IMU AND ULTRACAM D MISALIGNMENT CALIBRATION

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ABSTRACT

The use of in-flight control systems for controlling blocks of aerial photography is now an established procedure. The technology of GPS and an inertial measurement unit (IMU) integrated with an aerial camera, either analogue or digital, is regularly being used for production purposes. The importance of GPS and IMU measurements is increasing as there is greater and greater interest to work without ground control and strive towards direct georeferencing of imagery. Arguably, direct georeferencing can be considered with and without aerial triangulation as the use of automatically measured minor control points (tie and pass points) can be easily and efficiently undertaken by modern aerial triangulation software.

Critical to the success of direct georeferencing, particularly without aerial triangulation, are the IMU measurements and therefore the determination of the geometric relationship between the IMU and the camera geometry. As experience is gained from undertaking misalignment (boresight) calibrations a number of interesting results are being produced.

To study the calibration of the integration of the sensors the IESSG has adapted its aerial triangulation software 3DB. This paper will present the results from trials using a Vexcel UltraCam D digital camera and ZIESS RMK TOP 15 film camera fitted with an Applanix POS AV, GPS/IMU integrated system. Various image configurations have been considered in the analysis.

INTRODUCTION

Critical to the success of direct georeferencing, where aerial triangulation is not used, are the IMU measurements and therefore the determination of the geometric relationship between the IMU and the camera geometry (Smith et al., 2006). So the main objective of this paper is to investigate the determination of the relationship between the camera and IMU (boresight calibration) for the Vexcel UltraCam D digital camera and for the ZEISS RMK TOP 15 film camera. As experience is gained from undertaking misalignment (boresight) calibrations a number of interesting results are being produced.

The correct determination of the misalignment matrix is very important because any errors in the misalignment between the IMU body frame and the image coordinate system will cause errors in object point coordinate determination using GPS/IMU for direct sensor orientation (Mostafa, 2003).

The theory behind this relationship is well documented by a number of researchers (for example, Jacobson, 2003) and commercial system providers (for example, Mostafa, 2002). As the availability of suitable inertial systems has become more widespread the theory has been put into practice. The integration of inertial sensors with analogue cameras produced a number of challenges particularly in terms of the stability of the mounting which led to considerable interest in the calibration (boresight calibration) between the IMU and the camera (Smith et al., 2006). This naturally leads to some discussion on how frequently the boresight calibration needs to be performed.

More recently, there has been the emergence of aerial digital cameras specifically designed and built for photogrammetry. These aerial digital cameras brought further challenges when combined with GPS and IMU sensors (Smith et al., 2006). The camera forms part of an integrated system with GPS and IMU sensors. Examples of these can be found in Smith et al. (2005) and Cramer (2005). These cameras are rigorously calibrated for their internal optical geometry and the stability of the camera geometry (Mostafa, 2002). Having been designed to accommodate an IMU and GPS as an integral part of the sensor system the relationship should be inherently stable and well known (Mostafa, 2002). The existing procedures produced from experiences undertaking boresight calibrations with analogue and non-metric digital cameras are expected to be suitable for applying to this new range of digital cameras. Boresight calibration experience with these cameras is now being gained from practical observation. The questions still remain partially unanswered with regard to frequency of calibration and optimum procedures for quality and efficiency.

As there is limited experience of undertaking boresight calibrations with the UltraCam D camera some analysis is presented on the impact of changing the main variables in the calibration procedure. Investigations to asses the effect of different parameters on the boresight determination accuracy have included in this paper. These parameters are the number images, the number of ground control points and the number of tie points used in the aerial triangulation. The computation process to compute the misalignment matrix has been undertaken through an aerial triangulation program 3DB.

