THE PERFORMANCE ANALYSIS OF A UAV BASED MOBILE MAPPING SYSTEM

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KEY WORDS: Direct georeferencing, INS, GPS, UAV

ABSTRACT:

In order to facilitate applications such as environment detection or disaster monitoring, developing a quickly and low cost system to collect near real time spatial information is very important. Such a rapid spatial information collection capability has become an emerging trend in the technology of remote sensing and mapping application. In this study, a fixed-wing UAV based spatial information acquisition platform is developed and evaluated. The proposed UAV based platform has a direct georeferencing module including an low cost INS/GPS integrated system, low cost digital camera as well as other general UAV modules including immediately video monitoring communication system. This direct georeferencing module is able to provide differential GPS processing with single frequency carrier phase measurements to obtain sufficient positioning accuracy. All those necessary calibration procedures including interior orientation parameters, the lever arm and boresight angle are implemented. In addition, a flight test is performed to verify the positioning accuracy in direct georeferencing mode without using any ground control point that is required for most of current UAV based photogrammetric platforms. In other word, this is one of the pilot studies concerning direct georeferenced based UAV photogrammetric platform. The preliminary results in term of positioning accuracy in direct georeferenced mode without using any GCP illustrate horizontal positioning accuracies in x and y axes are both less than 20 meters, respectively. On the contrary, the positioning accuracy of z axis is less than 50 meters with 600 meters flight height above ground. Such accuracy is good for near real time disaster relief. Therefore, it is a relatively safe and cheap platform to collect critical spatial information for urgent response such as disaster relief and assessment applications where ground control points are not available.

INTRODUCTION

As the number of devastating disasters increases due to climate change, a quickly and low-cost system for collecting near real-time spatial information has become very important. Rapid spatial information collection has become a trend in remote sensing and mapping applications. Airborne remote sensing, more specifically aerial photogrammetry, with film-based optical sensors (analog) has been widely used for high-accuracy mapping applications at all scales and for rapid spatial information collection for decades. Recently film-based optical sensors have been replaced by digital imaging sensors. Figure 1 shows the procedures applied in conventional aerial photogrammetry.

In general, the necessity for Ground Control Point (GCP) was so evident that all operation methods relied on it. Only recently has Direct Geo-referencing (DG) become possible by integrating the Global Positioning System (GPS) and an Inertial Navigation System (INS), allowing all exterior orientation information to be available with sufficient accuracy at any instant of time (Schwarz et. al., 1993). The integration of GPS/INS puts the geo-referencing of photogrammetric data on a new level and frees it from operational restrictions. Together with digital data recording and data processing, it has initiated the era of multi-sensor systems.

Operational flexibility is greatly enhanced in all cases where a block structure is not needed. Costs are considerably reduced, especially in areas where little or no ground control is available. The accuracy of existing commercial systems is sufficient for many mapping applications. As shown in Figure 1, the cost and production efficiency are improved significantly with DG-based photogrammetric platforms. However, there are some limitations to existing DG-based photogrammetric platforms. The cost of renting a plane to conduct aerial photogrammetry is high and there are strict regulations and complicated procedures for obtaining a permit to conduct a flight plan in Taiwan. In addition, the flexibility and capability of conducting small-area surveys or rapid spatial information collection are rather limited. Therefore, a DG-ready airborne platform that is relatively free of government regulations and reduces flight cost while maintaining high mobility for small-area surveys and rapid spatial information collection is desired for urgent response applications such as disaster relief and assessment.

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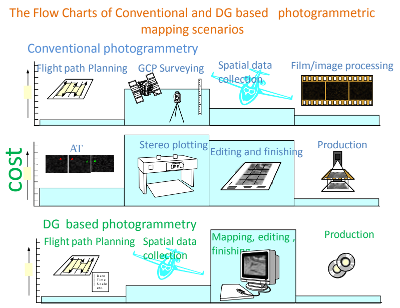

Figure 1 Procedures applied for conventional aerial photogrammetry (adapted from Dorota, 1996)

Table 1 summarizes a comparison of various candidates for photogrammetric platforms in terms of system configuration and applications. Generally speaking, the selection of candidate platform is application-dependent. The primary objective of developing Unmanned Aerial Vehicle (UAV) based photogrammetric platform is to meet requirements such as small operational area, rapid deployment, low cost, high mobility, and acceptable accuracy. Therefore, it is not practical to use these platforms as replacements for conventional photogrammetric applications.

