

Digital image georeferencing from a multiple camera system by GPS/INS

Mohamed M.R. Mostafa^{a,*}, Klaus-Peter Schwarz^b

^a Applanix Corporation, 85 Leek Crescent, Richmond Hill, Ontario, Canada L4B 3B3

^b Department of Geomatics Engineering, The University of Calgary, Calgary, Alberta, Canada T2N 1N4

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Abstract

In this paper, the development and testing of an airborne fully digital multi-sensor system for digital mapping data acquisition is presented. The system acquires two streams of data, namely, navigation (georeferencing) data and imaging data. The navigation data are obtained by integrating an accurate strapdown inertial navigation system with a differential GPS system (DGPS). The imaging data are acquired by two low-cost digital cameras, configured in such a way so as to reduce their geometric limitations. The two cameras capture strips of overlapping nadir and oblique images. The GPS/INS-derived trajectory contains the full translational and rotational motion of the carrier aircraft. Thus, image exterior orientation information is extracted from the trajectory, during post-processing. This approach eliminates the need for ground control (GCP) when computing 3D positions of objects that appear in the field of view of the system imaging component. Two approaches for calibrating the system are presented, namely, terrestrial calibration and in-flight calibration. Test flights were conducted over the campus of The University of Calgary. Testing the system showed that best ground point positioning accuracy at 1:12,000 average image scale is 0.2 m (RMS) in easting and northing and 0.3 m (RMS) in height. Preliminary results indicate that major applications of such a system in the future are in the field of digital mapping, at scales of 1:5000 and smaller, and in the generation of digital elevation models for engineering applications. © 2001 Elsevier Science B.V. All rights reserved.

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1. Multi-sensor systems for mobile mapping

During the past two decades, the mapping sciences have progressively moved towards digital mapping, making use of multi-disciplinary developments in the geomatics field. Instead of regarding geodesy, photogrammetry, and remote sensing as separate sciences, they are seen more as an inte-

grated discipline today. Part of this development has been spurred on by systems capable of acquiring and fusing accurate globally referenced data in fully digital form with short turn-around-time in a cost-effective fashion. A mobile-mapping multi-sensor system is, thus, the product of integrating the concepts of kinematic geodesy and digital photogrammetry, to acquire, store, and process, measurable quantities that sufficiently describe spatial and/or physical characteristics of a part of the Earth's surface.

Various applications in GIS, airborne remote sensing, and resource mapping often require data

* Corresponding author. Tel.: +1-905-709-4600 ext. 274; fax: +1-905-709-7153.

E-mail address: MMostafa@applanix.com (M.M.R. Mostafa).

capture in fully digital form, with sufficient accuracy and in a cost-effective and fast manner. Therefore, integrated digital image acquisition and navigation systems have been developed for such applications (cf. Cramer et al., 1997; Mostafa et al., 1997; Toth and Grejner-Brzezinska, 1998). Such systems are part of a continuing effort which started earlier for the development of GPS-aided inertial navigation systems in support of geomatics applications [see Schwarz et al. (1993) for the mathematical model and proposed applications, and Abdullah (1997), El-Shemy (1996), Reid et al. (1998), Schwarz (1995), Škaloud et al. (1996) and Toth and Grejner-Brzezinska (1998) for applications].

2. Direct georeferencing model

As shown in Fig. 1, direct georeferencing of digital images can be described by first introducing the collinearity concept rearranged for object coordinates as:

$$\mathbf{r}_G^M = \mathbf{r}_E^M(t) + s_g \mathbf{R}_c^M \mathbf{r}_g^c(t) \quad (1)$$

where $\mathbf{r}_G^M$ is the georeferenced 3D vector of coordinates of an arbitrary object point G in the mapping frame (M-frame); $\mathbf{r}_E^M(t)$ is the 3D vector of coordinates of the exposure station E , of any imaging sensor, at the instant of exposure, in the M-frame; s_g

