COMPARATIVE ANALYSIS OF DIFFERENT APPROACHES FOR THE INCORPORATION OF POSITION AND ORIENTATION INFORMATION IN INTEGRATED SENSOR ORIENTATION PROCEDURES

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ABSTRACT:

The utilization of integrated GPS/INS for direct sensor orientation has received increasing attention by the airborne survey and remote sensing community in the past few years. The availability of high accuracy position and orientation information, obtained from the GPS/INS integration, allows the direct determination of the image orientation parameters without the need for ground control points. In direct sensor orientation, besides individual sensor calibration (camera, GPS and INS), the system mounting parameters calibration is also needed. More specifically, the geometric relationship between the sensors (mounting parameters) must be determined as well. Photogrammetric reconstruction using GPS/INS information can be performed using the following procedures: (i) Direct georeferencing and (ii) Integrated Sensor Orientation (ISO). In the direct georeferencing procedure, GPS/INS derived position and orientation information are used in a simple intersection procedure. In integrated sensor orientation, on the other hand, GPS/INS positions and attitudes are incorporated in a bundle adjustment procedure. The incorporation of position and orientation information in ISO procedures can be carried out using two different approaches. The first approach consists of extending existing bundle adjustment procedures with constraints (i.e., using traditional collinearity equations with additional constraints). In the second approach, GPS/INS information is directly incorporated in the collinearity equations. More specifically, the collinearity equations are modified to allow for direct incorporation of such information. In this paper, a comparative analysis between these different approaches, as it relates to the estimation of mounting parameters and photogrammetric reconstruction, is presented. The comparative analysis will be evaluated using simulated and real datasets.

1. INTRODUCTION

Photogrammetry focuses on accurate derivation of spatial and descriptive information from imagery to satisfy the needs of several applications such as mapping, DEM generation, orthophoto generation, construction planning, 3D visualization, and change detection. Technological advances in the last three decades have changed considerably the airborne survey mapping practices. Traditionally, image-based topographic mapping has been performed using a single sensor, more specifically a large format analogue camera. The concept of sensor orientation, crucial for the object-space reconstruction from overlapping images, has relied on the availability of ground control points (GCPs) in the survey area. The development of bundle adjustment (or aerotriangulation) procedure reduced considerably the amount of GCPs to orient each image. Although reduced, the required amount is still significant in a conventional bundle adjustment. With the advent of GPS, the position of the exposure station is obtained directly while its orientation can be determined in a GPS-assisted aerotriangulation (AT) procedure. Therefore, the need for GCPs could be completely eliminated. Nonetheless, the complete elimination of GCPs in a GPS-assisted AT would still require block structure and a substantial number of tie points. Direct sensor orientation, without the need for GCPs and aerotriangulation, became possible with the introduction of GPS/INS-assisted photogrammetric systems. The integration of GPS and inertial systems has been stimulated by their complementary error behaviour. GPS offer high absolute accuracy position and velocity information, but its relative accuracy (i.e., short term noise) is dependent on the data quality and observation approach. Inertial systems, on the other hand, provide very high relative accuracy for position, velocity and attitude information, but the absolute accuracy decreases with time (Schwarz, 1995).

Accurate 3D reconstruction requires careful calibration of the photogrammetric system. Object-space reconstruction obtained through a traditional indirect georeferencing approach is illustrated in Figure 1 and Equation 1.

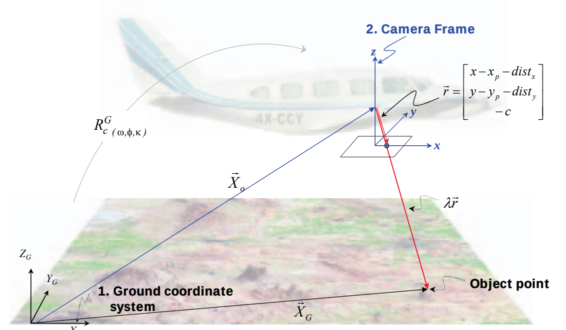

Figure 1. Coordinate systems and involved quantities in the point positioning equation based on indirect georeferencing procedure.