Table 1 Comparison of various airborne photogrammetric platforms

Platform	System						Applications						
	IMU	GPS	LIDAR	Camera	DG payload weights	Cost	Large area	Small area	Mobility	Weather limitation	DG accuracy(3DRMS)	Cyber city	Rapid Disaster Relief
Fixed wing aircraft	*Tactical grade*	*Geodetic grade*	*Yes*	*Digital/ film*	*>50kg*	*High*	*Yes*	*Yes*	*Low*	*High*	*<20 cm*	*Yes*	*Low*
Helicopter	*Tactical grade*	*Geodetic grade*	*Yes*	*Digital*	*>50kg*	*High*	*No*	*Yes*	*Low*	*High*	*<20 cm*	*Yes*	*Low*
UAV	*MEMS*	*L1 phase*	*Yes*	*Digital*	*<25 kg*	*Low*	*No*	*Yes*	*High*	*Low*	*<50 cm*	*Yes*	*High*
UAV Helicopter	*MSMS*	*L1 phase*	*Yes*	*Digital*	*<10kg*	*Low*	*no*	*yes*	*high*	*low*	*<50 cm*	*yes*	*High*

THE TECHNUCAL CONFIGURATIONS OF PROPOSED PLATFORM

The configuration of the proposed DG-based UAV photogrammetric platform is shown in Figure 2. The components of each module are described in detail below.

The proposed UAV platform is shown in Figure 3.The proposed UAV is designed for medium-range applications. The maximum operational range is 50 kilometers and the real time video transmission range is 100 kilometers with extended range communication links. The flexible flight altitude and two-hour endurance time make it suitable for small-area and large-scale photogrammetric missions.

Figure 4 shows the DG module designed in this study for facilitating GCP-free photogrammetry and INS/GPS Positioning and Orientation System (POS) aided bundle adjustment. The data storage module used to record the measurements collected by the Inertial Measurement Unit (IMU) (MMQ-G), GPS (AEK-6T) and the synchronized time mark used to trigger camera (Canon EOS 5D Mark II) is Antilog from Martelec. Due to the limitations of payload and power supply, a PC- or notebook-based data storage module is unsuitable. Therefore, a simple mechanization that can store measurements communicated over serial ports is desired. Antilog was chosen due to its flexibility, low power consumption, and reliability. Similarly, since Canon EOS 5D Mark II has its own storage mechanization, it is not included in this module.

Figure 5 illustrates the set up of the DG module within the UAV platform. As shown in this figure, the MMQ-G is set right on top of the camera.

