TOWARDS A CLOSER COMBINATION OF DIRECT AND INDIRECT SENSOR ORIENTATION OF FRAME CAMERAS

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ABSTRACT:

Direct georeferencing is defined as direct measurement of exterior orientation parameters, using positioning and orientation sensors, such as the Global Positioning System (GPS) and inertial navigation system (INS). Imaging sensors, most frequently supported by direct georeferencing, are digital cameras, lidar systems, multi-spectral scanners, or synthetic aperture radar (SAR). While for scanning sensors the use of direct georeferencing is compulsory, frame digital cameras can also directly benefit from this technique of sensor orientation. With direct sensor orientation, the requirement for ground control points (GCP), tie point matching and aerial triangulation (AT) is significantly reduced. The most expensive part of these three requirements is the need of GCP and under exclusion of this part the other two parts are always available for images from digital frame cameras. This paper is focused on the integration of this existing additional information into the Kalman filter used for direct georeferencing with GPS and INS. The aim is to use the relative orientation information of images extracted with the aid of tie points as an additional update to support the drifting gyros of the inertial measurement unit (IMU) directly like GPS does for the accelerometers.

1. INTRODUCTION

The determination of the exterior orientation parameters is a fundamental condition for the use of any kind of imagery in a photogrammetric way. After this step, the information in the so called georeferenced image can be obtained in the chosen coordinate system. The georeferencing can be done in different ways also depending on the nature of the sensor.

Traditionally, georeferencing is done indirectly under joint use of known ground control points (GCP) and their corresponding image coordinates. For multiple images, this approach is named aerial triangulation (AT) or automatic aerial triangulation (AAT), if tie points are provided using digital image matching methods. Neighboured images are connected via tie points using the well known photogrammetric collinearity equations. The exterior orientation parameters for each image of an image block can be estimated within a least-square adjustment known as bundle block adjustment. Schenk (1997) shows an eminent compilation of aerial triangulation and the grade of automation with a summary of the workflow from preparation of the images over point transfer and mensuration, and finally the block adjustment. This approach is enhanced by differential kinematic GPS positions for determining the camera exposure centres.

A newer approach to determine the exterior orientation parameters is the direct georeferencing (also known as direct sensor orientation (DSO)). In this case, the parameters for each image are determined directly by a combination of satellite (at present normally GPS) and inertial navigation system (INS) measurements. For e.g. line and laser scanner systems direct georeferencing is indispensable because of the needed exterior orientation information for each single measurement. A detailed view of inertial navigation systems and their integration with GPS is shown e.g. in Jekeli (2001).

Already, in Colomina (1999), the author raises the question: "GPS, INS and aerial triangulation: What is the best way for the operational determination of photogrammetric image orientation?" It is clearly shown that direct georeferencing as well as indirect georeferencing have advantages and disadvantages. A key point is a cost reduction possibility of a pure GPS/INS only solution. After a unique initial investment, direct georeferencing can be cheaper than the indirect method since no cost intensive GCP and no strong block configuration are needed. On the other hand, the system is not necessarily reliable if it runs without any GCP.

Against this background, several approaches were developed to reduce the dependence of the indirect georeferencing method from GCP and to improve the reliability of direct georeferencing by combination of direct and indirect georeferencing. A comparison of different approaches was reported in Heipke et al. (2002), a recent commercial solution is described e.g. in Mostafa and Hutton (2005).

In this paper, after an introduction into GPS/INS integration methods and Kalman filtering and an overview about possible approaches in section 2, a new integration concept for GPS/INS Kalman filtering with additional updates for the exterior orientation angles from aerial triangulation is presented in section 3. This approach is independent of GCP and only uses tie points of the aerial triangulation.

In Cramer (1999), the author asks the question: "Direct geocoding – is aerial triangulation obsolete?" Taking up this question, the aim of the new approach is not to make aerial triangulation obsolete but to use the additional existing orientation information from the images to enhance the advantages of direct and indirect georeferencing without ground control. A view on further possibilities is given in section 4 together with the discussion of this approach and future work.

2. STATE OF THE ART IN COMBINED SENSOR ORIENTATION

In this section some strapdown inertial navigation algorithms and Kalman filter equations are shown in order to lay the basis for the presentation of the new integration approach. Afterwards, other existing approaches of combined sensor orientation are recapitulated for classification of the new approach and for comparison.