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$$\vec{X}_G = \vec{X}_o + \lambda\, R^G_{c\,(\omega,\phi,\kappa)}\, \vec{v} = \vec{X}_o + \lambda\, R^G_{c\,(\omega,\phi,\kappa)} \begin{bmatrix} x - x_p - dist_x \\ y - y_p - dist_y \\ -c \end{bmatrix} \qquad (1)$$

where:

$\vec{X}_G$: ground coordinates of an object point;

$\vec{X}_o$: vector from the origin of the ground coordinate system to the camera perspective centre;

$R^G_{c\,(\omega,\phi,\kappa)}$: represents the rotation matrix relating the ground and image coordinate systems;

$\vec{X}_o$ and $R^G_{c\,(\omega,\phi,\kappa)}$: are defined by the exterior orientation parameters (EOP) of the exposure station $(X_o, Y_o, Z_o, \omega, \phi, \kappa)$, which are determined in the bundle adjustment procedure together with the ground coordinates of the tie points.

λ: scale factor that can be determined from overlapping imagery in the bundle adjustment procedure;

x, y: image coordinates;

$x_p, y_p, c, dist_x, dist_y$: principal point coordinates, principal distance and the distortions in the *x* and *y* coordinates.

As can be observed in Equation 1, in a traditional indirect georeferencing procedure, the photogrammetric system calibration involves only the camera calibration procedure. Experiments have shown that, even for erroneous camera calibration parameters, accurate object space reconstruction might be still obtained (Cramer et. al., 2000; Habib and Shenk, 2001). Due to correlations among the IOP and EOP, uncorrected systematic effects are absorbed by the estimated orientation parameters so that the bundles are optimally fitted to the given control points and an accurate object space reconstruction is still guaranteed. When dealing with a multi-sensor photogrammetric system, which is the case of direct sensor orientation, besides the camera calibration, the system mounting parameters calibration is also needed. Moreover, camera calibration plays a more important role in the direct than in the indirect sensor orientation. This is mainly due to the fact that direct sensor orientation is an extrapolation procedure and errors are directly propagated to the object space (Habib and Shenk, 2001). For instance, errors in the calibration parameters cannot be compensated by the exterior orientation parameters. Therefore, reliable camera and system mounting parameters calibration are essential to obtain accurate object space reconstruction. In the camera calibration procedure, the internal characteristics of a camera, which are defined by its Interior Orientation Parameters (IOP), are determined. In the system mounting parameters calibration, on the other hand, the lever-arm offset and boresight angles relating the photogrammetric system components, such as the camera, the GPS and INS systems are determined.

There exist several factors that might limit the performance of the direct sensor orientation. For instance, the quality of photogrammetric system calibration (i.e., camera and mounting parameters calibration), the GPS data quality (which is mainly dependent on the distance from the base station, satellite geometry, and continuity of the GPS lock), the type of the IMU system used, and the quality of the GPS/INS integration process. Moreover, the stability of the parameters determined in the calibration procedure is also an issue. Over the last few years extensive investigations on the performance of GPS/INS-assisted photogrammetric systems have been carried out (e.g., Toth, 1998; Toth, 1999; Jacobsen, 2000; Cramer et. al., 2000; Wegmann, 2002; Baron et. al., 2003). The results from the performed investigations, especially the results from the OEEPE test on "Integrated Sensor Orientation" (Heipke et. al., 2002), have demonstrated that the accuracy of direct sensor orientation is mainly limited by the quality of the photogrammetric system calibration, which is, as already mentioned, composed by the camera and the system mounting parameters calibration.