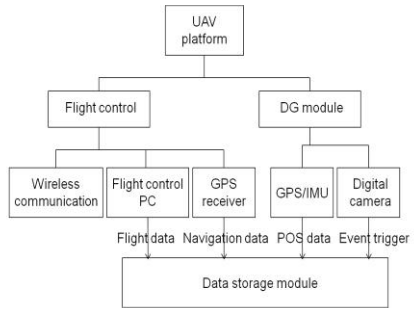

Figure 2 Configuration of proposed DG-ready UAV photogrammetric platform

Figure 3 Photograph of proposed UAV platform

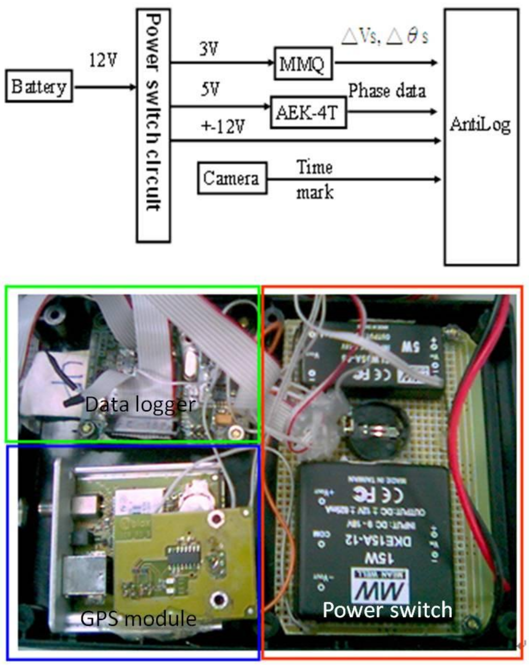

Figure 4 Configuration of DG module

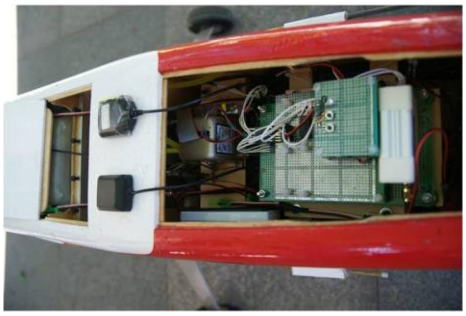

Figure 5 Setup DG module in UAV

THE DATA PROCESSING STRETEGY

Equation (1) and Figure 6 illustrate the general concept of the airborne DG. With this implementation, the coordinates of the mapping feature can be obtained directly through measured image coordinates.

$$r_i^m = r(t)_{nav}^m + R(t)_b^m (s_i R_c^b r_i^c + r_{ins}^c - r_{ins}^{GPS}) \tag{1}$$

The physical meanings of R_c^b, r_{ins}^c, and r_{ins}^{gps} are given in Figures 6 and 7, respectively. A two-step boresight calibration procedure is implemented in this study to acquire the rotation matrix (R_c^b) between the camera and INS by using the rotation matrix (R_b^m) provided by INS and the rotation matrix (R_c^m) provided by conventional bundle adjustment during the calibration procedure (Fraser, 1997):

$$R_b^c = R_m^c (R_m^b)^T \tag{2}$$

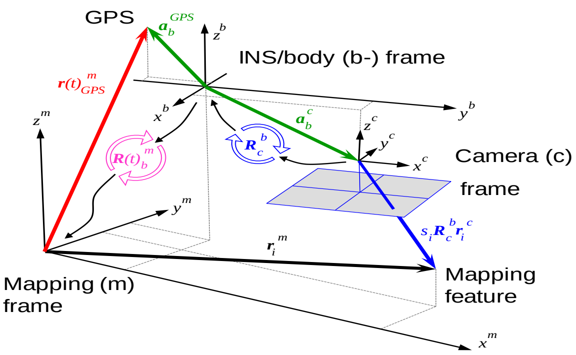

Figure 6 Concept of airborne DG

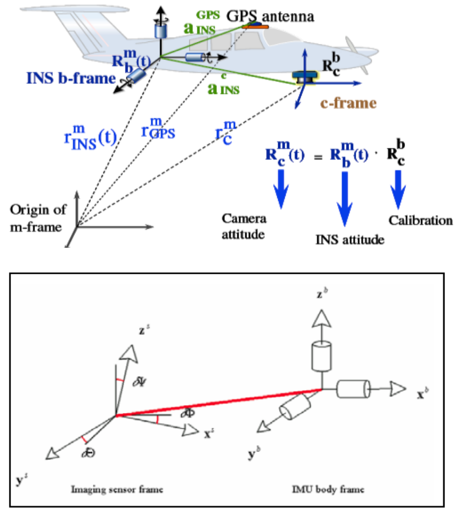

Figure 7 System calibration

The lever arm r_{ins}^{gps} between the GPS phase center and the IMU center is determined using a surveying process. The lever arm r_{ins}^c between the camera center and the IMU center is determined using a two-step procedure by comparing the output of conventional bundle adjustment and INS/GPS integrated POS solutions during the calibration process using:

$$r_c^b = R_m^b \cdot \begin{pmatrix} X_{INS}^m - X_{ci}^m \\ Y_{INS}^m - Y_{ci}^m \\ Z_{INS}^m - Z_{ci}^m \end{pmatrix} \tag{3}$$

Figure 8 illustrates the INS/GPS POS-assisted Aerial Triangulation (AT) based photogrammetric process and DG-based photogrammetric process implemented in this study, respectively.

