Direct Georeferencing in Aerial Photogrammetric Mapping

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Preamble

Aerial photogrammetric mapping is a well-established industry. Its methods have been evolving progressively but not explosively over many decades. Entrenched, reliable procedures have been developed to overcome pitfalls along the processing chain, allowing the delivery of high quality mapping products. Understandably this has resulted in the entrenchment of most people thinking as they design, capture and adjust blocks of photographs. With Integrated GPS/INS technology, however, one can step outside of this "blocked-block" philosophy since the parameters of a camera's Exterior Orientation (EO) are computed directly. In many cases this means the photogrammetric procedures that were once followed verbatim can now be by-passed completely. The application of navigation technology to directly georeference imagery data is booming and the industry tends to furnish systems that require minimal input from the user. As these "measuring boxes" turn into black boxes and the length of the processing chain extends, the users may quickly find themselves lost in the complexity when something does not stand up to their expectations. Hence, understanding the technology fundamentals as well as its limits may save time and effort and may avoid surprises. The goal of this column is to facilitate the transition process when starting to apply direct georeferencing by GPS/INS to aerial film-based imagery.

Simple Concept

Recall the algebraic relation that transforms the image observed co-ordinates r^c_g to the mapping co-ordinates r^m_i (as presented in the first-column in the October issue of PE&RS, pp1105-11):

$$r^m_i = r^m_{INS}(t) + R^m_b(t)\,a^b - s_g R^m_b(t) R^b_c r^c_g$$

where r^c_g comes from image measurements, s_g is solved for the stereoscopic processing, a^b and R^b_c are derived from the system calibration and the translation r^m_{INS} vector and the rotation matrix R^m_b are delivered by the GPS/INS on-board measurements. What more does the user need to know?

In theory nothing, but when it comes down to the error propagation and thus the overall performance of the system, users should definitely educate themselves about the type of instrument used, how the inertial system is aligned and how its performance is coupled with operational maneuvers and the gravity field. Users also should be aware of the influence of the sensor placement on the accuracy of EO parameters. It also may be useful to realize that the GPS/INS output may not be directly linked to the desired mapping frame as suggested by the above equation. Finally, it is important to understand that in many cases the overall limiting factor on system accuracy is not the GPS/INS but rather the calibration accuracy of a^b, R^b_c and the parameters of camera interior orientation. Before looking into some of these points in more detail let me say a few words about the GPS/INS technology itself.

Enabling Technology

GPS found its way into airborne mapping right from its deployment. It is taking a little bit longer for the inertial technology to do so, given that it has already been evolving for over 40 years (a brief history of which was presented in an earlier column). The most promising technologies enabling direct measurement of camera orientation came with the concepts of ring laser gyros (RLG) and fiber optic gyros (FOG), as well as the later evolution of a strapdown dry tuned gyros (DTG). The orientation accuracy potential of these technologies is summarized in Table 1. Most of the numbers indicated in the table have been confirmed experimentally during numerous tests conducted in the last three to five years.

Although the RLG is a conceptually older technology, its accuracy remains unbeatable thanks to its inherently and extremely good bias and scale factor stability. At very low rotation rates little complication arises that needs to be circumvented by other means. The gyro is usually sensitive to vibrations and therefore the instrument cluster needs to be mounted in a mechanical frame designed to mitigate them. Depending on the adopted mount for the camera, this type of vibration damping may affect the instantaneous attitude observation with respect to the imaging device. However, its low 0.002 to 0.01 deg/hour drift rates are advantageous and the user should expect better overall performance with

continued on page 209

Table 1: Inertial attitude determination performance with GPS aiding

	Navigation grade (usually RLG)		Tactical grade (usually FOG, DTG)	
Time	ω - φ (deg)	κ (deg)	ω - φ (deg)	κ (deg)
1 sec	0.0008 - 0.0014	0.0008 - 0.002	0.001 - 0.02	0.001 - 0.05
1-3 min	0.0014 - 0.003	0.004 - 0.005	0.005 - 0.04	0.008 - 0.1
Absolute-longer time	Same as over 1-3 min but maneuver dependent			

continued from page 207

respect to other strapdown technologies in the airborne environment especially when long flight lines are flown.

The FOG and DTG seem to be the most popular technologies currently used in airborne mapping thanks to their better cost-performance ratio. The IMU's built around these gyros usually belong to tactical-grade class, although at least one navigation-grade FOG product is now available on the market. Although less stable than RLG, their strengths for direct georeferencing come in low sensitiveness to vibrations (FOG), better instantaneous pointing accuracy (DTG), long life span and small size and weight. The dimensional aspects allow the IMU to be mounted directly on most existing aerial cameras, which helps in preserving the needed assumption of a rigidly mounted sensor block. Small IMU size also clears the way to new specialized applications like the hand-held, anywhere pointing systems operated from the helicopter.

What is (not) Solved by the Integration?

GPS and inertial systems are ideal synergistic partners, as their error dynamics are different and uncorrelated. The following are the main and well-known advantages:

- The integration with GPS solves the problem of "calibrating" the instrument errors (i.e. residual gyro and accelerometer biases, scale factors etc.) in a strapdown system.
- Similarly, the GPS provides a means of "in-flight alignment," removing the need for the aircraft to be held stationary due to "north-seeking" process prior to flight.
- The inertial system provides a means of smoothing the noisy velocity outputs from the GPS, and a continuous high-bandwidth measurement of position and velocity.