2.1 Strapdown inertial navigation

Following Savage (1998a), inertial navigation is the process of calculating position by integration of velocity and computing velocity by integration of total acceleration. Total acceleration is calculated as the sum of gravitational acceleration, plus the acceleration produced by applied nongravitational forces. An INS consists of a navigation computer, a precision clock, an accelerometer and gyro assembly, gravitational model software, and an attitude reference, normally provided by a software integration function using inputs from a three-axis set of inertial angular rate sensors. A rigid attachment of the inertial sensors within a chassis to the vehicle in which the INS is mounted has been denoted as a strapdown INS (SINS).

The functions executed in the INS navigation computer are the angular rate into attitude integration function, use of the attitude data to transform acceleration into a navigation coordinate frame where it is integrated into velocity, and integration of the velocity into position. In Savage (1998a) and (1998b) the algorithm design for strapdown inertial navigation integration is explained in detail.

Here, a summary of the relevant equations to obtain the exterior orientation from accelerations and angular rates measured by an inertial measurement unit (IMU) is given resting upon formulas and symbols used in Titterton and Weston (2005) and using the navigation frame (n-frame) mechanisation. For a terrestrial navigation system operating in a local geographic reference frame the navigation equation may be expressed as follows:

$$\dot{\mathbf{v}}_e^n = \mathbf{f}^n - [2\boldsymbol{\omega}_{ie}^n + \boldsymbol{\omega}_{en}^n] \times \mathbf{v}_e^n + \mathbf{g}_1^n \,, \tag{1}$$

where $\mathbf{v}_e^n$ represents velocity with respect to the Earth expressed in the n-frame defined by the directions of true north, east and the local vertical, in component form:

$$\mathbf{v}_e^n = \left[v_N \quad v_E \quad v_D \right]^T . \tag{2}$$

$\mathbf{f}^n$ is the specific force vector as measured by a triad of accelerometers and resolved into the n-frame; $\boldsymbol{\omega}_{ie}^n$ is the rotation rate of the Earth expressed in the n-frame, dependent on the Earth's rate Ω and the current latitude φ :

$$\boldsymbol{\omega}_{ie}^n = \Omega \left[\cos\varphi \quad 0 \quad -\sin\varphi \right]^T . \tag{3}$$

$\boldsymbol{\omega}_{en}^n$ represents the rotation rate of the n- frame with respect to the Earth-fixed frame. This quantity may be expressed as follows:

$$\boldsymbol{\omega}_{en}^n = \left[\frac{v_E}{R_0 + h} \quad \frac{-v_N}{R_0 + h} \quad \frac{-v_E \tan\varphi}{R_0 + h} \right]^T , \tag{4}$$

where R_0 is the radius of the Earth and h is the height above the surface of the Earth. $\mathbf{g}_1^n$ is the local gravity vector determined by a gravity model.

To implement the solution of the navigation equation, it is necessary to transform the specific force measurements $\mathbf{f}^b$ from the accelerometers of the IMU into the n-frame. This can be accomplished using the well known direction cosine representation of attitude, the required transformation is achieved using:

$$\mathbf{f}^n = \mathbf{C}_b^n \mathbf{f}^b . \tag{5}$$

The construction of the direction cosine matrix $\mathbf{C}_b^n$ which relates the body frame to the n-frame and the computation of attitude will not be described in detail here. For further studies the reader is referenced to Jekeli (2001) and Titterton and Weston (2005).

The navigation equation (1) may be expressed in integral form as follows:

$$\mathbf{v}_e^n = \int_0^t \mathbf{f}^n dt - \int_0^t [2\boldsymbol{\omega}_{ie}^n + \boldsymbol{\omega}_{en}^n] \times \mathbf{v}_e^n dt + \int_0^t \mathbf{g}_1^n dt . \tag{6}$$

Finally, position $\mathbf{x}_e^n$ may be derived by integrating the velocity vector, as follows:

$$\mathbf{x}_e^n = \int_0^t \mathbf{v}_e^n dt . \tag{7}$$

The choice of integration scheme depends on the application. For short range, low accuracy applications, a low order scheme such as rectangular or trapezoidal integration is adequate. For aircraft applications a higher order integration scheme such as Simpson's rule or fourth-order Runge-Kutta integration may be needed.

2.2 GPS/INS integration

In principle, a strapdown solution for INS measurements is sufficient to receive exterior orientation parameters. But the performance of an INS is characterised by a time-dependent drift in the accuracy of the position estimates it provides. The rate at which navigation errors grow over time is governed predominantly by the accuracy of the initial alignment, imperfections in the inertial sensors and the dynamics of the trajectory followed by the host vehicle. Improved accuracy can be achieved through the use of more accurate sensors, but there are limits to the performance before the cost of the inertial system becomes prohibitively large.