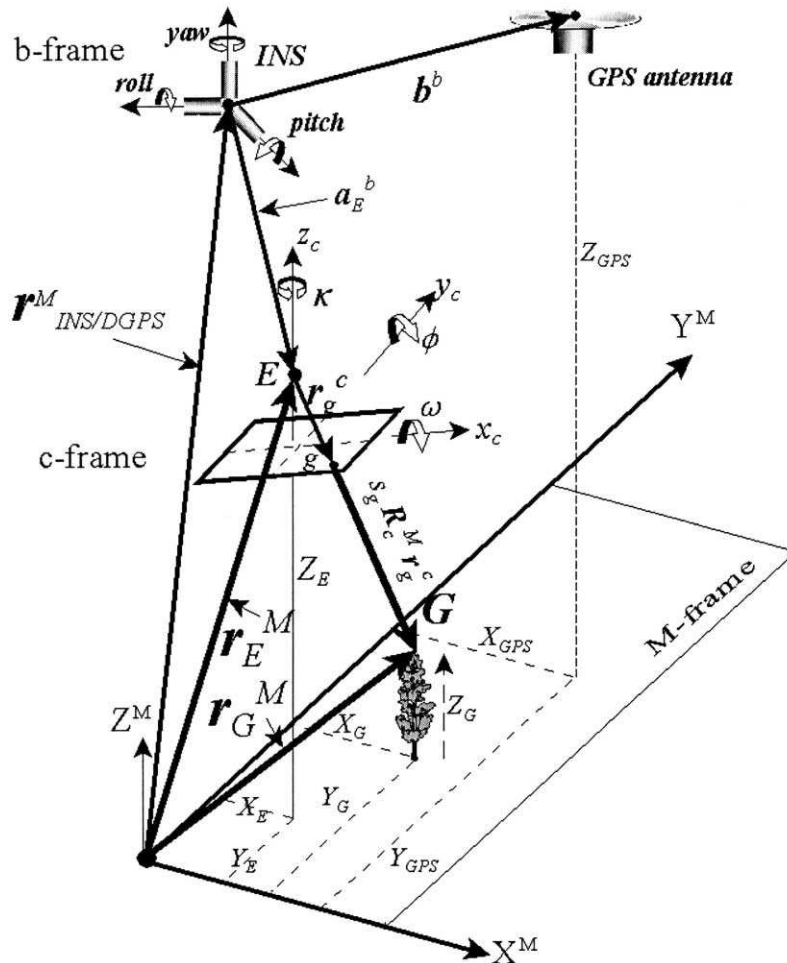


Fig. 1. Elements of direct georeferencing (see explanations in text).

is a scale factor per point per image for each imaging sensor, implicitly derived during the 3D photogrammetric reconstruction of objects using image stereopairs and therefore not explicitly computed in practice; $\mathbf{R}_c^M(t)$ is a matrix rotating each imaging sensor camera frame (c-frame) into the M-frame utilising the three photogrammetric rotation angles ω , φ and κ (cf. Moffit and Mikhail, 1980); and $\mathbf{r}_g^c(t)$ is the 3D vector of coordinates of the image point g in the c-frame, expressed by:

$$\mathbf{r}_g^c(t) = \left(x_g^c - x_{pp}^c; \frac{y_g^c - y_{pp}^c}{k}; -f \right) \quad (2)$$

where x_g^c and y_g^c are the image coordinates of point g corresponding to the object point G ; x_{pp}^c and y_{pp}^c are the principal point offsets from the CCD format centre; k is a scale factor accounting for the non-squareness of the CCD pixels; f is the calibrated focal length of the lens in use.

Since the imaging sensor(s), the GPS antenna, and the INS centre do not occupy the same point in 3D space, Eq. (1) can be modified to include the

position and orientation offsets which is expressed by the formula:

$$\mathbf{r}_G^M = \left(\mathbf{r}_{\text{INS/DGPS}}^M(t) + \mathbf{R}_b^M(t) \mathbf{a}_E^b \right) + s_g \left(\mathbf{R}_b^M(t) \mathbf{R}_c^b \right) \mathbf{r}_g^c(t) \quad (3)$$

where $\mathbf{r}_{\text{INS/DGPS}}^M(t)$ is the 3D vector of coordinates of the INS centre in the M-frame; $\mathbf{R}_b^M(t)$ is a matrix rotating the INS body frame (b-frame) into the M-frame; $\mathbf{a}_E^b$ is an offset vector between the INS centre (b-frame origin) and the imaging sensor exposure station E ; $\mathbf{b}^b$ is an offset vector between the INS centre and the GPS antenna centre that is measured and compensated for during GPS/INS data post-processing; $\mathbf{R}_c^b$ is a matrix rotating each imaging sensor c-frame into the INS b-frame.

