A SINGLE STEP CALIBRATION PROCEDURE FOR IMU/GPS IN AERIAL PHOTOGRAMMETRY

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ABSTRACT:

System calibration is required in integrated IMU/GPS systems to account for the spatial offset and misalignment between IMU, GPS and camera frames; synchronization is to be maintained, to predict IMU/GPS position and orientation data at the mid-exposure time of the images. To this aim, measurement on the ground, complemented by a calibration flight over a test field, are performed. Depending on the mathematical model, a two steps or a single step procedure may be used to recover the calibration parameters. Within the OEEPE test "Integrated Sensor Orientation" the authors proposed a simple but effective two steps procedure, where calibration parameters are computed as a weighted average of the discrepancies between the EO parameters of the images derived from block adjustment and those computed from the IMU/GPS data. Here a new single step calibration procedure is presented, where the calibration parameters are explicitely inserted in the collinearity equations and the IMU/GPS data are considered as pseudo-observed quantities, replacing EO parameters as unknowns in the block adjustment. Applied to the same OEEPE data set , the new procedure yields the same results of the previous one, with less ground control points.

1. INTRODUCTION

1.1 Integrated IMU/GPS systems

Integrated positioning and orientation systems composed by an Inertial Measurement Unit (IMU) and GPS receivers allowing direct georeferencing of images in aerial photogrammetry are on the market since a few years. They are slowly making their way into operation in several photogrammetric companies: to the authors knowledge, in Italy there are currently at least two such systems. Despite the impressive results shown in several tests (Burman 1999, Cramer 1999, Cramer et al. 2000, Skaloud 1999), their acceptance in map production is still hindered in Italy by the lack of technical prescriptions for their use in mapping projects. While this happened also to GPS-assisted Aerial Triangulation (even today not always accepted as a standard way to provide block control), a number of reasons (some indeed technical, some perhaps psychological) suggest these systems to be further investigated before gaining full acceptance in everyday practice.

1.2 Control information and reliability

If the evolution started by GPS-supported AT can be interpreted as a move from indirect sensor orientation (EO parameters computed by using gcp and tie points) to direct sensor orientation (EO parameters directly measured), the great promise of IMU/GPS is to skip AT altogheter. In this respect, the way control information is provided and affects the computation of tie point coordinates is changing; but the way we look at the control information itself is also changing. It is well known that errors in the gcp are hard to find, but ground control networks are trusted. Not so with the new technology: currently, we lack simple and trusted procedures to verify the measured orientation parameters. Even an independent check of the GPS solution by using more ground stations is often, thought simple at a first sight, not so easy (how many stations? how do you weigh solutions from stations at rather different distances? what do you do if they don't agree?); independent control of the attitude, on the other hand, is just impossible. Lack of details on IMU/GPS data processing and of clear indices of the computed E.O. quality does not add to customer's confidence. Indirect checks of inner and outer consistency are certainly possible by photogrammetric measurements, but they involve either relative orientation or use of gcp, i.e. just what companies dream to dispense with.

Adding to this lack of confidence on IMU/GPS data is the different behaviour of the control information, moved from ground to the sensor (Jacobsen 2000). While in conventional AT gcp limit the extent of block deformation (therefore making the computation of tie point coordinates an interpolation process), in GPS-assisted AT most of the control moves away from the ground, so computing tie points coordinates becomes in fact more an extrapolation: block deformations are therefore less effectively controlled. The interaction between adjacent images provided by the block structure nevertheless still provide reliability checks of the GPS positions. In IMU/GPS on the contrary we have outright extrapolation, so there is no way to bound the influence of unmodelled factors (I.O. changes, film deformation, etc.) or to highlight possible systematic effects (drifts) of the IMU/GPS solution.

1.3 System calibration

As with GPS-assisted AT, since the sensors are physically separated and do not record data synchronously, a system calibration is required to account for the spatial offsets and misalignment between IMU, GPS and camera frames;

moreover, reference to a common time scale is to be maintained, to allow the interpolation of the IMU/GPS navigation data to the mid-exposure time of the images. In this respect, IMU/GPS systems highlight another trend in modern photogrammetry towards an overall system calibration, rather than just a camera calibration.

While offsets between the different sensors are generally measured with theodolites to the centimeter accuracy, misalignment angles cannot be determined with enough accuracy with surveying instruments and have to be determined indirectly by photogrammetry. What's the best (i.e. operational and economic) way to perform it? How often should it be repeated? These questions are still, to some extent, open. One of the major efforts towards clarifying these issues and assess the performance of IMU/GPS systems has been the OEEPE test "Integrated Sensor Orientation", recently completed (Heipke et al, 2002).

