigate the feasibility of the deformation measurement of a large-scale solar power plant on reclaimed land by using images acquired by a non-metric digital camera on board a micro UAS.

Ground monitoring is a common application in remote sensing, for which ground-based and satellite-based tools are widely used, and recent studies show that UAS have potential for this application. Rau et al. (2011) presents the use of a fixed-wing platform with a consumer-grade camera to perform landslide detection and vegetation indices computation. Niethammer et al. (2011) studies landslide monitoring through the generation of ortho-mosaic and DTMs with the use of open-source software. Carvajal et al. (2011) describes the use of a quadracopter carrying a 12 Mpx camera to characterize landslides on road ditches. Shi et al. (2011) presents a method for object-change detection dealing with large rotations in pairs of UAS-based images, aiming at infrastructure monitoring applications.

7.4. Cultural heritage

The surveying of archaeological sites using UAS has now become common. Again, the ease of UAS operation has been key for its choice and, also very important, the quality of processed measurements has reached a level sufficient to convince the cultural heritage community. The topic is now well-established in most of the PaRS congresses (see UAV-g congress, in editions 2011 and 2013).

Rinaudo et al. (2012) describes the use of a Hexakopter, by Mikrokopter, equipped with a Sony NEX-5 to generate the DSM and orthophoto of a Roman villa archaeological site located in Aquileia (Italy), a well-known UNESCO WHL site. In Seitz and Altenbach (2011), a quadracopter by the same company is used, together with a 14 Mpx camera, to produce image mosaics and 3D models in Germany and Cambodia. Mészáros (2011) reports on the ortho-mosaic production in a recently discovered ruin in Hungary using a fixed-wing UAS, an RGB camera and an in-house open-source autopilot.

Remondino et al. (2011) describes the aerial image acquisition campaign carried out in Veio, Italy, over the ancient Etruscan city. Using Microdrone quadri-rotors equipped with a Pentax Optio A40, aerial images with 1 cm GSD were acquired and a dense matching using MicMac post-processing software delivered a point cloud of around 40 million points. Another documented area of study is the Maya site in Copan, Honduras, over which a model helicopter equipped with a Nikon SRL camera of 12 Mpx was flown, obtaining GSD of 1 cm and delivering DSM. Finally, a heritage area in Pava, Italy was also flown with a Microdrone MD4-200, again with 1 cm GSD and producing DSM at 5 cm in resolution. Comparison with check points show around 3 and 2 cm in planimetry and height, respectively. Additionally, this paper includes a structured analysis and review of UAS-based PaRS, from platforms to processing and looking forward to future perspectives.

Research has been performed on the combination of TLS and oblique aerial imagery from UAS (Fiorillo et al., 2012; Eisenbeiss, 2009) for 3D reconstruction which is often the preferred product to be delivered in archaeology and ancient building surveying.

7.5. Traditional surveying, conventional mapping and photogrammetry, and cadastral applications

Cramer et al. (2013) provides a state-of-the-art overview on the use of UAS by some European National Mapping Agencies (NMAs). The consulted NMAs were aware of the potential of UAS. They follow most recent developments and work on a possible integration of UAS data in their production lines. Many of those NMAs are also involved in local uses, such as cadastral applications, land management/land consolidation or disaster monitoring.

Manyoky et al. (2011) describes the use of a UAS—a Falcon 8 with a Panasonic Lumix DMC-LX3—, for cadastral surveying and its comparison with conventional data acquisition methods. Further, Cunningham et al. (2011) analyses the opportunities and presents the experiences on the use of UAS for cadastral mapping, focusing on rural Alaska.

van Hinsberg et al. (2013) report on the use of UAS for high-precision parcel boundary determination, of up to 3 cm which is similar to conventional land surveying. This exercise is important when ownership of one or more parts of a parcel changes, as seller(s) and buyer(s) are legally obliged to identify the new boundaries and, usually, are unable to attend the on-site identification session.

Eyndt and Volkmann (2013) claim that UAS PaRS can be considered as another surveying tool, and even that, in several situations, it is an advantageous alternative to traditional surveying.

Mayr (2011a) and Gülch (2012) describe the Personal Aerial Mapping System (PAMS) system, from SmartPlanes (Sweden), composed of a small fixed-wing platforms and an RGB camera, for DTM/DSM and orthomosaic generation. The former paper is a user report, that describes first-hand experiences in operating the system, and the later paper reports on the application of standard photogrammetric pipeline for the processing of UAS images, using software packages as MATCH-AT, MATCH-T DSM, OrthoMaster and OrthoVista.

Harwin and Lucieer (2012) proposes the application of the multi-view stereopsis technique, combining photogrammetry and computer vision, to imagery acquired from a multi-rotor micro-UAS of a natural coastal site in southeastern Tasmania, Australia. The point cloud is further densified with patch-based multi-view stereo techniques, producing 1–3 cm point spacing, and conclusions point that sub-decimeter coastal erosion can be monitored.

Grün et al. (2012) presents the use of high-resolution satellite imagery (GeoEye-1) to produce DTM, and its completion by using UAS imagery to produce high resolution 3D models of man-made structures, applied in this case to historical buildings in Bhutan.

