Camera Orientation without Aerotriangulation: System Performance and Productivity

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ABSTRACT

The technology of determining attitude and position of sensors was evolved, in the last few years, from defense and space applications to affordable commercial airborne applications. Performance of such technology was also enhanced to meet the stricter technical specifications required for positioning and orienting an airborne photogrammetric mapping camera.

An integrated airborne acquisition system consisting of a carrier phase dual-frequency GPS receiver, a strapdown Inertial Navigation System (INS), and WILD RC30 aerial camera was put in full production for the last two years to support a variety of 1:1,200 to 1:12,000 scale airborne mapping activities. The highlight of this experience was a pilot project which included Cumberland and Fayette counties in the state of Tennessee. This pilot is part of a statewide parcel-level GIS development initiative.

Accuracy validation for the Tennessee pilot project was conducted through ground and photogrammetric surveyed map verification. Over 40-ground control points were collected and ten ortho-rectified map sheets were generated to verify the accuracy of the IMU-derived photogrammetric products.

In many cases, The ability of the IMU to determine camera position and attitude (X, Y, Z, ω, ϕ, κ) was comparable to the results obtained from the process of aerial-triangulation. In addition, the quality of the resulting map products was within the parameters of all major map standards used in United States of America. However, in other cases the performances of the IMU failed to satisfy the required quality on many other projects.

INTRODUCTION

Direct measurement of the image or camera position and orientation (X, Y, Z, ω, ϕ, κ) represents a major advance in the photogrammetric process and one which will re-define the use of ground control and aerial triangulation as part of the mapping process. Integrated GPS and inertial technology has made it possible to precisely measure the position and orientation parameters describing the attitude of the aircraft at the instant of exposure.

Traditionally, and for the last few decades, airborne Photogrammetry relied upon the presence of ground control points in the project area and which are imaged on overlapping photographs. As the camera and GPS system collects photography, the orientation of the camera is typically unknown. Classical procedures require surveying a number of points on the ground and using advanced mathematical adjustments to compute the position and orientation of the sensor. This process, referred to as aerial triangulation, consumes a significant part of the mapping process, and is a requirement to successfully utilize imagery for further compilation and extraction of elevations and features. To generate accurate map products, with the various images rectified to each other, requires the sensor orientation to be measured to certain accuracy (Skaloud et al., 1996 Abdullah, 1997). Over the past several years, differential GPS has been documented to provide the required positional accuracy, using “on-the-fly” ambiguity resolution techniques for the carrier phase ambiguities for the higher accuracy, and differential code techniques for the lower accuracy. Using GPS to position the sensor itself, without orientation parameters, has allowed a reduction in ground control of 70 to 95% through the utilization of the airborne GPS assisted aerial triangulation. By installing an IMU on the sensor, and measuring the orientation of the platform, the requirement to establish a ground control network, and to perform the aerial triangulation process, become unnecessary to accurately rectify the imagery for the map compilation process, Figure 1.

In recent years several publications confirmed the potential of utilizing the integrated inertial navigation system (INS)/GPS technology for georeferencing remotely sensed data (Schwarz, et al., 1993, Schwarz, 1995, Ackermann, 1995, Skaloud et al., 1996). However, it was only recently that the photogrammetric mapping industry gave serious consideration to the use of the integrated GPS/inertial technology to measure camera attitude to an accuracy that enables the process of photogrammetric mapping without the determination of exterior orientation parameters from aerial triangulation or other photogrammetric means (Abdullah, 1997, Hutton, et al., 1997, Abdullah, et.al., 1999).

The EarthData group acquired a state of the art position and orientation system called *POS/DG* manufactured by APPLANIX of Ontario, CANADA . By blending high rate measurements of acceleration and angular rate vectors from inertial sensors (accelerometers and gyros) with position and velocity measurements provided by the GPS receiver, POS/DG computes a dynamically accurate, broadband solution for all motion variables with performance characteristics better than those of either GPS or inertial alone. Using GPS data to calibrate inertial sensor errors on-line, POS/DG maintains the dynamic fidelity of the inertial solution while removing long-term systematic drifts from position and orientation derived from an inertial measurement system alone.

DATA COLLECTION – TENNESSEE PILOT PROJECT

The EarthData group acquired new black and white aerial photography over the entirety of Cumberland and Fayette counties in Tennessee. The photography was flown at altitudes of 15,000’ and 3,600’ or photo scales of 1:30000 and 1:7200, respectively. The photography was acquired in April 1998 using a WILD RC30 aerial camera system with a 6” focal length (152.980 mm) mounted with the IMU. On each flight, differential GPS with carrier phase observations (DGPS) and IMU data were collected using suitable GPS base stations within each county.