Direct sensor orientation can be performed in two different ways: (i) Integrated sensor orientation (ISO) and (ii) Direct georeferencing (Jacobsen, 2004). In the integrated sensor orientation, the GPS/INS derived position and attitude information are used as prior information in the bundle adjustment procedure together with the image coordinates of tie points. This simultaneous adjustment of a number of tie points within a bundle adjustment procedure allows further improvement in the exterior orientation parameters. In the direct georeferencing, on the other hand, the object space coordinates of the image points are obtained from a simple intersection procedure using the GPS/INS-derived EOP. The main limiting factor of the direct sensor orientation procedure is the stability of the system mounting parameters and the camera IOP. Any error in such parameters will propagate directly to the ground coordinates. In contrast to the traditional bundle adjustment, in the ISO procedure errors in the IOP are not absorbed by the EOP. It should be noted that, in the presence of appropriate flight and control configuration, which allows the recovery of the camera IOP and the system mounting parameters, the ISO provide the most reliable solution for high accuracy applications since such system calibration parameters can be refined (Cramer et. al., 1999). Also, different from the traditional bundle adjustment procedure (without GPS/INS information) and a GPS-assisted AT, in the integrated sensor orientation fewer tie points are required. Khoshelham et. al. (2007) has investigated the influence of the number and distribution of tie points on integrated sensor orientation. In that work, it was demonstrated that one tie point per model would be sufficient. Several authors (e.g., Jacobsen, 2000; Heipke et. al., 2002; Wegman, 2002; Khoshelham et. al., 2007) have noticed large remaining y-parallaxes in the photogrammetric model, which makes the use of direct georeferencing for stereo plotting not always possible. The use of integrated sensor orientation, regardless of performing system calibration or using ground control, eliminates these remaining parallaxes. In Khoshelham et. al. (2007), it was demonstrated that although the object space accuracy is not significantly improved (when compared with the direct georeferencing), regardless of the number and distribution the tie points in the ISO procedure, significant reduction of the y-parallax in the photogrammetric model is obtained. Also, this reduction is observed even when having only one tie point per model. The general recommendation from the OEEPE test on "Integrated Sensor Orientation" (Heipke et. al., 2002) was that, due to some open questions and uncertainties, the direct georeferencing should be applied only in low accuracy applications, like in orthophoto production. In higher quality requirement applications, the integrated sensor orientation is recommended.

The incorporation of the GPS/INS derived position and attitude information in an integrated sensor orientation procedure can be done directly in the collinearity equations, or they can be done by extending existing bundle adjustment procedures with additional constraints. This paper starts by outlining these two different approaches, followed by a discussion of the system mounting parameters calibration. A comparative analysis through experimental results between the different approaches for the incorporation of GPS/INS derived information, as it relates to the estimation of mounting parameters and photogrammetric reconstruction, is presented. The comparative analysis will be evaluated using simulated and real datasets. Finally, the paper presents some conclusions and recommendations for future work.

2. METHODS FOR THE INCORPORATION OF POSITION AND ORIENTATION INFORMATION IN ISO PROCEDURES

There exist two approaches for incorporating the GPS/INS derived position and orientation information in an ISO procedure. The first method, denoted in this paper as "Method 1", extends existing bundle adjustment procedures with additional constraints. More specifically, the traditional mathematical model shown in Equation 1 is extended with the constraints in Equations 2 and 3. This method has been widely used by the research community (e.g., Cramer and Stallmann, 2002; Smith et. al., 2006; Wegmann, 2002, Honkavaara et. al., 2003; Honkavaara, 2004; Yuan, 2008).

$$\vec{X}_{GPS/INS} = \vec{X}_o + R^G_{c\,(\omega,\phi,\kappa)}\,\vec{P}_G \tag{2}$$

$$R^G_{b\,(yaw,\ pitch,\ roll)} = R^G_{c\,(\omega,\phi,\kappa)}\,{R^b_{c\,(\Delta\omega,\Delta\phi,\Delta\kappa)}}^{-1} \tag{3}$$

Where:

- $\vec{X}_{GPS/INS}$: is the vector from the origin of the ground coordinate system to the origin of the IMU coordinate system. This vector is derived from the GPS/INS integration procedure while considering the lever-arm offset between the phase centre of the GPS antenna and the IMU body frame;
- $\vec{P}_G$ is the offset between the camera perspective centre and IMU coordinate systems (lever-arm offset vector), defined relative to the camera coordinate system);
- $R^G_{b\,(yaw,\ pitch,\ roll)}$: rotation matrix relating the ground and IMU coordinate systems (derived through the GPS/INS integration process);
- $R^b_{c\,(\Delta\omega,\Delta\phi,\Delta\kappa)}$: rotation matrix relating the IMU and camera frame coordinate systems (defined by the boresight angles).

The second method, denoted in this paper as "Method 2", consists of directly incorporating the GPS/INS derived position and attitude information and the system mounting parameters in the collinearity equations. This method has not been much investigated by the research community yet, only by few authors (e.g., Pinto and Forlani, 2002). The concept and mathematical model used in such method is illustrated in Figure 2 and Equation 4, where it is shown that the position of the object point, $\vec{X}_G$, is derived through the summation of three vectors ($\vec{X}_{GPS/INS}$, $\vec{P}_G$, and $\vec{r}$) after applying the appropriate rotations: $R^G_{b\,(yaw,\ pitch,\ roll)}$ and $R^b_{c\,(\Delta\omega,\Delta\phi,\Delta\kappa)}$, and scale factor λ.

$$\vec{X}_G = \vec{X}_{GPS/INS} + R^G_{b\,(yaw,\ pitch,\ roll)}\,R^b_{c\,(\Delta\omega,\ \Delta\phi,\ \Delta\kappa)}\left(\lambda\begin{bmatrix} x-x_p-dist_x \\ y-y_p-dist_y \\ -c \end{bmatrix} - \vec{P}_G\right) \tag{4}$$

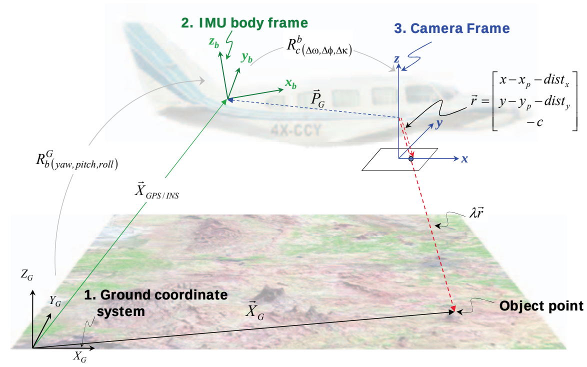

Figure 2. Coordinate systems and involved quantities in the point positioning using GPS/INS-assisted photogrammetric system.

Although method 1 has been extensively investigated in previous work, the performance of method 2 is still an open research task. Also, a comparative analysis between these two different approaches has not been presented yet. In the experimental results section, simulated and real datasets are used to carry out such analysis. The performance of the methods will be evaluated through the quality of the estimated mounting parameters and photogrammetric reconstruction.