An alternative approach is known as integrated navigation. This technique employs some additional source of navigation information to improve the accuracy of the INS. Careful selection of fundamental characteristics leads to lower costs, but potentially more accurate and reliable navigation. Normally GPS is the additional source. Other sources like star trackers, surface radar trackers, magnetic measurements or altimeters offer additional possibilities. They will not be further discussed here, but can be found in literature like Titterton and Weston (2005).

Integrated navigation systems attempt to take advantage of the complementary attributes of GPS and INS (as shown in table 1) to yield a system that provides greater precision than either of the component systems operating in isolation.

	GPS	INS
measurement principle	distance from time delays or phase measurements	inertial accelerations
system operations	reliance on space segment	autonomous
output variables	positions, time	positions, orientation angles
long-wavelength errors	low	high
short-wavelength errors	high	low
data rate	low (≤ 10 Hz)	high (> 50 Hz)
instrument cost	low ($20,000, geodetic quality)	high ($100,000, med./high accuracy)

Table 1. Essential characteristics of GPS and INS as precision position devices, adapted from Jekeli (2001)

Titterton and Weston (2005) distinguish four main classes of integration architecture:

- Uncoupled systems in which GPS is used simply to reset the INS position at regular intervals of time.
- Loosely coupled systems in which the INS and GPS estimates are compared, the resulting differences forming the measurement inputs to a Kalman filter.
- Tightly coupled systems in which the GPS measurements of pseudo-range and pseudo range rate are compared directly with estimates of these quantities by INS in one Kalman filter.
- Deeply coupled systems which combine the GPS signal tracking function and the GPS/INS integration into a single algorithm.

The processing algorithms fall into two basic categories: centralised and decentralised. As the name implies, centralised processing is associated with tight or deep system integration wherein the raw sensor data are combined using one central process. Decentralised processing is characterized by a sequential approach and associated with uncoupled systems and loose system integration, where processes of individual systems provide solutions that are combined by a master process.

In section 2.1, the navigation equations were developed. These equations are differential equations for velocity and position, where the force functions are the sensed accelerations that are properly oriented with information provides by the gyros. How the sensor errors affect the position and velocity is described by error dynamics equations. These equations can be derived applying a differential operator to the navigation equations and are linear under the assumption that the errors are small enough to be represented by differential perturbations of the system dynamics. Given some initial conditions, the differential equations can integrated to yield the error in position, velocity, and orientation at any time after the initial time. These errors are identified as the state of the system, representing the departure of the indicated inertial navigation quantities from their actual values. We would like to estimate the state of the system at any time with external knowledge about this state, where this external information is given in the form of independent GPS observations.

A best estimate is derived based on knowledge of the expected errors in the model and the measured signal using a Kalman filter. Kalman filtering has become a well-established technique for combining navigation data in integrated systems (e.g. Grewal and Andrews (2001)).

A Kalman filter consists of two different parts. One is the prediction step, used if no supporting information is available from GPS on account of the lower data rate. The other is the filtering step in which the new GPS position can be included in the processing system as an innovation.

The state variables at time t_k comprise a vector $\mathbf{y}_k$. Some information is needed to start a recursive algorithm. Usually we do not know the true values of the state variables at the starting time t_0, but we assume to know the mean and the covariance of the process, which is our initial optimal estimate:

$$\hat{\mathbf{y}}_0 = \mathrm{E}\{\mathbf{y}_0\}, \tag{8}$$

$$\mathbf{S}_{\hat{\mathbf{y}}_0} = \mathbf{S}_0, \tag{9}$$

where $\mathbf{S}_0$ is a full-rank covariance matrix.

The state at any time t_k, propagates according to the state transition matrix $\mathbf{T}_{k,k-1}$. In the absence of observations, we seek the best estimate at time t_k, being the expected value given all prior information. This is known as prediction and labelled by a superscripted minus:

$$\hat{\mathbf{y}}_k^- = \mathbf{T}_{k,k-1}\hat{\mathbf{y}}_{k-1}. \tag{10}$$

The state-transition matrix is assumed constant over the time interval between two time increments t_{k-1} and t_k and can be derived from the navigation equations of the strapdown solution in section 2.1 depending on quantity and type of the states. A decentralised loosely coupled approach with 16 states is described in Jekeli (2001). Many other approaches are possible with more or less states and can be found in the literature.