3. Multi-sensor system configuration

The configuration shown in Fig. 2 acquires two separate streams of data, namely, the navigation and

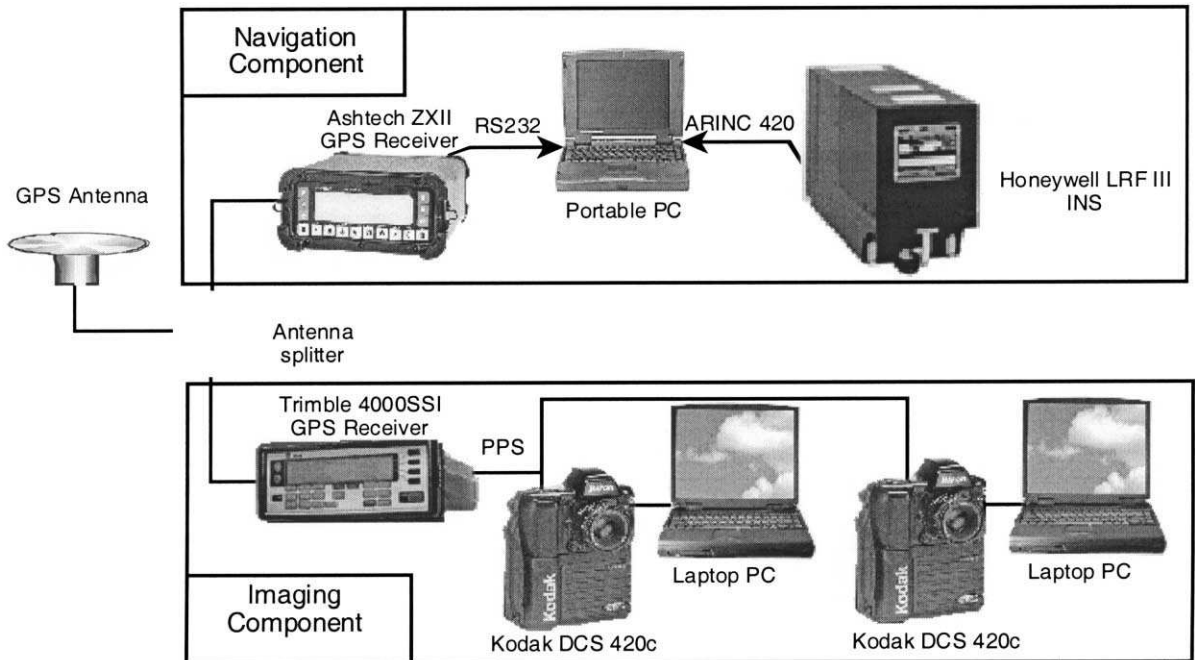


Fig. 2. Hardware configuration.

the imaging data. The navigation data is collected using a Honeywell LRF III inertial navigation system, and an Ashtech ZXII GPS receiver, connected to a portable computer for raw data acquisition and storage for subsequent post-mission processing. The image data is collected by two low-cost Kodak DCS420c digital cameras equipped with a 1.5×1 K CCD chip ($9 \mu\text{m}$ pixel resolution). To synchronize the INS, GPS, and image data in a common time frame, the INS records are stamped in real-time by the Ashtech GPS receiver PPS (pulse per second) signal, while a Trimble GPS receiver event marker pulse is used to store the instant of time when an image is captured by one of the cameras. Therefore, all the data are synchronized in the GPS time frame during data logging. The data acquisition is controlled by a real-time data logging software which downloads the GPS/INS/imagery data to the host computers, and time tags the imagery and INS records by the GPS receiver-derived time pulse.

4. Geometric design of a multi-camera system

Several researchers reported on the point positioning accuracy achievable from digital imaging sensors such as the three-line CCD sensors (Cramer et al., 1997), or digital frame cameras (DFCs) (cf. Mostafa et al., 1997). Height determination with the small format cameras is poorer by a factor of three to five compared to horizontal coordinate accuracy (Schwarz et al., 1993; Mostafa et al., 1998). These results were confirmed by simulations. Poor height determination accuracy is due to the poor quality of the 3D space intersection, which can be demonstrated by the intersection (parallax) angle γ between individual camera exposure stations and an arbitrary single ground object, which can be expressed by Eq. (4).

$$\gamma = 2 \tan^{-1} \left(\frac{w P_s (1 - O)}{2f} \cos \left(\frac{L_{\text{FOV}}}{2} \right) \right),$$

$$L_{\text{FOV}} = 0^\circ \quad \text{GP at image centre}$$

$$L_{\text{FOV}} = 2 \tan^{-1} \left(\frac{L_p}{f} \right) \quad \text{GP at image edge} \quad (4)$$

where, w is the image size (in pixels) parallel to flight direction; P_s is the pixel size; O is the overlap

percentage between two stereo images; L_{FOV} is the camera lateral field of view angle; and L_p is the lateral location of a ground point (GP) in an image. Note that γ is mainly a function of w , for the same overlap percentage.

