TOWARDS A NEW PARADIGM FOR HIGH-RESOLUTION LOW-COST PHOTOGRAMMETRYAND REMOTE SENSING

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ABSTRACT:

Current mobile primary data acquisition systems can be grouped in three main categories: terrestrial, manned airborne and satellite borne. This paper discusses whether Unmanned Aircraft Systems (UASs) together with the appropriate sensing and navigation-orientation payloads can constitute a new, fourth data acquisition paradigm of the high-resolution and low-cost type. For this purpose, and based on practical experience gained at the Institute of Geomatics (IG), some fundamental issues of UAS-based photogrammetry and remote sensing (PRS) are reviewed; from the geomatic aspects of navigation and orientation, to the manifold of already existing applications and to various regulatory initiatives that the main aviation authorities are conducting. The paper identifies technical challenges and advantages specific to UAS-based PRS and concludes that, beyond the technical aspects, one key issue is the integration of UAS in the civilian non-segregated airspace.

1. INTRODUCTION

A typical UAS consists of an Unmanned Aircraft (UA), a Control System (CS) —usually a Ground Control System (GCS)— and a communications data link between the UA and the CS. In civilian applications, the vast majority of UAs are equipped with sensors and perform some form of remote sensing. The term and concept of UAS have been recently introduced to replace those of Unmanned Aerial Vehicle (UAV) which is just a component of an UAS.

UAs can be categorised in terms of weight, altitude and range, and other criteria. According to weight we have micro UAs (less than 2kg), mini UAs (2 to 8 kg), small UAs (8 to 25-30 kg) and tactical UAs (25-30 to 400 kg). Figure 1 shows an example of a small UA for PRS applications. (Sometimes, UAs weighting less than 150 kg are also referred to as small UAs.) According to altitude and range we have Low Altitude Long Endurance UAs, Medium Altitude Long Endurance (MALE) UAs (5.5 to 18 km), High Altitude Long Endurance (HALE) UAs (above 18 km) and others. UA classification issues is of the utmost importance for worthiness and certification issues and a current hot topic in the aviation community. The above categories are not comprehensive, given just for the sake of clarity and may easily change in the next months.

UASs date back to the 19th century and modern UASs date back to the Second World War. Historically, UASs have had a strong military presence for scouting and attack missions since their use in the battlefield involves no risk of loss of human life. The dominant role of the defense and espionage industry notwithstanding, the civilian applications and their overall use have expanded dramatically over the past years. The statement can be easily proven by a quick Internet web search. Among their many uses, we can mention Earth observation and aerial surveying, precision agriculture, environment monitoring and sampling, general scientific research, surveillance, communications, advertising, media, audio broadcasting and meteorology.

Requiring no on board human pilots has advantages and disadvantages. The fundamental advantage of UASs is that they are not burdened with the physiological limitations and economic expenses of human pilots. As a result, UAs use to be cheaper, smaller and lighter than their manned siblings. UAS operations are therefore far less expensive (20-30 /hr for a 10 kg payload) than any manned aircraft and far more environmentally friendly (generate less CO_2 and noise). Furthermore, there are areas and circumstances where manned aircrafts cannot be flown and where unmanned systems can, like low altitude flights.

The fundamental disadvantage of UASs is that they do not benefit from the sensing and intelligent features of human beings and, therefore, they are less able to react to unexpected situations. Mainly because of this, the usage of UASs is not yet sufficiently regulated by the civil aviation and security authorities. This is a major barrier to the development of the UAS natural market. Other, derived, issues are those related to communication links (reliable, long range, low weight, out of line-of-sight, sufficient bandwidth), collision avoidance and homeland security.

The above mentioned advantages and the availability of the Global Positioning System (GPS), together with the unstoppable miniaturization of computer and sensing technology, have calledthe attention of many professional communities to the use of UAS. In this paper we explore the feasibility of high-resolution airborne PRS with UAS.

Figure 1: An AIN's UA with the IG's PRS sensor and navigation-orientation payloads: GPS L1/L2 receiver, LN200 IMU, Hasselblad Biogon SWCE 903 and the PRS navigation-orientation Control Unit. (Photographs courtesy of AIN.)

2. THE UA COMPONENTS OF AN UAS-BASED PRS SYSTEM

In (Colomina et al., 2007) the classification of the components of an UAS-based PRS system is organized in two dimensions: the CS/UA dimension and the application dependent/independent one. In this paper we are interested in just describing the UA-PRS application item which contains the PRS sensor payload and the PRS navigation-orientation payload. The *PRS sensor payload* contains the set of all sensors with the exception of the navigation ones, their storage devices and the mechanical interfaces (sensor bay or platform). The PRS sensor payload may be assembled rigidly or with shock mounts, into the UA structural frame. Depending on the sensors, this payload may include a Control Unit (CU) in charge of spatio-temporal inter-sensor calibration, data storage, possibly real-time sensor data processing, and PRS mission control.