ASSESSMENTS OF RESULTS

One of the most difficult issues that requires addressing is how to assess the quality of the boresight calibration. In general, a way to check the quality of any measurement is by comparing results with a measurement from significantly higher quality equipment or measurement system (Smith et al., 2006). This would then provide a benchmark or reference measurement to compare against. In the past this has been very difficult to achieve as far as IMU measurements are concerned as there has been little equipment available to compare against the high quality geodetic grade IMU often used (Smith et al., 2006). It has also not necessarily been a trivial task to integrate a second IMU into what is already a complex integration problem.

The alternative is to assess the results from a posteriori statistical analysis from the computation or the assessment the quality of the resulting photogrammetric product. The first method is an internal assessment while the second is often an external assessment. The results presented here show internal analysis through the parameter standard errors and the image residuals and the external assessment is through the RMSE of check point residuals

THE TEST SITE

Three UltraCam D boresight calibration flights are analysed over the established Milton Keynes site used by Simmons Aerofilms Ltd. A traditional flight plan was used with a flying height of 880m, a nominal forward overlap of 60% and a nominal side overlap of 20% for all flights. These were undertaken due to the camera being moved between two aircraft. Figure 1 shows a typical flight plan of the block flown

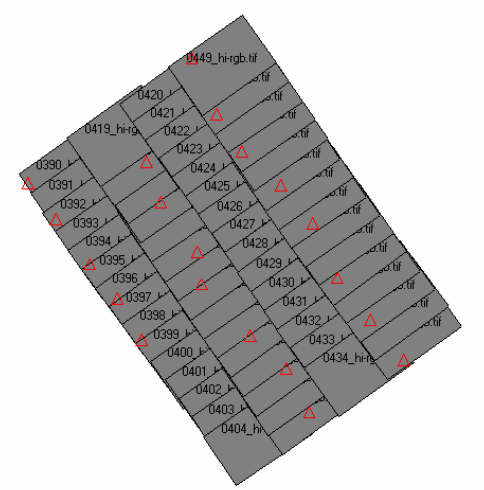

Figure 1. Block of 60 images taken at 880m flying height – using the UltraCam D

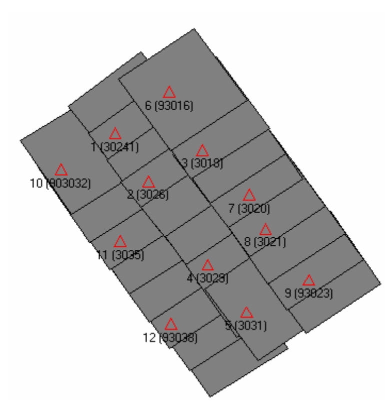

Figure 2. Block of 24 photographs taken at 880m flying height – using the metric ZEISS RMK TOP 15

To enable some comparison to take place with a frame camera, results from a 24 photograph metric ZEISS RMK TOP 15 block are assessed. The images are taken at 880m flying height and an imagery scale of 1:6000 over the same test area, see Figure 2. The data from the frame camera taken at scale 1:6000 was specially chosen as it has the same swath width as the UltraCam D digital camera.

Two tests were undertaken in assessment some of the effects on the calibration determination:

- The effect of the number of images and number of ground control points on the determination of misalignment matrix.
- The effect of number of tie points on the determination of misalignment matrix

TEST 1-THE EFFECT OF THE NUMBER OF IMAGES AND NUMBER OF GROUND CONTROL POINTS ON THE DETERMINATION OF MISALIGNMENT MATRIX

To evaluate the boresight calibration using a different number of strips and ground control points, the calibration flights on 06/05/2005 for UltraCam D and on 09/09/2003 for RMK TOP 15 were selected. Table 1 and Table 2 show the results for what might be considered the extreme scenarios for UltraCam D digital camera and RMK TOP 15 film camera. Changes of misalignment angles from reference solutions have been shown in Table 1 and Table 2. The reference boresight angles in Table 1 are those determined using the block configuration of 4 strips and 11 ground control points, and in Table 2 are those determined using the block configuration of 3 strips and 9 ground control points