Since positioning accuracy depends on the intersection geometry γ (which is dependent on image size), the theoretical accuracy of height determination can be derived by standard error propagation techniques. This yields:

$$\sigma_{Z_G} = \sqrt{2} \sigma_{\text{pxl}} \frac{(Z_E - Z_G)^2}{2 Z_E \cdot f \cdot \tan \left(\frac{\gamma}{2} \right)} \quad (5)$$

where, σ_{Z_G} is the height standard deviation of ground object point G; σ_{pxl} the image measurement precision; and Z_E and Z_G the height of the exposure station and the ground point G, respectively, in the M-frame.

Note that the effect of image position and orientation has been neglected in order to separate and emphasize the effect of intersection geometry. Fig. 3 shows σ_{Z_G} for different intersection angles and different flight altitudes. In Fig. 3, three ranges have been identified. They correspond to $\gamma < 20^\circ$, $20^\circ \leq \gamma \leq 40^\circ$, and $\gamma > 40^\circ$. The poorest accuracy is achieved in the first range. In the second range, a significant accuracy improvement is obvious, while the accuracy improvement is minimal in the third range. On the other hand, the typical intersection angle for the 1.5×1 K cameras used in this system ranges from 3° to 10° . This leads to the lowest theoretical height accuracy. Larger format DFCs can provide better intersection quality. At the time of system development, however, they are more expensive for such a low-cost system and their image acquisition data rate is much poorer than that of the 1.5×1 K cameras. Therefore, the imaging component of the system has been designed to include two low-cost 1.5×1 K digital cameras, one of which is nadir, and the other is oblique. This allows for covering the same ground scene with a nadir and an oblique image that, when simultaneously processed, provides a wider intersection angle and thus better height accuracy. This concept has been validated through computer simulations, which showed that height determination accuracy is improved by a factor of 3.5 using such a

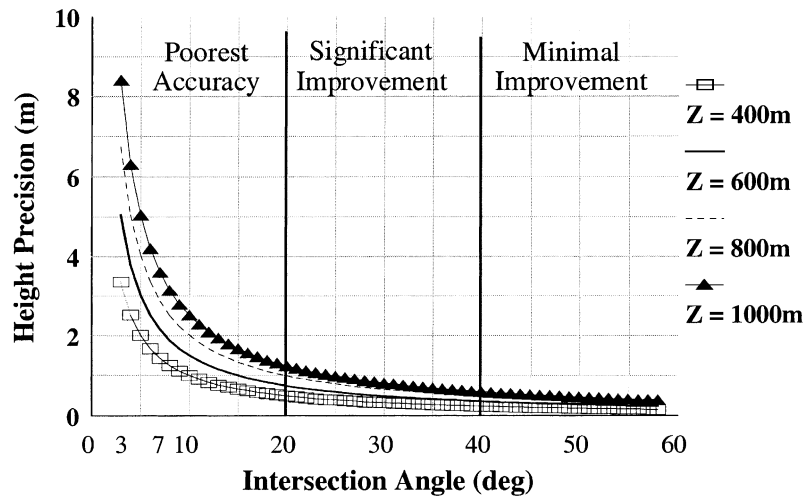


Fig. 3. Height determination precision as a function of the image ray intersection angle.

system. Stereo image matching becomes involved in this case; see Cochran (1995) for a detailed discussion.

5. System calibration

The overall system calibration is required to relate GPS-derived positions, INS-derived attitude parameters, and imagery-derived object point coordinates. Two approaches were followed to calibrate the system. Next, each of these approaches is discussed in some details.