Within the test's activities, the authors used a two-step calibration procedure (Forlani, Pinto 2002) which modifies, as far as the stochastic model is concerned, the method proposed in (Skaloud 1999). By comparing the EO elements obtained by a bundle block adjustment with the EO elements measured by the IMU/GPS data, the calibration parameters (besides the misalignment angles, an offset between the IMU/GPS solution and the photogrammetric solution for the camera projection centres was considered) were estimated as a weighted average of the discrepancies between the EO of the block adjustment and those provided by INS/GPS. The effectiveness of the weighting procedure was reflected on the RMS of the differences on check points computed by direct georeferencing, in the order of 7 cm for N, E and 12 cm for elevations.

In this paper, a different calibration procedure is presented, where the calibration parameters are inserted in the collinearity equations. The projection centre position is replaced by the sum of the position vector of the origin of the IMU and the offset vector from IMU to camera projection centre, while the rotation matrix from image to object space is expressed as the product of a rotation from image to body frame and then from body to object frame. The IMU pre-processed observations (i.e. the coordinates of the projection centre in object space and the rotations from the IMU system to the local level system) are introduced as pseudo observations in the adjustment.

The procedure has been tested with real and simulated data. With the OEEPE dataset, the estimates of the calibration parameters were the same computed by the previous procedure, even when using just a minimum of gcp, without loss of accuracy. Simulations have been performed to find out the amount of ground control still necessary and to estimate biases in the solution and in the ground coordinates of the tie points.

2. MATHEMATICAL MODEL

2.1 The collinearity equations modified

Introducing the calibration parameters directly into the collinearity equations, the bundle adjustment of the calibration block will yield directly their estimates, based on the IMU pseudo-observations and on the block geometry determined by the tie points. Let's start from the collinearity equation in vector form:

$$r_i^L = r_j^L + R_c^L s_i r_i^c \tag{1}$$

where: r_i^L = position of point i in object space, a cartesian system L conveniently located in the block area;
r_i^c = image coordinates of point i in the camera frame c;
r_j^L, R_c^L, s_i = EO parameters of image j (position of the projection centre, rotation matrix from c to L), scale factor for image point i.

Let's assume that IMU/GPS positions refer to the projection centre and that IMU angles provide the rotation from IMU (the body frame b) to L; r_i^L can be obtained as:

$$r_i^L = r_{j\,IMU/GPS}^L + R_b^L [\, s_i R_c^b r_i^c + a^b \,] \tag{2}$$

where: $r_{j\,IMU/GPS}^L$ = IMU/GPS-computed position of the projection centre of image j, in the L frame;
R_b^L = rotation matrix from body frame b to L frame at time t;
R_c^b, a^b = calibration parameters: the rotation matrix from c to b; offset between the IMU/GPS-derived and the photogrammetrically-derived perspective centre position in the b frame.

Comparing (1) and (2) we get for the EO of image j:

$$\begin{aligned} r_j^L &= r_{IMU/GPS}^L + R_b^L a^b \\ R_c^L &= R_b^L R_c^b \end{aligned} \tag{3}$$

The IMU provides the rotations from b to the istantaneous local level system lj, defined as a cartesian frame with origin at the IMU position when image j is taken, z axis pointing upwards along the direction of the gravity vector and y axis in the meridian plane, in N direction. If we assume also L to be a local level system fixed to some ground point, the matrix R_c^L can be decomposed as the product of four rotation matrices:

$$R_c^L = R_G^L R_{lj}^G R_b^{lj} R_c^b \tag{4}$$

where:
R_b^{lj} = rotation from b to lj, measured by IMU;
R_{lj}^G = rotation from lj to the geocentric frame G; depends only on the geographic coordinates of the lj origin in G;
R_G^L = rotation from L to the G frame; depends only on the geographic coordinates of the L origin in G.

We therefore substitute $r_{IMU/GPS}^L + R_b^L a^b$ for r_j^L and the product $R_G^L R_{lj}^G R_b^{lj} R_c^b$ for R_c^L in the collinearity equations, removing the dependence on EO parameters. The modified equations are then linearized with respect to the components of the vector a^b, the angles ω, φ, κ of R_c^b, the components of $r_{IMU/GPS}^L$ and finally with respect to the ground coordinates of the tie points. The functional model for the block adjustment is complemented by the pseudo-observation equation of each IMU/GPS data (either positions and angles) and the pseudo-observation equation of the coordinates of the gcp.