The *PRS navigation-orientation payload* typically contains GPS receivers, inertial sensors, other navigation devices like barometric altimeters and magnetometers, and a Control Unit (CU). It provides a real-time navigation solution —including time synchronization signals and data— which may be used as an input to the UA Flight Control System (FCS) and to the PRS sensor payload. Usually, it stores observational data for a posteriori precise sensor orientation. The CU is a computer that synchronizes, reads and stores the measurements of the navigation and orientation instruments and that runs the real-time navigation SW. In figure 2 the IG's CU for small and tactical UAs can be seen.

3. ON THE COMPATIBILITY OF HIGH-RESOLUTION AND LOW-COST IN UAS-BASED PRS

High-resolution —and high-quality— at low cost is feasible thanks to the progress in sensor technology, HW "miniaturization" and SW or, more to the point, in computer models for navigation-orientation and remote sensing.

HW miniaturization precisely means small volume, low weight and low power consumption. A PRS sensor payload based on optical cameras of 20 Mpx to 40 Mpx may take as little as 4 l of volume, 7 kg of weight and 30 W of power. The size of a GPS dual frequency board with WAAS/EGNOS navigation capability is about $8.5 \times 12.5 \times 1.7$ cm^3, weighs about 80 g and requires less than 5 W. A tactical grade IMU requires some 0.6 l of volume, 0.8 kg of weight and 16 W of power. The requirements of other secondary navigation sensors like barometric altimeters and magnetometers are almost negligible with respect to the previous amounts. A PRS navigation-orientation CU requires 3 l of volume, some 1.8 kg of weight and less than 20W. If we take into account that medium-format cameras (figure 3) can be turned into metric cameras with the appropriate orientation and calibration SW tools, we are in front of high-resolution, high-quality, lightweight and moderate cost systems.

The overall cost of the above configuration is around 70 k€. We are aware that the cost of the HW components of a system may represent as little as a third or less of the final cost for the final user. Moreover, the overall cost of a product or service based on a low-cost system may end up being higher than the cost of the same product or service based on more expensive infrastructures; at the end, it is overall price performance what counts. However, the low-cost and high-quality levels achievable with the previously described equipment on board of small UAs may capture some market segments and open new ones.

An example of a PRS payload for a small UA

In Figure 1 an experimental system consisting of a small UA (payload capacity up to approximately 10 kg), a navigation-orientation payload, its CU (figure 2) and a medium format camera (figure 3) can be seen. The system has been integrated by AIN and the IG within the frame of the uVISION project (Colomina et al., 2007). The navigation-orientation payload includes a geodetic grade GPS L1/L2 receiver Novatel OEMV, a tactical grade Northrop-Grumann Litton LN200 IMU, a Honeywell HPB barometric altimeter and a Leica Vectronix DMC-SX magnetometer. The navigation-orientation CU is based on a PC104 architecture and a Linux operating system; besides the main board and standard communications boards it includes a time synchronization board. The sensor payload is composed of a Hasselblad Biogon SWCE 903 camera with a Kodak DCS Pro Back Plus digital backplane of 16.6 Mpx and time synchronization electronics. The camera and the IMU are rigidly assembled and isolated from the mechanical vibrations of the helicopter engine and rotor. Figure 4 shows two Siemens star targets photographed in static (engine off) and kinematic (engine on) modes. The system weighs less than 10 kg and requires some 50 W of power.

Figure 2: IG's PRS navigation-orientation Control Unit based on the PC104 architecture (≈ 13 × 20 × 18 cm3, ≈ 2 kg).

4. ON SENSOR NAVIGATION, CONTROL, ORIENTATION AND CALIBRATION IN UAS-BASED PRS

Sensor navigation is the real-time determination of a sensor's orientation elements, usually the position of the origin of the sensor [instrumental] reference frame and the attitude of this frame. Sensor control can be regarded as a specialized mission control task; it refers to the operation of the sensor (switch on, stabilization, heading correction, triggering, etc.) according to a given sensor mission plan and with the help of the sensor navigation data. Thus, for instance, navigation of a frame camera is a prerequisite for its further stabilization through some form of camera control. Sensor orientation and calibration are well known topics in PRS and, in the context of this paper, require no further discussion. The mentioned tasks, from sensor navigation to calibration, mainly depend on two technologies: trajectory determination —in the sense of time-Position-Velocity-Attitude (tPVA) determination— and sensor calibration and orientation (SCO) in PRS —i.e., direct sensor orientation (DSO), indirect or integrated sensor orientation (ISO) and other methods.