Table 1. The changes in misalignment angles for the UltraCam D using different number of strips and ground control points

Number of strips/GCP/ CP	Changes in misalignment angles (arc-min)			Standard error (arc-min)			RMSE of image coordinate (µm)		RMSE on check ground control points (m)		
	roll	pitch	yaw	roll	pitch	yaw	x	y	X	Y	Z
Four/11/6	0	0	0	0.072	0.059	0.067	1.90	1.77	0.105	0.138	0.109
Four/8/9	0.017	-0.047	-0.127	0.059	0.048	0.058	1.93	1.74	0.127	0.084	0.128
Four/5/12	0.017	-0.043	-0.159	0.059	0.048	0.059	1.93	1.74	0.133	0.076	0.154
Four/3/14	0.022	-0.037	-0.220	0.059	0.047	0.061	1.92	1.74	0.141	0.079	0.154
Four/1/16	0.021	-0.007	-0.200	0.059	0.047	0.061	1.92	1.74	0.147	0.113	0.173
Four/0/17	0.019	-0.011	-0.195	0.059	0.047	0.061	1.97	1.67	0.110	0.162	0.147
Three/11/6	-0.032	-0.071	0.159	0.074	0.061	0.069	1.84	1.65	0.161	0.072	0.142
Three/8/9	-0.038	-0.133	0.015	0.069	0.055	0.067	1.86	1.65	0.148	0.168	0.152
Three/5/12	-0.020	-0.111	0.028	0.069	0.055	0.067	1.86	4.64	0.164	0.172	0.169
Three/3/14	0.002	-0.070	0.063	0.069	0.055	0.073	1.84	1.54	0.132	0.131	0.169
Three/1/16	0.013	-0.123	0.083	0.070	0.055	0.070	1.83	1.54	0.148	0.110	0.153
Three/0/17	0.014	-0.099	0.028	0.070	0.055	0.074	1.80	1.52	0.155	0.143	0.144
Two/8/3	0.010	0.075	-0.147	0.084	0.067	0.083	1.84	1.33	0.157	0.117	0.096
Two/7/4	0.012	0.045	-0.100	0.083	0.066	0.083	1.84	1.34	0.140	0.097	0.126
Two/5/6	0.005	0.043	-0.228	0.082	0.066	0.087	1.84	1.33	0.175	0.067	0.097
Two/3/8	0.009	0.086	-0.271	0.083	0.065	0.093	1.83	1.32	0.181	0.104	0.147
Two/1/10	0.001	0.093	-0.411	0.084	0.065	0.093	1.83	1.32	0.151	0.110	0.149
Two/0/11	0.003	0.105	-0.325	0.083	0.065	0.094	1.83	1.32	0.158	0.113	0.153
One/4/2	-0.267	-0.166	-0.003	0.144	0.120	0.136	1.95	1.04	0.162	0.080	0.075
One/3/3	-0.218	-0.040	-0.086	0.160	0.122	0.143	1.95	1.03	0.158	0.073	0.134
One/2/4	-0.214	0.025	-0.113	0.142	0.119	0.134	1.95	1.03	0.138	0.073	0.130
One/1/5	-0.068	0.393	-0.059	0.217	0.127	0.155	1.93	1.03	0.259	0.03	0.122
One/0/6	-0.173	16.537	0.343	10.947	0.130	0.206	1.91	1.01	3.082	2.633	1.586

Table 2. The changes in misalignment angles for the RMK TOP 15 using different number of strips and ground control points