3. SYSTEM MOUNTING PARAMETERS CALIBRATION

In the system mounting parameters calibration, the geometric relationship between the sensors is estimated (i.e., the lever-arm offset and the boresight angles). Two main approaches can be distinguished in the literature for the estimation of the system mounting parameters: two-step or single-step procedures. In the two-step procedure, the system mounting parameters are estimated by comparing the GPS/INS position and orientation results with the exterior orientation parameters determined from an independent aerotriangulation (bundle adjustment) solution. The estimated EOP from the bundle adjustment procedure (i.e., ω, ϕ, κ, and X_o, Y_o, Z_o), obtained using the model shown in Equation 1, and the GPS/INS derived positions and orientations (w.r.t. the IMU body frame) are usually utilized in Equations 3 and 4 to come up with an estimate for the lever-arm offset ($\vec{P}_G$) and the boresight angles ($\Delta\omega, \Delta\phi, \Delta\kappa$), respectively. Each image will give an estimate for the boresight angles and the lever-arm offset. Due to the lower accuracy of the estimated EOP, the images located at the extremities of the flight lines are usually disregarded from the analysis (e.g., Skaloud, 1999; Jacobsen, 1999). In Skaloud (1999), the mounting parameters are estimated for each image separately and then the results undergo an average weighting procedure. In Grejner-Brzezinska (2001), the resulting linear system from Equations 3 and 4 are solved using a least-squares adjustment procedure to derive an estimate of the system mounting parameters. Due to its simplicity, i.e., any bundle adjustment software can provide EOP values for the system calibration; the two-step procedure has been extensively used by several authors (Toth, 1998; Toth, 1999; Cramer, 1999; Jacobsen, 1999; Skaloud, 1999; Cramer and Stallmann, 2001; Yastikli and Jacobsen, 2005; Casella et. al., 2006). However, the two-step approach presents several drawbacks. One of the disadvantages of this method is that correlations among the EOP are ignored and some errors in the IOP are absorbed/compensated by the EOP (Cramer and Stallmann, 2002). In Jacobsen (1999) high correlation among the EOP was observed due to insufficient flight configuration. In (Cramer et. al., 2000) correlations among the EOP and IOP resulted in systematic vertical offsets in the derived photogrammetric product. Moreover, the two-step procedure demands a calibration site with ground control points and a block with very strong geometry to perform the AT (aerial triangulation) procedure.

In the single-step procedure, the system mounting parameters are estimated in the bundle adjustment through an ISO procedure. Therefore, the system mounting parameters can be estimated using either one of the two ISO procedures described in the previous section. Besides less strict flight and control requirements, the single-step is considered a more robust method to handle the dependencies among the EOP and IOP parameters, since the IOP can be refined together with the mounting parameters, if needed. The importance of the estimation of the camera calibration parameters together with the system mounting parameters have been highlighted by several authors (Jacobsen, 2001; Jacobsen, 2003; Cramer and Stallmann, 2002; Wegmann, 2002; Honkavaara et. al., 2003; Honkavaara, 2004). In Honkavaara (2003), several block control configurations were empirically investigated using simulated and real datasets. In Habib et. al. (2010), the concept of a rigorous analysis for investigating the optimum flight and control requirement for estimation of the system mounting parameters was introduced. The devised optimum flight configuration in that work for reliable estimation of the system mounting parameters consists of two side lap cases and one vertical control point. The first side lap case consists of two strips captured in opposite directions with 100% side lap; while the second side lap case consists of two flight lines, which are flown in the same direction with the least side lap possible. Figure 3 illustrates such configuration.

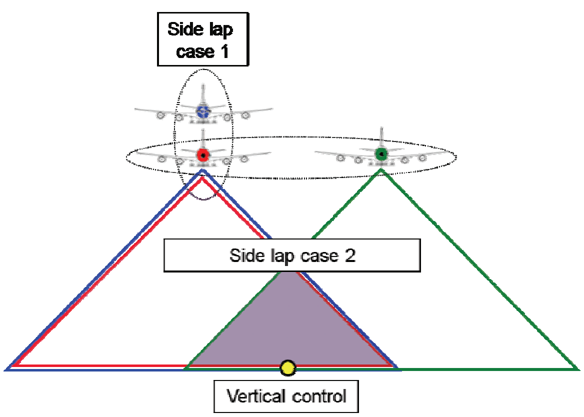

Figure 3. Optimum flight and control configuration for the estimation of the photogrammetric system mounting parameters.

4. EXPERIMENTAL RESULTS

In this section, experimental results using simulated and real datasets are presented to test the validity of the approaches for the incorporation of GPS/INS information in ISO procedures. A comparative analysis is performed in terms of the quality of the estimated system mounting parameters and the quality of the photogrammetric object space reconstruction.