Small unmanned autonomous vehicles and their cost target define a somewhat new scenario: the PRS navigation-orientation and sensor payloads may be exposed to unfriendly electromagnetic and mechanical environments that may require HW and SW protection techniques; rotary wing UAs (helicopters) are as common as fixed wing UAs (airplanes); the low cost of small UAs open the market to players who may not use the sophisticated PRS HW and SW gear and the experienced PRS operators. The next two sections are devoted, therefore, to tPVA determination and to sensor orientation and calibration for the particular case of UAS-based PRS with small UAs.

4.1 tPVA trajectory determination

In UAS-based PRS, tPVA trajectory determination either in real-time (for sensor navigation, sensor control and real-time applications) or in post-processing (for precise sensor calibration and orientation) is, in principle, a similar problem to the traditional airborne PRS one. It is accomplished through the PRS navigation-orientation payload which may or may not be used as the real-time navigation input for the auto-pilot or UA FCS. As a result, the PRS navigation-orientation payload may have to fulfill safe navigation requirements which, depending on the need of mechanical isolation between the PRS sensor payload and the UA main body, may require filtering techniques and vibration analysis.

Figure 3: EPFL's Hasselblad Biogon SWCE 903 (≈ 17 × 21 × 17 cm3, ≈ 5 kg).

There are two main challenges in tPVA trajectory determination for UAS-based PRS: high integrity (controlled accuracy and high reliability) of the real-time solution and high accuracy and precision of the post-processed solution for sensor calibration and orientation.

Integrity is a hot topic in satellite navigation and it is addressed in various ways: GPS augmentations with signal integrity monitoring like the US Wide Area Augmentation System (WAAS) or the European Geostationary Navigation Overlay System (EGNOS); GPS Receiver Autonomous Integrity Monitoring (RAIM); GPS receiver hybridization with additional and complementary sensors; Autonomous Integrity Monitoring (AIM) of hybrid navigation systems; Global Navigation Satellite System (GNSS) configurations with GPS and the Russian GLONASS and in the future with GPS and the EU Galileo system. Further to this, in recent years, the use of hybrid nvigation systems with redundant IMU configurations of various kinds have been proposed (Colomina et al., 2004), integrated, tested and analysed (Waegli et al., 2008) with encouraging results. As of today, dual frequency GPS receivers with WAAS/EGNOS an capabilities, possibly GLONASS capable, with algorithm redundant IMU configurations, barometric altimeters and magnetometers plus an AIM capability can provide 1- m level accuracy and sufficient integrity for unmanned operations.

Figure 4: Siemens star target from a distance of 20 m [preliminary results].

For the mentioned configuration, optimal accuracy and precision in tPVA trajectory determination is pursued with sophisticated sensor models; from GPS signal modeling, including integer ambiguity resolution, to the calibration of the IMUs. The estimation of the tPVA parameters and the rest of the model parameters with, typically, forward and backward Kalman filtering should render, in principle, accurate and precise trajectories. However, in small UAs and, particularly, in rotary wing UAs, the vibrations caused by the engines generate "noisy" inertial observations which are known to integrate into strong drifts when solving the INS mechanization equations for navigation. (The same holds for manned helicopters.) In (Wis et al., 2008), a novel method and algorithm for real-time denoising of inertial observations and its results will be described. The method is the natural extension of the numerical integration methods of Ordinary Differential Equations (ODE) where the analytical exact integration of an interpolating polynomial is replaced by the analytical exact integration of a fitting polynomial. Figure 5 shows preliminary results of the proposed technique for a static acquisition time interval at the end of a PRS mission where the blue curve corresponds to the proposed least-squares fitting technique and the red one to a standard interpolating one.

4.2 DSO, ISO and in between

Once the tPVA task is accomplished, the SCO task must be performed consistently with the specific cost, time and technical requirements of the PRS mission and with data that may be suboptimal with respect to the usual airborne standards. SCO is usually seen as a method and procedure that can be performed in either one of two modes, DSO and ISO, and with absolute control functional models. In our approach, DSO and ISO are the ends of an interval of methods where the effort of measuring image coordinates [of tie and ground control points] can be tuned as a function of the precision, accuracy and reliability of project specifications (Colomina, 2007). In our approach, as well, the SCO model can be selected from a family of spatio-temporal absolute and relative SCO models according, again, to project specifications (Blázquez, 2008). This "two dimensional" approach to SCO —with the mode and the model dimension— can be applied to any sensor and platform combination, but in the case of UAS-based PRS is of particular relevance. We illustrate this next with some ideas on DSO and ISO for UAS-based PRS.