Number of strips/GCP/CP	Changes in misalignment angles (arc-min)			Standard error (arc-min)			RMSE of image coordinate (μm)		RMSE on check ground control points (m)		
	roll	pitch	yaw	roll	pitch	yaw	x	y	X	Y	Z
Three/9/3	0.000	0.000	0.000	0.122	0.104	0.122	3.88	4.04	0.249	0.057	0.155
Three/6/6	-0.045	0.030	0.039	0.120	0.102	0.121	3.86	4.05	0.255	0.054	0.179
Three/4/8	0.076	-0.042	0.007	0.115	0.098	0.117	3.88	4.06	0.452	0.090	0.165
Three/2/10	0.091	-0.049	0.166	0.110	0.094	0.114	3.86	4.05	0.520	0.109	0.218
Three/1/11	0.098	-0.086	0.003	0.108	0.091	0.113	3.77	4.03	0.599	0.127	0.277
Three/0/12	0.141	-0.083	0.026	0.107	0.089	0.114	3.70	3.96	0.676	0.163	0.365
Two/8/4	0.392	-0.064	0.133	0.154	0.128	0.149	3.54	3.94	0.292	0.079	0.133
Two/6/6	0.302	-0.061	0.273	0.151	0.124	0.148	3.41	3.91	0.314	0.113	0.245
Two/4/8	0.475	-0.051	0.116	0.149	0.120	0.149	3.39	3.86	0.344	0.190	0.289
Two/2/10	0.379	-0.045	0.062	0.142	0.114	0.150	3.36	3.88	0.409	0.192	0.366
Two/1/11	0.300	-0.050	0.088	0.140	0.112	0.149	3.34	3.88	0.490	0.165	0.365
Two/0/12	0.377	-0.037	0.055	0.136	0.106	0.143	3.34	3.85	0.642	0.168	0.396
One/5/2	-1.074	0.047	0.064	0.232	0.189	0.205	2.79	3.82	0.106	0.109	0.096
One/4/3	-0.960	0.008	0.141	0.229	0.186	0.201	2.75	3.80	0.268	0.144	0.135
One/2/5	-0.637	-0.371	0.419	0.274	0.168	0.199	2.39	3.81	0.541	0.188	0.281
One/1/6	-0.494	-0.359	0.245	0.354	0.174	0.204	2.43	3.79	0.528	0.184	0.282
One/0/7	-20.741	0.547	0.266	10.867	0.417	0.229	2.07	3.67	5.066	3.059	3.038

The results in Table1 and Table 2 show that calibrating the boresight using one strip without ground control points yields significantly poorer precision in the boresight pitch component for UltraCam D digital camera and poorer precision in the boresight roll component for RMK TOP 15 film camera. The heading component of the boresight for both cameras does not seem to be effected by the ground control points at all because in-flight GPS fixing it. Furthermore, there is no difference between only two ground control points or using all of them as far as the boresight precision is concerned.

Also Table 1 and table 2 show that the average roll and pitch standard error for UltraCam D is 0.079 arc-min which is equivalent to about 2.4μm on the image or about 2cm on the ground. For RMK TOP 15, the average roll and pitch standard error is 0.145 arc-min which is equivalent to about 6.5μm on the image or about 3.7cm on the ground. Interestingly the image residuals for UltraCam D are significantly smaller; the average RMSE image coordinate is 1.88μm in x and 1.59μm in y. Also the check points residuals for UltraCam D are smaller. The average RMSE check pints is 0.152m, 0.105m, and 0.137m in X, Y, and Z respectively. With RMK TOP 15 film camera, the average RMSE image coordinate is 3.35μm in x and 3.92μm in y, and average RMSE check pints is 0.418m, 0.133m, and 0.247m in X,Y, and Z respectively.

The results in Table 1 and Table 2 show that the changes in the roll angle with the RMK TOP 15 are almost close to one arc-min when a single strip configuration is used. This is almost four times greater than the changes in the roll angle of with UltraCam D when the same configuration is used.

In general, the results for UltraCam D digital camera show that there are not significant differences in the misalignment components, between using different strips and ground control points configurations, except the results from one strip without ground control points configuration. The maximum difference for misalignment with UltraCam D between 4 strips and one strip block configuration is 0.006 deg in pitch, but the maximum for misalignment with film camera between 3 strips and one strip block configuration is 0.018 deg. The four strip computations with UltraCam D show an improvement in the standard errors of the misalignment angles over the other strip configurations. However, there is little change in the check point RMSE.