A ground control network that consisted of targeted and photo-identifiable ground control was developed for each county. Some of those control points were collected to support the aerial triangulation solution required for the IMU boresight offset determination, while the remaining number of control points were used to verify the IMU-derived camera position and orientation parameters.

Since the GPS and the IMU are physically displaced from the perspective center of the camera, a constant displacement exists between the GPS/IMU position and the camera perspective center. The amount of this displacement is measured by conventional surveying technique prior to the flight mission (Skaloud et al., 1996). Similarly, a constant offset in the orientation of the IMU axes and the camera axes exists after each installation process. These offsets must be accurately determined to obtain correct orientation angles of the camera. In order to achieve this, an accurate aerial triangulation solution was computed for a well-controlled block of photography.

PROCEDURE AND RESULTS ANALYSIS – TENNESSEE PILOT PROJECT

IMU Stability:

To verify the stability of the IMU’s performance over time and under different operating conditions, the boresight area was flown four times over a period of two days. This was resulted in four sets of misalignment angles between the IMU body frame and the camera (photogrammetric) frame. These misalignment angles were used in the inertial solution to compute four sets of exterior orientation parameters (X, Y, Z, ω, ϕ, κ) for all the photographs collected for the two counties.

Check-points assessment:

This process included orienting the analytical or softcopy photogrammetric station with exterior orientation values obtained from the IMU. The selected ground control points were then measured stereoscopically (ground truth). Three to five measurements were taken for each control point and a statistical mean value was calculated to represent the measured easting, northing, and elevation for each of the checkpoints. The photogrammetrically-derived coordinates were then compared to their corresponding surveyed values to determine a statistical mean and Root Mean Squares of discrepancies between the two sets.

A total of 13 control points (not including the eight points utilized in the aerial triangulation solution) were selected to assess the quality of the exterior orientation parameters obtained from the IMU for low-altitude or 1” = 100’ scale mapping. (Some of these points appeared in more than one stereo-model though there was an even distribution over the Fayette County block.) A total of 24 control points was selected to assess the accuracy of the high-altitude or 1” = 400’ scale mapping. Table (1) represent the IMU accuracy assessment for the low altitude. The table shows four different sets of measurements derived from the four different boresight determinations as mentioned earlier. Table 2 represents the IMU accuracy assessment for the high altitude flights.

One set of IMU-derived exterior orientation parameters was used to evaluate the feasibility of the IMU- derived position and angles to support map production for Cumberland County. Eight ground control points, some of which appeared in more than one stereo-model, were measured in a manner similar to that presented for Fayette County. Table 3 represents the results of comparing the surveyed coordinates with IMU- supported photogrammetric measurements. The results in Table 3 are consistent with the results obtained for Fayette County.

To provide a larger statistical sample, additional thirty-six photo-identifiable points distributed over ten map sheets were measured using exterior orientation parameters from both the IMU and aerial triangulation. The two sets of measurements were then compared to the ground surveyed coordinates of the same points that were identified and surveyed by the Tennessee DOT. The results of the later comparison are included in Table 4.

Map Fidelity:

To further confirm the validity of the IMU’s performance, ten map sheets (scale 1”=100’) were compiled for Cumberland County. The data for the maps was collected to the technical specifications for the Tennessee parcel GIS project. The purpose of this part of the evaluation was:

- To collect three-dimensional breaks lines and mass points to support the ortho-rectification process for the ten sheets.
- To evaluate the accuracy of the rotation angles measured by the IMU and its effect on the operator’s ability to capture 3-D data stereoscopically. Less accurate angles will cause unwanted rotations (e.g. excessive parallax) between photographs from the same flight line or photographs from adjacent photographs. Evaluating the relative orientation of each stereo-model is one of the indicators of the quality of the-IMU derived exterior orientations.
- To evaluate the edge-match or mismatch between adjacent sheets. This is also directly related to the quality of the rotation angles and position of the camera station as measured by the IMU.

Orthophoto Quality:

To further confirm the ability of the IMU in support of orthophoto image mapping, ten orthophoto sheets (scale 1”=100’) with a ground sampling distance of 0.5’ were generated using:

- 1:7500 black and white imagery in Cumberland county scanned at 14 um;
- A digital terrain model (DTM) collected using IMU-derived exterior orientation parameters to orient the analytical plotter;
- IMU-derived exterior orientation parameters to orient the Softplotter during ortho-rectification.

A total of 22 measurements (shifts) were measured over the seams between the ten sheets, as shown in figure (2), and statistical values were derived and are presented in Table (5).