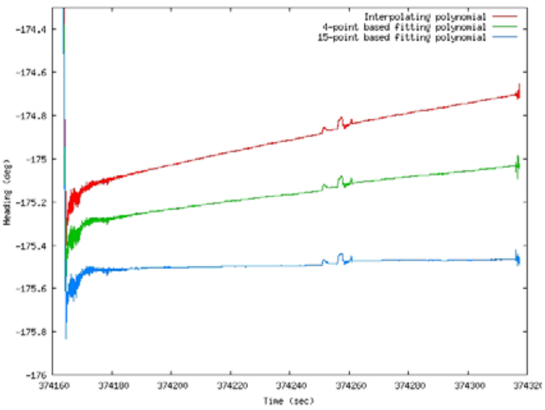

Figure 5: Heading determination improvement with an ODE least-squares numerical integration algorithm [preliminary results].

On the foreseen advantages of UAS-based PRS is its flexibility, particularly in the case of rotary wing UAs since calibration maneuvers before and/or after the mission can be performed at a rather low additional burden (time, cost and later measurement effort). Thus, a DSO based mission can be preceded or succeeded by a comprehensive and quick calibration maneuver by acquiring "calibration" image data at various altitudes and headings. In this way, in the bundle adjustment with the "calibration" image data, calibration parameters are not correlated to the image orientation elements and in turn they are realistically determined. In other words, a significant number of parameters of a physical-oriented calibration model are well determined.

The above DSO related arguments hold as well for ISO, where the standard mission can be complemented with the mentioned calibration maneuvers in such a way, that in addition to the physical-oriented self-calibration parameters (like the Conrady-Brown 5 parameter set or the δf, δx_0, δy_0 one), numerical-oriented self-calibration parameters (like the Ebner 12 parameter or Grün 44 parameter sets) can be determined. As a result, a total calibration concept and model can developed which consists of pre-calibration and self-calibration steps with physical-oriented and numerical-oriented functional models respectively. More specifically, the collinearity model can be extended with two sets of additional parameters, the physical-oriented one and the numerical-oriented one.

At the other end of the ISO complexity and in one of the contexts of UAS-based PRS —that of low cost, fast mapping and moderate accuray requirements— there are other possibilities like expediting the bundle adjustment with the INS/GPS derived aerial control, a small number of ground control points and just image observations for the ground control points and just image observations for the ground control points. Clearly, this procedure will not deliver at the same level of accurcacy as the usual ISO, but will be more robust than DSO with respect to reference frame mistakes.

We conclude this section by noting that appropiate modeling —i.e., features on the SW side— can simplify the HW complexity, a relevant issue in UAS-based PRS. A nice example is that of temporal calibration in ISO (Blázquez, 2008). With this model, if the internal sensor time delays are constant there is no need to synchronize the navigationorientation payload to the sensor payload as the mentioned delays can be estimated in the ISO step.

5. ON THE FEASIBILITY OF COMMERCIAL UAS-BASED PRS

There are UAS civilian success stories, like the use of UAs in agriculture in Japan. In this section we are interested in discussing the feasibility of the commercial use of UAS for PRS. Note, that we are not addressing the various forms of remote sensing in its broad sense —embodying biological, chemical, electromagnetic and gravity sensors. Globally, those have already been identified as the main future application of UAS technology. We are rather addressing the professional mapping markets. We stand on the opinion that while some challenges have to be faced before the use of UAS in PRS goes universal, there are many applications that constitute both a business opportunity today and a platform for maturing the technology for the future.

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5.1 The outstanding challenges

For an UA to be flown on a large commercial scale, three challenges shall be faced and solved: UAS reliability, UAS integration in the civilian airspace and UAS social acceptance and safety reputation.

Reliability. A significant part of current UAS technology has been developed for use in military applications, where the need for UAS has outweighed the lack of reliability. Therefore, generally speaking, UAS technology requires improvements to be made to its reliability. Obvious issues are the vulnerability of GPS-based navigation technology, the need for reliable data links and the predominant use of a single engine. The use of GPS as the sole means of navigation is, certainly, an issue. However, wide area augmentation services of GPS and of the coming Galileo system, the Safety of Life (SoL) service of Galileo, and their hybridization with redundant IMU configurations, barometric altimeters and magnetometers will provide a sufficient degree of navigational integrity (section 4.1). Reliable data links, particularly for long range UAS, can be based on satellite communications. Single engine configurations can be replaced by double engine ones —or equivalent redundant configurations— such that the UA be able to fly on one of the two engines. It goes without saying that higher reliability can easily translate into more weight and power consumption.