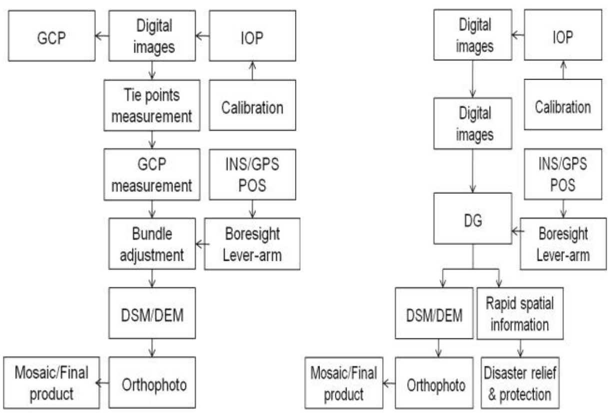

Figure 8 Proposed (left) INS/GPS POS-assisted AT-based photogrammetric (right) DG-ready photogrammetric procedures

Post-mission processing, when compared to real-time filtering, has the advantage of having the data of the whole mission available for estimating the trajectory (Shin and El-Sheimy, 2005). This is not possible when using filtering because only part of the data is available at each trajectory point, except the last. When filtering is used in the first step, an optimal smoothing method, such as the Rauch-Tung-Striebel (RTS) backward smoother, can be applied (Chiang et. al., 2004). It uses the filtering results and their covariances as a first approximation. This approximation is improved by using additional data that was not used in the filtering process. Depending on the type of data used, the improvement obtained by optimal smoothing can be considerable (Gelb, 1974).

For the geo-referencing process which puts POS stamps on images and the measurement process that obtains the 3D coordinates of all important features and stores them in GIS database, only post-mission processing can be implemented based on the complexity of those processes (El-Sheimy, 2002). Therefore, most commercially available DG systems operate in real-time only for data acquisition and conduct most of the data processing and analysis in post-mission mode. Figure 9 illustrates the Loosely Coupled (LC) INS/GPS integrated scheme implemented in this study.

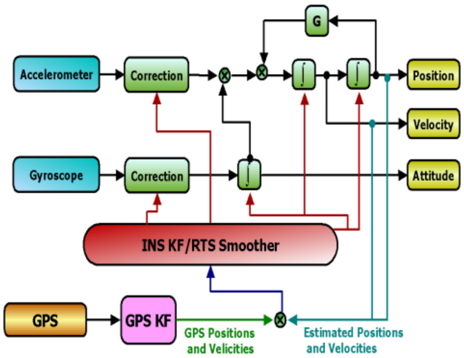

Figure 9 Loosely coupled INS/GPS integrated scheme

RESULTS AND DISCUSSIONS

To validate the performance of proposed platform, a field test was conducted in the fall of 2011. The area of the test zone is 3 kilometers * 3 kilometers, which is covered by the red square shown in Figure 10. The blue region illustrates the fly zone approved for this test.

Figure 10 Proposed DG-ready photogrammetric procedure

Flight planning

The flight altitudes set for aerial photography is 600 meters above ground. Owing to the limit of the payload and the impact of side wind affecting the attitude of UAV, the endlap and sidelap were increased to 80% and 40% respectively to insure that the coverage of the stereo pair can overlap completely during the test flight. Although more images have to be processed, it can be guaranteed that the completed coverage of the stereo pair. Figure 11 illustrates the flight path.

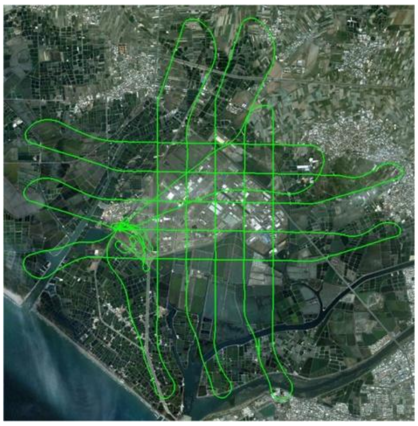

Figure 11 Trajectories of test flight

Calibration results

In this study, the camera calibration process was implemented first to obtain the Interior Orientation Parameters (IOP) of camera. Then the lever arm and boresight angle were calibrated after installing the cameras on the UAV. Consequently, the performance analysis of DG accuracy was performed by comparing DG results with checking points with precisely known coordinates. Table 2 shows the preliminary IOP result. The error of the camera calibration is accepted at this stage. This number may be improved in the future work.