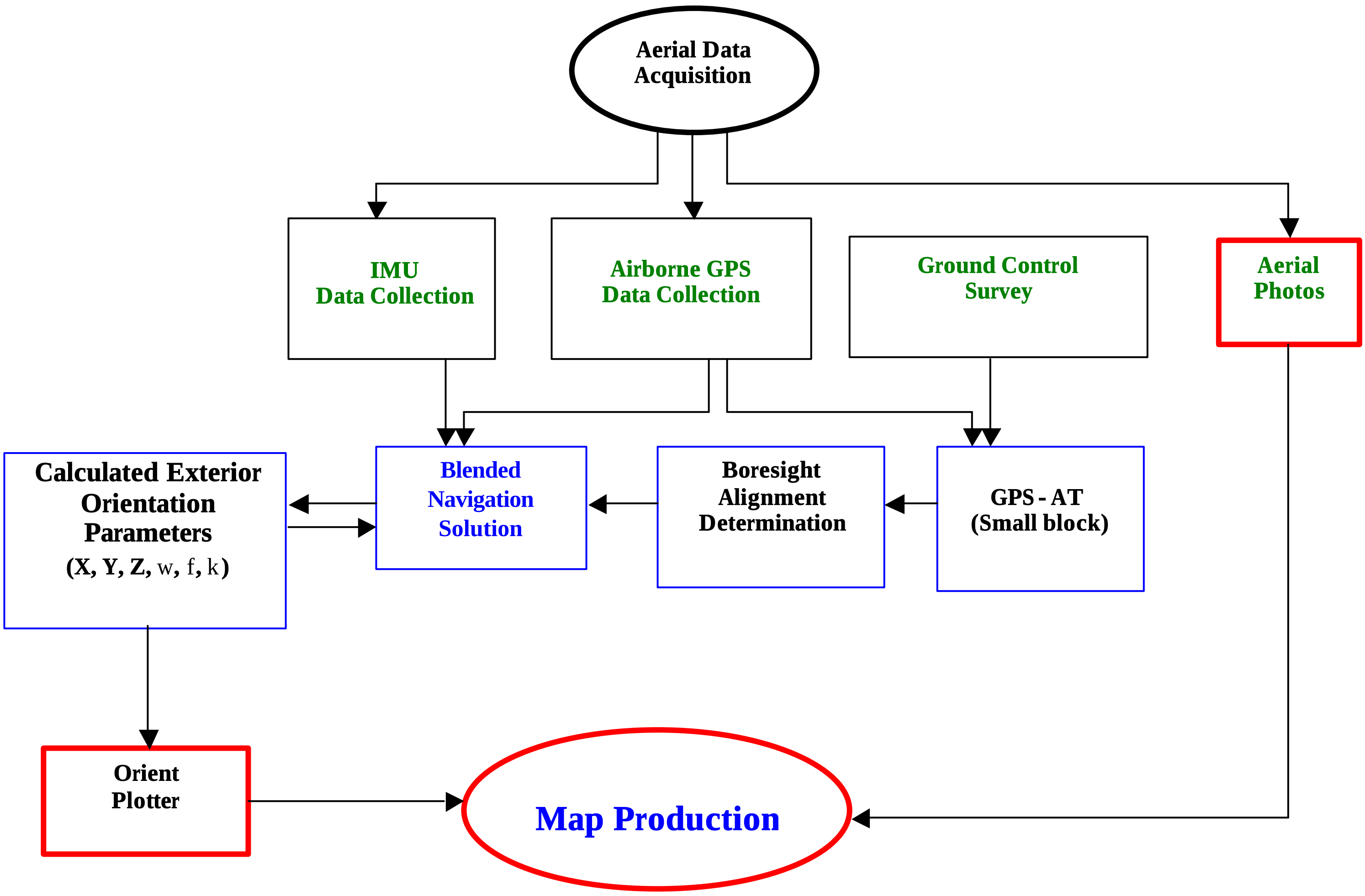

Figure (1) Flowchart of the IMU/map production process Table (1) Results of Ground Control Points in Fayette County