Integration in the civilian airspace. Currently there are many initiatives, projects, professional associations and government agencies dealing with the integration of UAs in the regulated civilian airspace. At the international level, the International Civil Aviation Organization (ICAO) has created the Unmanned Aircraft Systems Study Group (UASSG) with, among others, the purpose of developing a regulatory concept for UASs. The North Atlantic Treaty Organization (NATO) has been active in the topic for years, mainly in the operation of military UASs in the non segregated air space. It has or is about to produce standards on standard interfaces, on airworthiness requirements, on Aerial Traffic Management (ATM) and others. In Europe, the European Commission's (EC) regulatory agency, the European Aviation Safety Agency (EASA) and the European Organisation for the Safety of Air Navigation (EUROCONTROL) have to be mentioned. EASA is currently working on the UAS certification policy and EUROCONTROL does it on the integration of both military and civilian UASs in the non-segregated airspace. Also in Europe, the Working Group 73 "Unmanned Aircraft Systems" of the European Association for Civil Aviation Equipment (EUROCAE) elaborates materials *to support that unmanned aircraft can operate safely within non-segregated airspace in a manner compatible with other airspace users.* In the US, the Federal Aviation Administration (FAA), in addition to several regulations has created the Unmanned Aircraft Program Office (UAPO) whose goal is to regulate the operation of UASs in the non-segregated airspace no later than 2011. (The Department of Defense (DoD) and the National Aeronautics and Space Administration (NASA) are active in this field since many years.) Also in the US, Committee F38 of ASTM International, one of the largest voluntary standards development organization, has produced UAS standards, ranging from airworthiness, to terminology, to sense-and-avoid specifications. Last not least, the Japan UAV Association (JUAV) has established standards for the commercial use of UASs in non populated areas since 2004.

Common treats in the above mentioned initiatives are that an UAS shall satisfy national and/or international airworthiness criteria; that it shall be able to respond to ground-to-air and air-to-air voice communications; that it shall support a sense-and-avoid capability with respect to other aircraft, equivalent to that of a piloted plane and that it some procedures and maneuvers shall be automated.

Social acceptance and safety reputation. Damage caused by a flying vehicle depends on a number of factors like its kinetic energy (related to weight and speed) and its engine (combustion or electric). UA crashes are far less damaging than their manned counterparts but may be more frequent. Repeated successful flights over populated areas will pave the way for social acceptance of UAS operations while a few accidents will do a long lasting reputational damage. In the last years there have been successful experiences like the July 2004 historic flight over Amsterdam but also tragic accidents like the October 2006 Kinshasa crash where two people were killed and two other suffered from burns. The degree of social acceptance of UAS will ultimately depend on the popular combined perception of safeness and usefulness of UAS operations. And to this point, it is probably more than cost effective mapping that may count; support to search and rescue operations of people lost in the wilderness or adrift at sea are the kind of applications likely to generate the required empathy.

5.2 The immediate future

The discussed challenges notwithstanding, there are market niches that are an opportunity for actual business and further technology development and testing. Today, there are situations where the odds of losing a pilot are simply too great. Filming a volcanic eruption from close quarters, is an example of something that the market is willing to pay for and that we were not able to do before the UAS technology. However, beyond the one-of-a-kind applications, it is the general ones (section 1) that have the potential to develop future big markets. In the next few years the most likely scenario is that of three parallel tasks; surviving on special projects, further developing the technology and fighting the battle of integration in the regulated airspace.

6. CONCLUSIONS AND OUTLOOK

Like other professional communities, the PRS one has started to use the UAS technology and has recognized its big potential. In this paper we have discussed the technical and regulatory issues related to UAS-based high-resolution and high-quality PRS. On the technical side, a number of challenges have been identified and the solutions adopted by the authors at the IG have been outlined. Beyond the challenges, some advantages of the UAS technology for PRS have been explored.

The main challenge, though, for UAS-based PRS to become a mainstream technology is the clarification and the development of the regulatory issues; particularly, of the integration of UAs in the non-segregated civilian airspace. Indeed, this is not an easy task. However, the international UAS marketplace is growing fast and the aviation authorities and regulatory bodies are aware of this. Not so many years ago, the commercialization of medium- and high-resolution satellite images extended the paradigm of image acquisition. And the paradigm may continue to evolve...

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