As far as the stochastic model is concerned, due to lack of information (in terms of a variance-covariance matrix of the solution) from the IMU/GPS data processing, which is considered a proprietary information, we assign positions and angles accuracies according to manufacturer's specifications, therefore neglecting correlations arising from pre-processing. We also neglect the fact that the same stochastic parameters appear in the collinearity equations, to keep the model simple. The rank deficiency or critical configurations for the determination of the parameters are addressed in section 3.

2.2 The adjustment program CALGE

The mathematical model above has been coded in the adjustment program CALGE as a new software module. Originally designed for the joint adjustment of photogrammetric blocks and their control network CALGE has been updated several times to accomodate new observation types, such as the pseudo-observation of the GPS antenna at the exposure time in GPS-assisted AT (Forlani, Pinto 1994). Here GPS antenna positions are reduced to the projection centre via an offset vector; systematic discrepancies between the GPS and the photogrammetric solution may be adsorbed by strip-dependent or block-dependent additional shift and drift parameters. This module was extended to accomodate also attitude observations and has been used in the so-called "Integrated sensor orientation" of the above mentioned OEEPE test, a procedure where calibrated IMU/GPS data and image coordinates are used jointly to estimate EO parameters and tie point coordinates.

3. SIMULATED AND REAL TESTS

In order to evaluate the performance of the new method with the objective of finding a minimal sufficient configuration for the calibration block and possible critical configurations, simulations have been performed, varying number and location of gcp, with 4 block configuration. Case S1 (Figure 1) is the OEEPE calibration block, which consists of a 1:10000 block and a 1:5000 block flown over the same area, for a total of 151 images (5 strips, 2 flown twice, plus 2 cross strips, flown twice); forward and side-lap: 60%. Case S2 uses the two 1:5000 strips (66 images), Case S3 part of E-W strips (6+6 images, overlapping and flown opposite) and finally Case S4 just 6 images, from the same E-W strip.

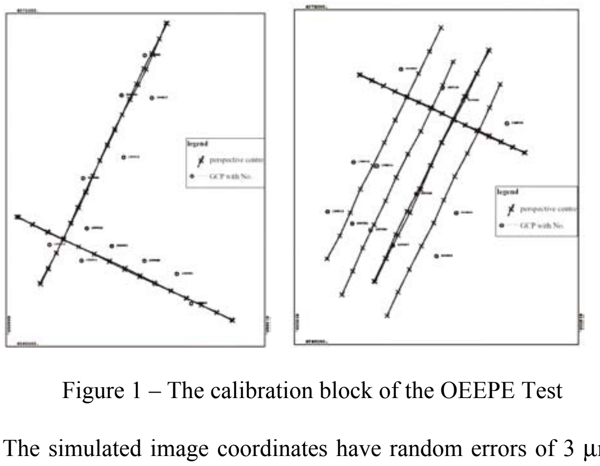


Figure 1 – The calibration block of the OEEPE Test

The simulated image coordinates have random errors of 3 µm, while IMU/GPS have errors of 5 cm in positions and 5 mgon in attitude data. Tests have been successfully performed to verify the convergence to "true" (simulated) values starting from 0 approximate values for the vector components and from values erroneous up to 5 deg for the misalignment angles.

3.1 Simulated tests: dependence on block shape and gcp.

3.1.1 Case S1. We used all available 20 gcp, 4 at the block corners, 1 in the middle (as full cp as well as height cp only), no gcp. The misalignement angles (i.e. the most important information to be recovered) are determined correctly and without decrease in accuracy, even without gcp. To some extent, the same can be said about the offset parameters a_x e a_y. As expected, things are different for a_z: at least 1 height gcp is needed because of the strong correlation of this parameter with tie points elevation; without gcp, a_z is not determinable.

3.1.2 Case S2. We used all gcp, 4 (one at each strip end), and finally 1 at the crossing between the strips. The pattern is much the same as for S1: reducing the ground control affects only the accuracy of the estimates of the a_z component; when minimum or no control is used, there is also a clear coupling with tie point elevations, which get the same bias as a_z. The estimation error in a_z is significant already when using a single gcp; on the contrary, the estimates of misalignement angles and those of the horizontal components a_x e a_y are not affected decreasing gcp's number; their accuracies are fairly comparable to those of S1.

3.1.3 Case S3. We have here just 12 images against 66 and no cross strip; we used 3 gcp configurations: 3 pairs every 2 bases, 1 point at each end and 1 in the middle. The error in the estimates of the *a* vector components increases by more than an order of magnitude, those of the misaligment angles are almost unaffected. Bias in the a_z does not translate exactly in shifts to the tie points heights as in S2. There is some correlation (0.67) between a_x and ϕ. Without gcp, the correlation increases and the condition number, is just acceptable.