Table (1) Results of Ground Control Points in Fayette County

Point ID	Discrepancies in X, Y, and Z based on boresight offset values determined from:												Point ID	Stereo-pair No.
	DAY 91 AM			DAY 91 PM			DAY 92 AM			DAY 92 PM				
	Delta X (ft)	Delta Y (ft)	Delta Z (ft)	Delta X (ft)	Delta Y (ft)	Delta Z (ft)	Delta X (ft)	Delta Y (ft)	Delta Z (ft)	Delta X (ft)	Delta Y (ft)	Delta Z (ft)		
LT01	-0.587	0.359	-0.747	-0.773	0.432	-0.621	-0.751	0.653	-0.693	-0.564	0.829	-0.625	**LT01**	6170_6171
LT01	0.368	0.089	0.119	0.788	0.254	0.096	-0.011	0.359	0.352	-0.164	0.675	0.146	**LT01**	6171_6172
LT01	-0.325	-0.065	-0.151	-0.174	-0.133	-0.264	-0.141	-0.335	-0.255	-0.523	-0.546	0.137	**LT01**	6185_6186
LT01	-0.660	0.199	-0.583	-0.378	0.147	-0.751	-0.158	0.286	-0.451	-0.129	-0.441	-0.395	**LT01**	6186_6187
LT02	-0.331	0.074	0.163	-0.465	0.187	0.318	-0.445	0.257	0.293	-0.170	0.555	0.232	**LT02**	6169_6170
LT02	-0.128	-0.144	-0.542	-0.216	0.020	-0.559	-0.544	0.076	-0.381	-0.523	0.437	-0.433	**LT02**	6170_6171
LT02	-0.022	-0.115	-0.912	0.140	-0.220	-0.776	0.072	-0.416	-0.701	-0.085	-0.717	-0.682	**LT02**	6186_6187
LT02	-0.340	0.197	-0.441	-0.354	0.065	-0.330	0.267	0.217	-0.804	0.035	-0.467	-0.314	**LT02**	6187_6188
LT04	0.286	-0.478	0.852	0.510	-0.605	0.829	0.541	-0.622	0.894	0.283	-0.922	0.869	**LT04**	6248_6249
LT05	-0.528	-0.175	0.901	-0.436	0.006	0.900	-0.150	-0.034	0.977	0.389	-0.716	1.121	**LT05**	6247_6248
LT06	-0.219	0.093	-0.726	-0.481	-0.082	-0.925	-0.120	-0.008	-0.734	0.292	0.063	-0.506	**LT06**	6160_6161
LT07	-0.288	-0.132	0.289	-0.099	-0.268	0.316	0.072	-0.313	0.425	0.108	-0.619	0.375	**LT07**	6163_6164
LT08	-0.262	-0.293	0.250	-0.162	-0.441	0.128	-0.364	-0.146	-0.622	0.245	-0.197	0.400	**LT08**	6000_6001
LT09	-0.134	0.106	0.450	0.045	-0.078	0.586	0.120	-0.081	0.470	-0.126	-0.280	0.578	**LT09**	6001_6002
LT09	0.072	0.309	-0.291	0.197	0.164	-0.362	0.228	0.085	0.146	0.640	-0.182	-0.075	**LT09**	6002_6003
LT10	0.225	-0.230	0.224	0.369	-0.299	0.447	0.380	-0.279	0.359	0.185	-0.497	0.517	**LT10**	6027_6028
LT10	-0.050	-0.008	-0.199	0.037	0.545	-0.215	0.437	0.570	-0.084	0.526	0.291	-0.188	**LT10**	6028_6029
LT11	-0.373	0.804	-0.030	-0.538	0.933	0.019	-0.435	1.046	0.180	-0.191	1.283	0.306	**LT11**	6051_6052
LT12	-0.064	0.505	0.344	-0.286	0.683	0.599	-0.263	0.559	0.364	-0.233	0.681	0.283	**LT12**	6049_6050
Average	-0.177	0.058	-0.054	-0.120	0.069	-0.030	-0.067	0.099	-0.014	0.000	-0.041	0.092		
RMSE	**0.328**	**0.298**	**0.512**	**0.402**	**0.382**	**0.548**	**0.348**	**0.421**	**0.545**	**0.337**	**0.616**	**0.501**		

Table (2) Discrepancies between surveyed and IMU-derived coordinates in Fayette County, high altitude photography

	Delta X (feet)	Delta Y (feet)	Delta Z (feet)
Average	0.045	-0.657	0.110
RMSE	**1.613**	**1.576**	**2.478**

Table (3) Discrepancies between surveyed targets and IMU derived coordinates in Cumberland County, low altitude photography.