The error covariance matrix of the state variables can be obtained, as follows,

$$\mathbf{S}_{\hat{y}_k^-} = \mathbf{T}_{k,k-1}\mathbf{S}_{\hat{y}_{k-1}}\mathbf{T}_{k,k-1}^T + \mathbf{G}_{k,k-1}\mathbf{S}_{u_k}\mathbf{G}_{k,k-1}^T, \quad (11)$$

where $\mathbf{S}_{u_k}$, is the covariance matrix of the noise process and $\mathbf{G}_{k,k-1}$, is the transition matrix between noise process and states.

This prediction step is carried out recursively for each strapdown solution as long as no new GPS solution is available. If a GPS solution exists an additional step called filtering can be carried out.

Identifying the a priori best estimate $\hat{\mathbf{y}}_k^-$, the best a posteriori estimate and the covariance matrix of the state variables based on the observation at time t_k are given by:

$$\hat{\mathbf{y}}_k = \hat{\mathbf{y}}_k^- + \mathbf{K}_k\mathbf{d}_k, \quad (12)$$

$$\mathbf{S}_{\hat{y}_k} = \mathbf{S}_{\hat{y}_k^-} - \mathbf{K}_k\mathbf{A}\mathbf{S}_{\hat{y}_k^-}, \quad (13)$$

where $\mathbf{K}_k$ is known as the Kalman gain matrix:

$$\mathbf{K}_k = \mathbf{S}_{\hat{y}_k^-}\mathbf{A}^T\mathbf{S}_{d_k}^{-1}, \quad (14)$$

and $\mathbf{d}_k$ as the innovation:

$$\mathbf{d}_k = \mathbf{l}_k - \mathbf{A}\hat{\mathbf{y}}_k^-, \quad (15)$$

with its covariance matrix:

$$\mathbf{S}_{d_k} = \mathbf{S}_{l_k} + \mathbf{A}\mathbf{S}_{\hat{y}_k^-}\mathbf{A}^T. \quad (16)$$

For loosely coupled integration of a new GPS position, the reduced observation vector $\mathbf{l}_k$ is defined, as follows:

$$\mathbf{l}_k = \mathbf{x}_{GPS,k} - \mathbf{x}_{e,k}^n, \quad (17)$$

where $\mathbf{x}_{GPS,k}$ contains the new GPS position and $\mathbf{x}_{e,k}^n$ comes from equation (7) of the strapdown solution in section 2.1. $\mathbf{S}_{l_k}$ is the covariance matrix of this observation, and $\mathbf{A}$ connects the new observation to the state vector. $\mathbf{A}$ simply consists of zeros in all elements except of the three elements, where the INS position and the GPS position have to be linked. Neglecting correlations and weights these elements are filled with ones.

The listed description provides all needed information to present the new integration concept but previously, a short overview of possible approaches is given in the next section.

2.3 Methods of combined sensor orientation

Even if GPS/INS integration is a form of combined sensor orientation as well, the interpretation of the term “combined sensor orientation” in this context stands for the combination of indirect and direct georeferencing methods.

There are at least three different possibilities to combine indirect and direct georeferencing.

- The autonomous approach: Generate a direct georeferencing solution for each image from a Kalman filter as shown above and generate an indirect georeferencing solution from a conventional aerial triangulation and only combine the results.
- Integrated sensor orientation: Use GPS/INS measurements as additional observations within a bundle adjustment. This approach is explained in detail as part of an OEEPE test in Heipke et al. (2002).
- Use aerial triangulation data as additional updates of the Kalman filter. Skaloud and Schaer (2003) named this method “reversed 1 step”.

The stability of the attitude angles between the IMU and the camera has been identified as one main error source of combined sensor orientation, at least for analogue photogrammetric cameras. These angles are named boresight angles. Since the boresight angles are not physically measurable quantities, they are typically determined by comparing the platform attitude angles derived from direct georeferencing with the photogrammetric angles computed from indirect georeferencing (autonomous approach).

The second option (integrated sensor orientation) is to modify the bundle adjustment equations to include three boresight angles as unknowns, in which case the INS angles are introduced in the least squares adjustment as observations along with their variances.

These two different approaches are far away from the original measurements and are mainly a combination of preprocessed results. The full information capability of the GPS/INS measurements will not be used. In the first approach a simple combination like subtraction of angles is only possible for short time steps with differential changes of the angles.

One can also envisage an approach where the boresight gets estimated as a state-vector parameter of an inertial navigator using aerial triangulation data as additional updates of the Kalman filter. This idea is realised in the new approach presented now in section 3.