Qin et al. (2013) reports on a mission in a quite complex urban area in the tropical city of Singapore with a Falcon 8 octocopter, developed by Ascending Technologies GmbH, with an off-the-shelf Sony NEX-5 camera.

8. Conclusions

We have reviewed the UAS technology for PaRS applications with emphasis on regulations, acquisition systems, navigation and orientation. The diversity and sophistication of the involved technologies is apparent: aeronautics, satellite and inertial navigation, computer vision, robotics, sensorics and, last not least, photogrammetry. Technologically speaking, UAS-sourced PaRS are mature enough to support the development of geoinformation products and services. At least for a first generation operational tools. Moreover, in spite of a still emerging and uncertain regulatory frame, customer demand and general interest is present to the point that there are already some UAS geoinformation niche markets; in particular a growing new market for small photogrammetric and remote sensing projects. The trend seems to be unstoppable. The majority of commercial PaRS applications are conducted with micro UAS and with off-the-shelf cameras. For this type of equipment, flight planning, flight navigation, guidance and control and data post-processing software exist. In particular, PaRS post-processing software for sensor orientation/calibration and for surface reconstruction is commercially available and production capable. It is already developed to a high level of automation to serve a market whose workforce is, in general, less specialized than that of the traditional airborne and space market. Computer vision techniques—originating from the computer vision community or from the modern PaRS community—have been instrumental in achieving this level of automation. INS/GNSS trajectory parameters, though necessary for real-time UA navigation and control, are seldom used in the mentioned post-processing orientation/calibration software—for DiSO and ISO—because of

Table 10
Examples of commonly used UAS in PaRS.

Name	Manufacturer	Weight (kg)	Endurance (h)	Integrated payload (i) or Payload weight (w)
Common fixed-wing unmanned aircraft				
SwingletCAM	SenseFly	0.5	0.5	(i) 16 Mpx RGB camera
GeoScan101	GeoScan	2	1	(i) 24.3 Mpx RGB camera
UX5	Trimble	2.5	0.83	(i) 16.1 Mpx MILC RGB camera
Pteryx	FotoMapy	5	2	(w) 1 kg w/o batteries
Sirius I	MAVinci	3	0.91	(i) 16 Mpx RGB camera
Kahu	Skycam	4	2	(i) Double-head 16 Mpx MILC RGB cameras
Common rotary-wing unmanned aircraft				
Geocopter	IGI	90	2	(w) 30 kg
Scout B1-100	Aeroscout	75	1.5	(w) 30 kg
R-MAX, type II	Yamaha	100	1	(w) 28 kg
Common multi-rotor unmanned aircraft				
md4-1000	Microdrones	3	1.46	1.2 kg
HT-8-2000	Height-Tech	2.4	0.28	2 kg
Aibot x6	Aibotix	2.4	30	2.5 kg
Falcon 8	Ascending technologies	1.45	0.33	0.75 kg
HexaKopter	MikroKopter	1.2	0.6	1 kg

Fig. 1. From top to bottom, left to right, each picture illustrates a UAV of each category in van Blyenburgh (2013): AeroVironment, USA—Nano-Hummingbird; Ascending Technologies GmbH, Germany—Falcon 8; CATUAV, Spain—Argos; Swiss UAV, Switzerland—Neo s300; Schiebel, Austria—Camcopter S100; MMIST, Canada—Snowgoose; Thales, UK—Watchkeeper; Selex ES, Italy—Nibbio; Insitu Inc., USA—Integrator; General Atomics Aeronautical Systems, USA—Predator A; QinetiQ, UK—Zephyr; Lockheed Martin, USA—Morphing UAS.

the performance limitations of current miniature IMUs. However, the pace of development of MEMS tactical-grade IMUs can change the orientation/calibration software landscape rapidly. Subsequent surface reconstruction and orthophoto generation leverage the recent achievements of high-density matching and the investments in the design of amateur and mass-market cameras. All in all, for small projects, UAS PaRS offers an unbeatable price-performant service and product. UAS PaRS is one of the rapidly developing UAS market niches like agriculture and others. Were it not because of them, we would not have the big regional players preparing UAS integration and regulation plans (ERSG and FAA roadmaps for the intergation of UAS in the airspace) and UAS testbeds (FAA). At the other end, small countries (recall the Trinidad and Tobago public bid for a national UAS-sourced mapping project) and regions plan UAS-sourced photo coverages. Additional research and technology are clearly required and are being conducted with the advantage that the entrance barriers in the field are low. We will definitely see more new UAS technologies and applications in PaRS in coming years.

Appendix A. UAS pictures and common PaRS UAS

In this annex, Fig. 1 presents some pictures from various systems, corresponding to each of the categories provided in van Blyenburgh (2013). All photos have been extracted from the UVS International Photo Library, supplied by UVS International, and are protected by the copyright of the producing company. The authors would like to thank UVS International for the supplied materials.

In addition, Table 10 presents UAS of three different types (fixed-wing, rotary-wing and multi-rotor) commonly used among the PaRS community, and their main characteristics are described.

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