5.1. The terrestrial approach

This approach is implemented in a static terrestrial fashion, where the digital cameras and the INS are tightly coupled using a metal frame, so as to ensure a fixed orientation offset (constant boresight), which is a key assumption in such an approach. The digital cameras are used to acquire a number of images to a precisely surveyed target field, from which their interior geometry, lens distortions, and, for each image, the position of the exposure station and the image rotation angles can be determined (for details, see Mostafa and Schwarz, 1999). The system was set up for 45 min at each station collecting inertial data while an image per camera was captured

to the target field. A total of 10 stations was occupied by the system. The 10 images per camera, together with 36 other images per camera that were captured before attaching the cameras to the frame, were introduced to a self-calibrating adjustment software (Lichti and Chapman, 1997), together with approximate orientation angles for each image, and accurate exposure station positions, to resolve for the camera interior geometry, lens distortions, and exterior orientation parameters. The extra 36 images per camera were captured in a configuration that was optimised to strengthen the network for high precision determination of the camera calibration parameters (cf. Fraser, 1997).

The inertial measurements were processed using KINGSPAD in a static mode imposing zero velocities constraint to avoid system position drifts. The calibration procedure was repeated after the test flight using the same approach of data acquisition. Table 1 shows the statistics of the orientation offset (boresight) between the INS b-frame and each camera c-frame in the pitch and roll angles for both nadir and oblique cameras resulting from the pre- and post-flight calibration, respectively. Note that the changes in the angles are within their estimated precision. The azimuth component is, however, of poorer quality than that of the pitch and roll. The precision of each camera yaw angle is about 40" and 30" for the pre- and post-flight calibration, while

Table 1
INS/camera relative pitch and roll (°)

Calibration parameter		Min.	Max.	Mean	σ
<i>INS / camera relative pitch</i>					
Pre-flight	INS-Nadir	2.30	2.33	2.312	0.009
	INS-Oblique	29.55	29.60	29.570	0.016
Post-flight	INS-Nadir	2.29	2.34	2.305	0.013
	INS-Oblique	29.56	29.59	29.580	0.009
In-flight	INS-Nadir	2.26	2.35	2.308	0.021
	INS-Oblique	29.53	29.76	29.660	0.045
<i>INS / camera relative roll</i>					
Pre-flight	INS-Nadir	3.11	3.15	3.130	0.010
	INS-Oblique	-1.43	-1.39	-1.410	0.013
Post-flight	INS-Nadir	3.12	3.16	3.140	0.011
	INS-Oblique	-1.41	-1.40	-1.406	0.009
In-flight	INS-Nadir	3.09	3.20	3.147	0.021
	INS-Oblique	-1.53	-1.36	-1.450	0.039

those of the INS are 2.9' and 3.2', respectively. The reason for that can be explained by the lack of horizontal accelerations exposed to the system during such static calibration procedure.

The estimated distortion parameters of the lenses used by each camera agreed within their estimated precision for both the pre- and post-flight calibration. For instance, Fig. 4 shows the radial lens distortion

profiles estimated during the pre- (solid lines) and post-flight (dashed lines) calibration for the nadir camera and the oblique camera, respectively. The digital camera calibration results agree with a previous work reported by Lichti and Chapman (1997) and Mills et al. (1996), especially for the nadir camera typically equipped with a 28-mm lens.

5.2. The in-flight approach

This approach has been used by Abdullah (1997), Cosandier and Chapman (1995), Mostafa et al. (1997) and Reid et al. (1998). In the case of the multi-camera system presented here, the geometry and imaging configuration differ significantly from those published by the aforementioned authors and, thus, this approach was first studied by simulations and, then, was verified using the test flight data. The general data-flow is shown in Fig. 5.

Due to the poor space resection geometry provided by the digital cameras at hand, the ground control used in the test flight was spatially distributed to strengthen the geometry as indicated in a nadir and an oblique digital images of the test flight shown in Fig. 6. The flight pattern was also designed to help reduce the correlation between the interior and exterior orientation parameters. The image