3. NEW INTEGRATION CONCEPT

First of all, the idea of the new integration concept will be described in detail. Subsequently, the necessary changes and extensions in the Kalman filter equations introduced in section 2.2 are given in section 3.2.

3.1 Idea

From airborne digital frame camera images – normally acquired in strips with 60-80 % overlap – the relative orientations of these images can be obtained by automatic aerial triangulation. Under the assumption of a known initial orientation of the first image in the navigation frame used for GPS/INS integration these relative orientations can be used as an update in the GPS/INS Kalman filter. Depending on flying altitude and the percentage of image overlap a new image with new relative orientation information is available approximately every two seconds providing the possibility to update the drifting IMU.

Similar to the GPS update in the filtering step of the Kalman filter a new update can be included containing the new attitude information from relative orientation. The needed extensions and changes in the Kalman filter equations for a loosely coupled integration described in section 2.2 are explained in the following section.

3.2 New Kalman Filter Update

As shown above, a Kalman filter consists of the two parts prediction and filtering. Since no new information has to be included within the prediction step the changes are concentrated in the filtering step starting with equation (12).

A new observation vector $\mathbf{l}_j^*$ has to be inserted similar to equation (17) at any time t_j if new attitude information is available from relative orientation, as follows:

$$\mathbf{l}_j^* = \begin{bmatrix} \varphi_{AAT} - \varphi_{INS} \\ \theta_{AAT} - \theta_{INS} \\ \psi_{AAT} - \psi_{INS} \end{bmatrix}_j , \qquad (18)$$

where an asterisk marks the changed values and φ_{INS}, θ_{INS} and ψ_{INS} (the Euler angles) may be derived directly from the direction cosine matrix $\mathbf{C}_b^n$ also used in equation (5). φ_{AAT}, θ_{AAT} and ψ_{AAT} are functions of the photogrammetric angles (ω, φ, κ) coming from the AAT process. Consequently a new covariance matrix $\mathbf{S}_{l_j^*}$ for the observation vector $\mathbf{l}_j^*$ is necessary and has to be introduced. The differences of the Euler and photogrammetric angels have to be small as it can be adopted for short time periods. Otherwise the angles must be combined using rotation matrices.

To connect the new observations to the right states in $\hat{\mathbf{y}}_j^-$ the Matrix $\mathbf{A}$ must be changed to $\mathbf{A}^*$ with ones for the three elements touching the attitude angles in the state vector and zeros for all the rest of them. With these changes, equations (12) to (17) can be applied whenever new attitude information is available from a new image.

In the next section, the presented concept is discussed and checked for visible infirmities to derive future work. This will be done in the next section.

4. DISCUSSION AND FUTURE WORK

The new approach offers the chance to improve GPS/INS based image orientation and to make it more reliable because additional observations are enclosed but no additional unknowns.

Another point is the additional effort to introduce this concept in existing systems. The concept works always if attitude information from images can be made available. In the field of photogrammetry, images are the essential input and thus, attitude information can be derived under the condition that tie point matching is successful. The effort is reduced to the implementation of algorithms for automatic relative orientation (see e.g. Tang and Heipke (1996)), which are an essential part of any up-to-date digital photogrammetric workstation.

On the other hand, some constraints have to be kept in mind. One issue is the time synchronisation between the imaging events and the GPS/INS measurements. Also, the whole system has to be initialised and aligned and starting attitude angles are necessary for the first image to make orientation transfer from one image to the next possible. Furthermore, the continuous, recursive relative orientation process leads to a drift in itself. We expect that these drifts are significantly smaller than the gyro drifts, but at this point in time, experimental evidence for this assumption is not yet available.

These advantages and disadvantages also show the future work that has to be carried out. The algorithm must be implemented and tested with different data sets. After that, the results have to be compared with non-integrated solutions and with solutions that come from other integration concepts, e.g. those briefly discussed in section 2.3.

In summary, there is a possibility to obtain improved near real time photogrammetry results in the future if all work can be done in an automatic way (see e.g. Wu et al. (2004) and Earthdata (2005) for current real-time photogrammetric solutions).

There are also some recent developments in the field of GPS/INS integration that have to be kept in mind and maybe used to improve our own work. In Grejner-Brzezinska et al. (2005) new error modelling and compensation techniques that can potentially improve the GPS/INS system's performance are shown. The modernisation of the NAVSTAR GPS System with the new GPS IIF and GPS III satellites, including additional frequencies and Galileo, the new European global navigation satellite system (GNSS), bringing additional satellites and frequencies, will improve the accuracy, reliability and availability of the future GPS/INS systems (McDonald (2002)).

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