The synthetic data was simulated using the same configuration of the real dataset, which is illustrated in Figure 4. The real dataset utilized in this research work was acquired by a MFDC Rollei P-65. This camera has an array dimension of 8984x6732 pixels (53.904x40.392 mm → pixel size = 6µm) and a principal distance of 60 mm. As illustrated in Figure 4, the flight configuration consists of a total of six flight lines acquired in two flight dates, where four flight lines were flown in the E-W direction and two flight lines in the N-S direction, (in opposite directions) with 60% overlap (Figure 4). The flight lines flown in the E-W direction (L1, L2, L3, and L4) were acquired from a flying height of ~550 m (above MSL) and 50% side lap. The flight lines flown in the N-S direction (L5 and L6) were obtained from a flying height of ~1200 m (above MSL) and 100% side lap. A total of 32 images were acquired. It should be noted that the available dataset comply with the optimum configuration discussed in section 3. Also, the GPS/INS derived position and attitude accuracy is ±10 cm and ±10 sec, respectively. In the surveyed area, thirty-seven control points were established (accuracy ±10cm). These control points were used for check point analysis. The camera calibration parameters were determined through an indoor camera calibration technique using the Brown-Conrady distortion model.

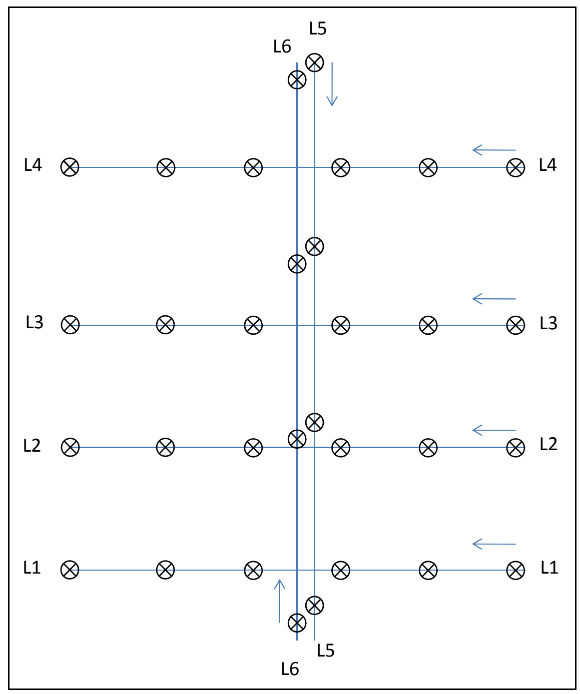

Figure 4. Configuration of the simulated and real datasets.

In the simulated data, the mounting parameters were simulated as 0.50, 0.50, and 1.00m for the lever-arm offset ΔX, ΔY, and, ΔZ, respectively; and 0.50º, 0.50º, and 181º for the boresight angles Δω, Δφ, and Δκ, respectively. The GPS/INS derived position and attitude accuracy was simulated with the same accuracy of the real data, i.e., ±10 cm and ±10 sec, respectively. The accuracy of the simulated vertical control point is ± 10cm. The estimated a-posteriori variance factor and the system mounting parameters using the simulated data and the two available approaches for the incorporation of the navigation information, are reported in Table 1. The average correlation among the estimated parameters in the bundle adjustment procedure was 0.12 and 0.08 for the methods 1 and 2, respectively. Correlations of 0.95 among the Z_o of some of the images were found in the method 1. The reported values in Table 1 reveal that both approaches provide compatible mounting parameters results, which demonstrate the equivalency of these two methods. The RMSE analysis shown in Table 2, which is computed by comparing the reconstructed object space using the estimated mounting parameters with the ground truth, confirms such finding.

Table 1. Estimated a-posteriori variance factor and system mounting parameters using simulated data, one vertical control point, and the two approaches for the incorporation of GPS/INS information in the ISO procedure.