There is no such thing as a perfect instrument and as strong as it is, the integration cannot completely eliminate all of the errors. In other words, the data integration handled by a Kalman filter/smoother cancels only the non-overlapping part of the sensor's error budget. Thus the 'width' of the error cancellation may overlap only partially with the motion of interest as a function of instrument type and precision and the dynamic of an aircraft. For that reason, de-noising inertial data prior to mechanization has proven in some cases to be indispensable for attitude determination and effective procedures have been developed for that purpose. Another significant portion of the residual orientation errors is most likely to be affected by the quality of the in-flight alignment. Usually, the data integrating filter/smoother keeps on refining the inertial platform all along the flight. The strength of this process is in its ability to decorrelate the misalignment errors from other error sources when sufficient dynamic is encountered. Its weakness lays in the susceptibility to be influenced by the changes of the accelerometer errors and the anomalous gravity field. Both act as a wrongly sensed acceleration that gets "eliminated" by readjusting the previously aligned platform. Dropping the coupling with the accelerometers is possible once the platform is aligned and high accuracy gyros are adopted (i.e. 0.002-0.01 deg/h). As the high frequency part of the anomalous gravity field is likely to remain unmodeled, this concept may be appealing for certain types of applications when operating over a "rough, unknown" gravity field or when flying long survey lines of constant velocity.

The positioning performance is obviously mainly governed by the accuracy of differential GPS and the ability to resolve correctly the ambiguities. Hence, the absolute positioning accuracy is in a range of 0.05-0.5m, depending on the baseline-length and differential atmospheric modeling although the relative short-term accuracy is much better.

Validity of the Concept

As new as it is, direct georeferencing in aerial photogrammetry already has its own history. Great ideas usually simmer simultaneously in different places and therefore it is hard to single out one individual who initiated the concept. Nevertheless, it can be safely claimed that the concept was studied for a long time by the academic community before the first commercial product arrived on the market. Therefore it may come as a surprise to somebody that a group at the University of Calgary successfully applied this concept almost ten years ago. It may be worth mentioning these already historical results, especially in light of the many tests devoted to the proof of the concept ever since.

At that time, an RLG-based IMU and geodetic type GPS receivers were flown with an LMK camera in three, about 10km long and slightly overlapping lines, at a photo scale of 1:10,000. The adjusted block of images served as the comparison of the GPS/INS attitude performance giving an RMS agreement in the range of 13-35 sec (0.004-0.009 deg). It is interesting to note that most results published since then fall more or less into this range, although being carried out over longer periods, using different equipment etc. A short-term accuracy of 3-10 sec (0.0008-0.0025deg) has later been confirmed for the same type of instrument with special filtering procedures in place. It should be mentioned, that although no special mount for the IMU and the camera was implemented, other factors such as calibration of camera interior orientation and the procedure of $^{g}_{F}$ and R^{c}_{I} determination were carefully looked at. In many cases, these parameters are often estimated without sufficient accuracy, and as a result they hamper the potential of a GPS/INS system for direct georeferencing.

The Position and Attitude Transfer

It is true that aerial photogrammetric mapping cannot be liberated completely from the concept of aero-triangulation (AT) when applying GPS/INS. Leaving aside the reliability issues, the need of precise R^{c}_{I} (boresight) determination calls for at least a small block adjustment with few but some ground control points. A practical experience showed that a 5x5 regular block of strong geometry is sufficient for that purpose. What is sometimes wrongly perceived is the hope that all the calibration parameters are found when their variance decreases under a certain level as indicated in the bundle adjustment. There is a strong correlation between these parameters and although operational aspects (i.e. flying from different directions, etc.) may result in their partial decorrelation, sorting out as much as

continued on page 210

continued from page 209

possible by independent means helps more. For instance, conducting a little close range survey and determining $^{g}_{F}$ and the IMU-GPS antenna displacement terrestrially will always outperform its indirect determination within the bundle adjustment. When ambiguities are fixed and with $^{g}_{F}$ determined the GPS/INS observation of the camera perspective should enter the adjustment with heavy weights. With high accuracy photo measurements and favorable geometry in place this should in turn provide sufficiently accurate B^{c} (i.e. 3-5 sec) even when interior orientation parameters are calibrated at the same time. Calibration procedures are now supplied either with certain bundle adjustment software or come as a part of the navigation system package. As powerful as they can be these products do not span the whole design/processing chain all the way and therefore cannot guard completely against mistreatment or misinterpretation.

The issues concerning stability of the mount in the carrier and the effects of vibrations on the instruments are not trivial but should worry the developers more than the user. The same is true for the correctness of time synchronization between the inertial, GPS and the camera that is very exigent when dealing with attitude data. Although the technology should now be mature enough in this respect, a simple check for constant delays may be worth implementing, for instance as a part of the boresight calibration.

Perspectives

In a relatively short time the GPS/INS technology made its way into the spectrum of airborne remote sensing applications. Indispensable in SAR and laser scanning systems, by design the new digital (line and frame) cameras have GPS/INS as the primary orientation system. The technology acceptance is taking longer in film-based aerial photogrammetry, mainly due to the progress towards automated AT (AAT). The AAT concept has been, idling for a long time as "assisted" AAT and the inclusion of GPS/INS data within a large AAT adjustment is sometimes perceived as a possibility to drop the need for operator backing. Although such an approach may be great in terms of reliability it increases the computational burden and does not give the flexibility needed when working with individual stereoscopic modules. On the other hand, as advanced as it is, the GPS/INS data processing still has a lot of room for improvements, mainly in the reliability and confidence issues. Filling these gaps may finally "unblock" the traditional concept of this field.

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