In summary, the misalignment matrix for UltraCam D digital camera and RMK TOP 15 film camera can be determined using different imaging configurations without the need for ground control points, except the single strip without the any ground control results.

TEST 2-THE EFFECT OF NUMBER OF TIE POINTS ON THE DETERMINATION OF MISALIGNMENT MATRIX

Table 3 and Table 4 show the changes of misalignment angles from reference solutions. The reference boresight angles in Table 3 are those determined using the block configuration with 1172 tie points, and in Table 4 are those determined using the block configuration with 368 tie points. The maximum change in misalignment angles is in the roll with a change of 0.173arc-min with the UltraCam D. The results do not show much difference, the largest being the UltraCam D results in roll, identifying a consistent and sufficient set of tie point observations. Also the results show that the effect of number of tie points is not limiting factor for boresight quality.

Table 3. The changes in misalignment angles for the UltraCam D using different number of tie points

No of GCP/ CP	No of Tie points	Changes in misalignment angles (arc-min)			Standard error (arc-min)			RMSE of image coordinate (µm)		RMSE on check ground control points (m)		
		roll	pitch	yaw	roll	pitch	yaw	x	y	X	Y	Z
11/6	1172	0	0	0	0.069	0.058	0.067	1.90	1.77	0.105	0.138	0.109
11/6	434	0.145	-0.019	0.026	0.077	0.066	0.077	1.84	1.86	0.122	0.108	0.099
11/6	368	0.165	-0.008	-0.014	0.072	0.059	0.067	1.86	1.76	0.110	0.135	0.113
11/6	268	0.173	0.004	-0.095	0.080	0.069	0.084	1.79	1.845	0.108	0.157	0.117

Table 4. The changes in misalignment angles for the RMK TOP 15 using different number of tie points

No of GCP/ CP	No of Tie points	Changes in misalignment angles (arc-min)			Standard error (arc-min)			RMSE of image coordinate (µm)		RMSE on check ground control points (m)		
		roll	pitch	yaw	roll	pitch	yaw	x	y	X	Y	Z
8/4	582	0	0	0	0.122	0.104	0.122	3.88	4.04	0.249	0.057	0.155
8/4	168	0.090	0.080	0.050	0.124	0.110	0.129	4.20	4.04	0.248	0.056	0.153
8/4	135	-0.028	0.015	-0.023	0.128	0.113	0.131	4.72	4.06	0.236	0.068	0.129

CONCLUSIONS

3DB software has been used successfully for computing the boresight misalignment for the UltraCam D digital camera and RMK TOP 15 film camera. The results show that significant changes can occur in the misalignment angles between the IMU and the camera if the camera is moved between aircraft, as might be expected. Results show that the boresight calibration can be determined for UltraCam D digital camera using different imaging configurations without the need for ground control points, except the single strip without any ground control results. The maximum difference for misalignment with UltraCam D between 4 strips and one strip block configuration is 0.006 deg in pitch, but the maximum for misalignment with film camera between 3 strips and one strip block configuration is 0.018 deg. Again as expected, the results show that using four strips rather than one has produced higher standard errors for the misalignment angles although little difference is shown by the check points.

On the other hand, the effect of number of tie points per block to compute the misalignment matrix is very minimal for both cameras. Also the results show that the effect of number of tie points is not limiting factor for boresight quality for both cameras.

So, the misalignment components are far easier to be determinined using UltraCam D data as any mix of strip and/or ground control points and/or tie point configurations may be used without noticeable change in the result (except single strip without ground control points).

ACKNOWLEDGMENT

The authors would like to thank the support of Simmons Aerofilms Ltd and the Jordanian Government.

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