	Delta X (ft)	Delta Y (ft)	Delta Z (ft)
Average	0.259	-0.135	0.345
RMSE	**0.622**	**0.307**	**0.706**

Table (4) Comparison of ground surveyed checkpoints to IMU-derived and aerial triangulation-derived coordinates

	Surveyed – IMU (ft)			Surveyed – AT (ft)		
	Delta X	**Delta Y**	**Delta Z**	**Delta X**	**Delta Y**	**Delta Z**
Average	**0.713**	**0.046**	**-0.636**	**0.967**	**-0.219**	**-0.234**
RMSE	**0.839**	**0.348**	**0.994**	**1.006**	**0.292**	**0.591**

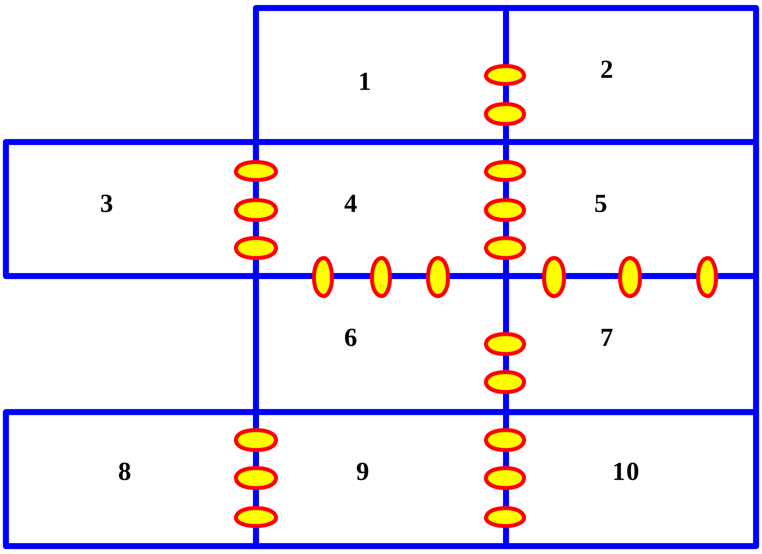

Figure (2) Layout of Ortho-sheets and measured distances.

Table (5) Accuracy of Ortho-sheets edge fitting

	Distance Value (ft)	
Average	**1.41**	**ft**
RMSE	**1.53**	**ft**

RESULTS'ANALYSIS – PRODUCTION PHASE

As for the pilot project, ground control points were always collected for every project to verify the performance of the measured value of the camera exterior parameters.

Analyzing tens of projects that were flown with the IMU support showed mixed results and variable performance. The performance ranged from the highest quality resembling that obtained in the pilot project, to lowest quality that resulted in an excessive parallax that hindered the use of the IMU-derived orientations in mapping many projects.

The parallax, in some instances caused only physical constraints for the compilers' eyes without effecting the mapping accuracy, while in other instances it resulted in both compilers' complaints and loss of mapping accuracy.

Results from several projects demonstrated that precaution should be exercised when dealing with such technology.

Looking into the cause of such varied performance was the most challenging task that has yet to be resolved. Many theories were derived to explain this variation. Among the most popular ones are the following:

- Mechanical stability of the IMU/camera mount
- IMU internal performance
- GPS quality
- Camera Internal stability

DISCUSSIONS AND CONCLUSIONS

Based on the research results, the following discussions and recommendations are made:

1. The results from the pilot project indicate that the IMU-derived maps are well within the horizontal and vertical accuracy requirements of the National Standard for Spatial Data Accuracy (NSSDA), which was endorsed by the Federal Geographic Data Committee (FGDC). In both cases, none of the measurements showed discrepancies in excess of the NSSDA accuracy figure for map scale of 1"=100' or 2.4' horizontally and 1.3' vertically, nor in excess of 9.8' horizontally for high altitude. Of the 29 high altitude measurements, only one measurement showed a discrepancy of 7.477' vertically, exceeding the NSSDA accuracy tolerance of 5.2' for the 1" = 400' scale with an 8' contour interval. However, the resulting RMSE for the set of 29 measurements was within the 2.7' assumed RMSE used to calculate the NSSDA vertical accuracy figure for the 1" = 400' map scale.

2. At it's best performance, the IMU-derived maps or orthophotos are within the industry standard and are comparable to those derived from conventional mapping means.

3. The results reveal that utilizing the IMU four times over a period of two days did not result in significant variations from ground truth. The four sets of discrepancies resulted in RMSE ranging from 0.298' to 0.616' for the horizontal coordinates and from 0.515' to 0.548' for the vertical.

4. For most cases, photogrammetric mapping processes can be accurately accomplished with exterior orientation parameters derived from the integrated airborne GPS/IMU.

5. Although the study showed the reliability of flying the IMU over a period of time without new boresight misalignment determination, further study should be conducted under different operating conditions and over varying time spans to determine how often boresight offset should be measured.

6. Further studies need to be conducted to investigate the cause of poor performance of the IMU in some instances.

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