	Method 1: Collinearity equations with added constraints	Method 2: Direct incorporation in the collinearity equations
$\hat{\sigma}_o^2$ (mm)^2	$(0.0030)^2$	$(0.0030)^2$
ΔX (m±m)	0.5332±0.03	0.5330±0.03
ΔY (m±m)	0.5065±0.03	0.5064±0.03
ΔZ (m±m)	1.1210±0.08	1.1172±0.09
Δω(deg±sec)	0.4994±11.3	0.4993±11.3
Δφ(deg±sec)	0.4976±12.4	0.4976±12.4
Δκ(deg±sec)	181.0036±10.5	181.0036±10.4

Table 2. RMSE analysis (using ninety five check points) for the two approaches for incorporation of GPS/INS information in the ISO procedure using simulated data and one vertical control point.

	Method 1: Collinearity equations with added constraints	Method 2: Direct incorporation in the collinearity equations
RMS_X (m)	0.033	0.033
RMS_Y (m)	0.050	0.050
RMS_Z (m)	0.165	0.163

In the performed experiments using real data, it could be verified that the given a-priori standard deviation of the available attitude (±10sec) was too optimistic in the adjustment procedure. Therefore, ±100sec was employed instead. As for the simulated data, the average correlation among the estimated parameters in the bundle adjustment procedure was slightly higher for method 1 (0.13 for method 1 and 0.10 for method 2, respectively). Correlations of 0.95 among the Z_o and among the ΔZ and Z_o of some of the images were found in the method 1. Table 3 reports the estimated a-posteriori variance factor and the system mounting parameters using the real dataset. Here again, quite compatible results were obtained from the two utilized approaches. Table 4 presents the RMSE analysis, which also demonstrates the equivalency of the tested approaches.

Table 3. Estimated a-posteriori variance factor and system mounting parameters using real data, one vertical control point, and the two approaches for the incorporation of GPS/INS information in the ISO procedure.

	Method 1: Collinearity equations with added constraints	Method 2: Direct incorporation in the collinearity equations
$\hat{\sigma}_o^2$ (mm)^2	$(0.0025)^2$	$(0.0025)^2$
ΔX (m±m)	-0.084±0.05	-0.084±0.05
ΔY (m±m)	-0.124±0.05	-0.126±0.05
ΔZ (m±m)	1.119±0.11	0.989±0.11
Δω(deg±sec)	-0.1254±18.6	-0.1253±19.2
Δφ(deg±sec)	0.8367±18.5	0.8368±18.8
Δκ(deg±sec)	179.5475±22.3	179.5476±22.6

Table 4. RMSE analysis for the two approaches for incorporation of GPS/INS information in the ISO procedure using real data, one vertical control point, and thirty six check points.

	Method 1: Collinearity equations with added constraints	Method 2: Direct incorporation in the collinearity equations
RMS_X (m)	0.09	0.09
RMS_Y (m)	0.09	0.10
RMS_Z (m)	0.12	0.14

5. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

In this paper, a comparative analysis between the two available approaches for the incorporation of GPS/INS position and orientation in integrated sensor orientation procedures was introduced. The paper started by outlining these two different approaches, followed by a discussion of the system mounting parameters calibration. Then, the comparative analysis through experimental results from the different approaches, as it relates to the estimation of mounting parameters and photogrammetric reconstruction, was presented. Even though both approaches provided quite compatible results, less correlation among the parameters were observed in method 2. Although satisfactory results were obtained with the utilized simulated and real datasets, the correlation issue observed in method 1 might be a concern when the utilized data do not comply with the optimum configuration. Also, method 2 is the most appropriate solution when dealing with multi-camera systems. Future work will focus on devising an optimum flight configuration for the estimation of the camera IOP, which are susceptible to changes under operational conditions, together with the system mounting parameters during the in-flight system calibration.

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