Table 2 The IOP of EOS 5D Mark II

Principal distance	c = 20.6478 mm
Principal point offset in x-image coordinate	xp = -0.0819 mm
Principal point offset in y-image coordinate	yp = -0.0792 mm
3rd-order term of radial distortion correction	K1 = 2.38021e-04
5th-order term of radial distortion correction	K2 = -4.75072e-07
7th-order term of radial distortion correction	K3 = 5.80760e-11
Coefficient of decentering distortion	P1 = 1.0121e-05
Coefficient of decentering distortion	P2 = 2.7671e-06
No significant differential scaling present	B1 = 0.0000e+00
No significant non-orthogonality present	B2 = 0.0000e+00

Figure 12 shows the Exterior Orientation Parameters (EOP) result. The estimated accuracy of image referencing is 0.33 pixels. The influence of the EOP is around 0.06 meters in terms of the three-dimensional positioning accuracy. Figure 13 illustrates the trajectory of INS/GPS integrated POS solutions during the test. The INS/GPS integrated POS solutions processed with Extended Kalman Filter (EKF) trajectory is shown in red line and RTS smoother is shown in green color, respectively. Because of the kinematic alignment process applied due to the use of low cost INS/GPS integrated POS module, the beginning (around 100 seconds) of EKF trajectory is not smooth. However, only smoothed trajectory provided by RTS smoother is applied for further processing.

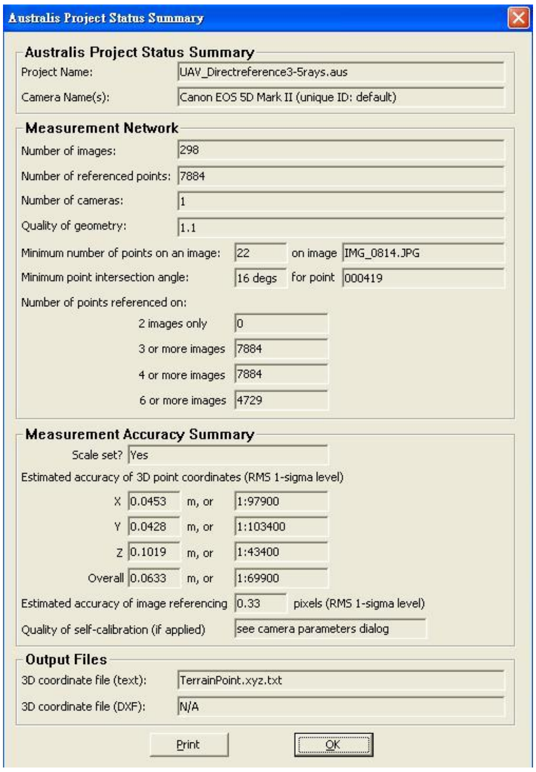

Figure 12 The EOP result

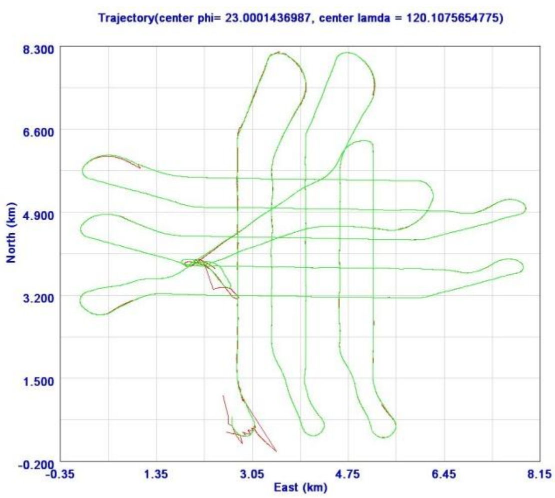

Figure 13 The trajectory of integrated POS

A two-step approach is implemented in this research to acquire the lever arm and boresight angle of each camera. Table 3 and 4 shows the lever arm and boresight angle results.