3.1.4 Case S4. Using only 6 images in a single pass, with the same gcp configuration of S3, the behaviour decreasing the gcp is less clear. There are correlations between some of the calibration parameters (from 0.75 with 6 gcp up to 0.96, using a single or no gcp); the condition number gets poorer.

3.2 Simulated tests: dependence on inner orientation.

A less exensive series of simulations have also been performed, only on the full OEEPE block, to gauge the sensitivity of the calibration procedure to errors in the IO.
While the estimates of the other parameters are not affected, errors in the principal distance end in a bias Δa_z proportional to the magnitude of the error Δc in the principal distance:

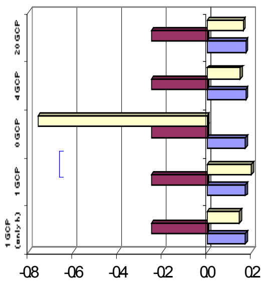
$$\Delta a_z = \Delta c (Z_0 / c) \qquad (5)$$

where Z_0 is the relative flight height.

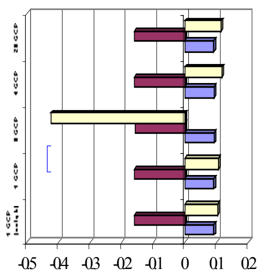
3.3 Tests on the OEEPE dataset

As anticipated, the method has also been applied to the OEEPE "Integrated Sensor Orientation" test data, where the image coordinates have been measured by the pilot centre at IPI, University Hannover while the IMU/GPS data processing was performed by the two companies taking part into the test.

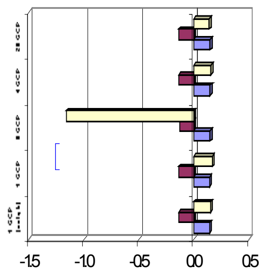
Also with this data set we estimated the calibration parameters with 5 different gcp configurations, the same used in the simulations. Besides, we computed the calibration, separately using the 1:5000, 1:10.000 and the joint block.



1:5000



1:10000



Joint block

Table 2 – Estimates for a_x, a_y , a_z with different ground control

Table 2 shows the graphs for the estimates *a* vector components. It is apparent that while a_x and a_y are pretty stable, irrespective of the ground control, a_z does not and cannot be estimated without control points.

The misalignment angles are also very stable and accurate in all cases; the best accuracy is obtained, as it could be anticipated, in the scale 1:10000.

As an example, Table 3 shows the estimates of the calibration parameters for the adjustments with 4 gcp. As it is apparent, the misalignment angles agree to the 1 mgon level or better, while there are significant differences, with respect to the theoretical accuracy, for the components of the vector *a*.

This has little impact on the ground, though. In order to evaluate the accuracy of the calibration on the ground, we computed the RMS of the discrepancies at check points (when calibrating with 4 gcp).

They range from 5 cm to 6 cm in x,y and height for the three blocks; the worst result (6 cm in all coordinates) is obtained for the joint block: which is slightly better than the results obtained with the two step calibration method on the same points (Forlani, Pinto 2002).

Block		[m]		[grd]
1:5000	*ax*	0.11	om	200.1319
	ay	-0.11	fi	-0.0578
	az	0.11	ak	-199.8016
1:10000	*ax*	0.18	om	200.1314
	ay	-0.17	fi	-0.0591
	az	0.19	ak	-199.8032
Joint	*ax*	0.15	om	200.1316
	ay	-0.14	fi	-0.0588
	az	0.16	ak	-199.8026

Table 3 – Calibration parameters estimates with 4 gcp

4. CONCLUSIONS AND PERSPECTIVES

Compared to the previously proposed two steps procedure, the new single step calibration procedure presented above, looks, in the opinion of the authors, a simpler and more economic way to perform calibration. The RMS on the check points on real data, in the order of a few cm, show that the procedure is effective. The results from the simulations point out that the need remain for some ground control and that a simple block, perhaps even just a short strip flown back and forth, may suffice to the purpose, especially since the misalignment angles can be determined with good accuracy.

We consider these, though, just as preliminary results, more relevant for an additional verification of the functional model than as a practical conclusion. Indeed, including just random errors may not be realistic enough: we want to continue the simulations also by adding systematic errors to INS/GPS data and investigate to what extent photogrammetry (i.e. the block geometry) need to be strong in order to highlight them.

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