Table 3 The result of lever arm

	Lever arm (m)
X	-0.9021623368
Y	1.8268121914
Z	0.6445930103
X Std	2.7574884306
Y Std	3.3726318188
Z Std	1.5847706356

Table 4 The result of boresight angle

	Boresight angle (degree)
Omega	-1.4515201324
Phi	2.6770528243
Kappa	7.4970658658
Omega Std	4.5468788389
Phi Std	5.3683224488
Kappa Std	43.2879510361

The Verification of DG Capability of Proposed UAV Photogrammetric Platform

The reference coordinates of the check points are obtained through the precise control survey with GPS RTK (Real Time Kinematic) technology and network adjustment. Therefore, the DG coordinates of those check points are then compared with their reference coordinates. The results are illustrated in Table 5. This study uses L1 carrier phase raw measurements that can be applied for differential GPS processing with single frequency carrier phase measurements and provides sufficient positioning accuracy in civil purpose such as mapping and disaster monitoring.

The primary error sources contributing to DG positioning error including 1~2 meters limited by the positioning accuracy of onboard INS/GPS integrated POS module and 10~15 meters limited by limited by the orientation accuracy of onboard INS/GPS integrated POS module, respectively. Generally speaking, the orientation accuracy provide by onboard INS/GPS integrated POS module is around 0.5 to 1 degree. When the flight height is 600 meters, the estimated positional error is around 10 meters if the angle offset is 1 degree. In other words, should the flight of UAV be reduced to 300 meters, the anticipated DG positioning accuracy of proposed system can be improved to be less than 10 meters level horizontally and 15 meters vertically, which is ideal for most of near real time disaster mapping and rescue applications.

Table 5 The result of the DG test

Check Point	dx (m)	dy (m)	dz (m)
CK04	-13.0887	-7.0016	24.1485
CK05	-0.7978	-27.3426	8.4432
CK06	0.0598	-12.5889	21.7812
CK09	24.8855	-9.2285	-37.1159
CK10	-2.9001	-23.0022	1.8811
CK11	-4.2406	-28.8566	-1.0560
CK14	-11.3992	-7.4635	-32.0528
CK15	27.5464	-7.1735	-24.8499
CK16	14.1284	-10.4432	-27.1230
CK17	-5.4037	-19.8891	6.2560
CK18	17.5816	-15.1054	33.2371
CK21	11.1323	-10.4747	-45.3404
CK22	-8.5327	-17.8854	35.5837
CK23	29.1723	-20.4770	31.2970
CK25	-5.7433	17.1590	-4.9786
CK26	-28.9066	-11.5493	-25.6467
CK30	-11.1859	-7.7349	-8.2511
CK33	28.6852	-11.7923	-49.9490
CK34	6.2856	-7.7870	-48.3672
CK67	7.5260	-28.9757	-45.1008
Average	3.7402	-13.3806	-9.3602
RMS	16.1319	16.7599	29.9633
STD	16.1000	10.3545	29.2032

CONCLUSIONS

This study develops a DG based UAV photogrammetric platform where an INS/GPS integrated POS system is implemented to provide DG capability of the platform.

The performance verification process indicates the proposed platform can capture the aerial images successfully. With the proposed low cost but high mobility DG based UAV based platform, the preliminary result illustrates horizontal DG positioning accuracies in x and y axes are both less than 20 meters, respectively. On the contrary, the positioning accuracy of z axis is less than 30 meters with 600 meters flight height above ground. Such accuracy is good for near real time disaster relief. Therefore, the DG ready function of proposed platform guarantees the mapping and positioning capability even in GCP-free environments, which is very important for rapid urgent response for disaster relief.

In addition, the future study will be conducted to implement a static ground calibration procedure to improve the DG positioning accuracy of proposed UAV based photogrammetric platform. The one-step approach will be developed to guarantee the accurate lever arms and boresight angles calibration and a cluster based tightly coupled integrated scheme will be investigated to guarantee the stability of POS solutions for practical GCP-free applications.

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