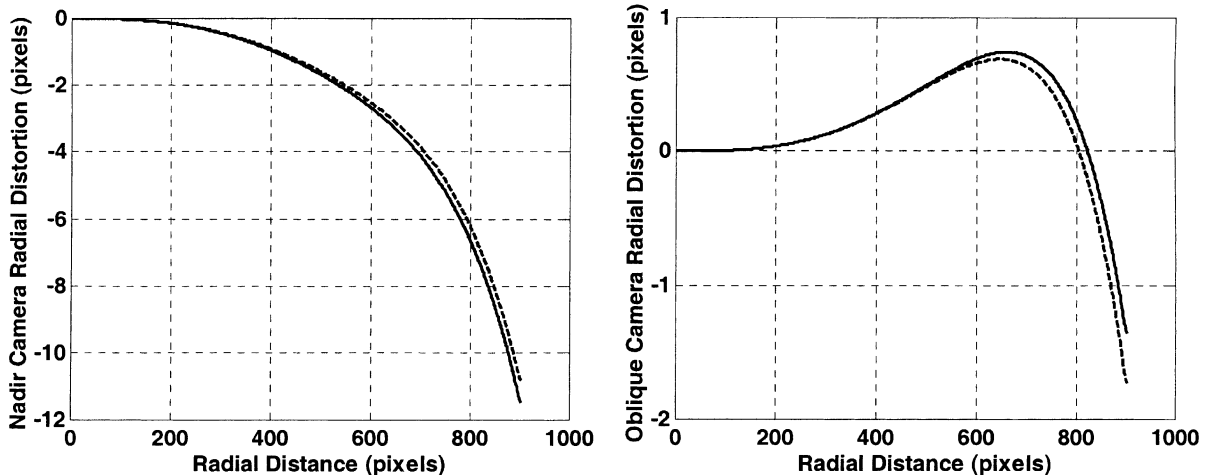


Fig. 4. Lens distortion profiles of the nadir camera (left) using a 28-mm lens and the oblique camera (right) using a 52-mm lens, for pre-flight (solid lines) and post-flight (dashed lines).

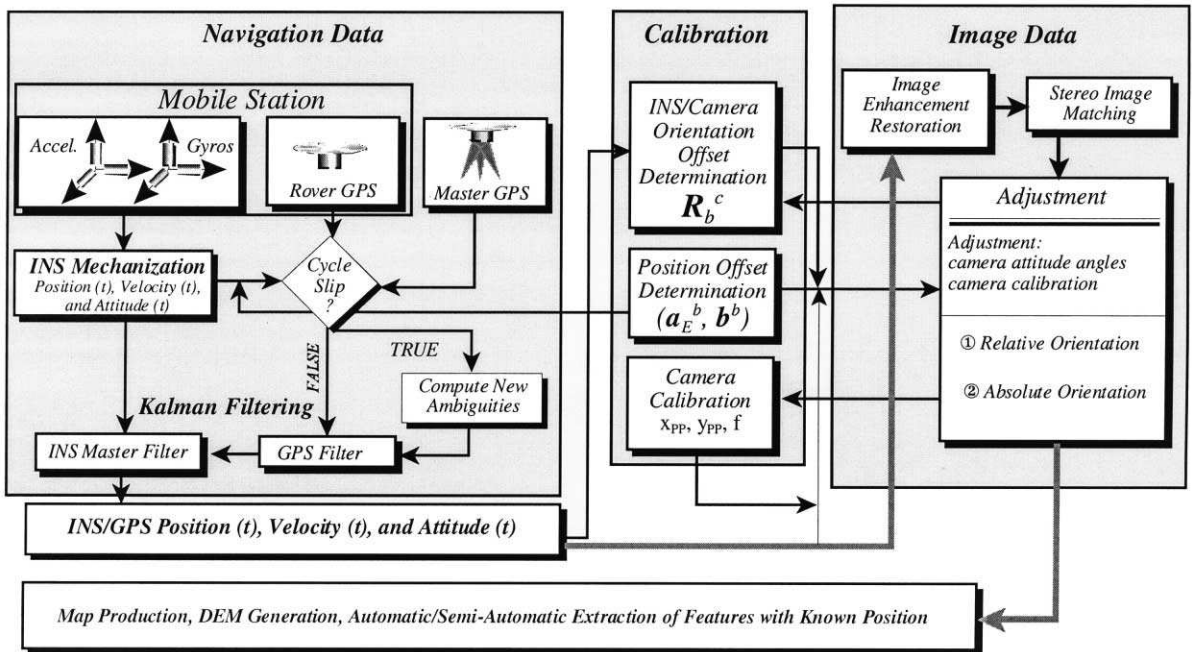


Fig. 5. The multi-sensor system data-flow (in-flight calibration case).

dataset was first processed using GPS-assisted aero-triangulation to decorrelate image exposure station positions from image attitude angles, for better recovery of image attitude angles, to subsequently determine each INS/camera boresight. Table 1 shows the estimated INS/camera roll and pitch offsets for both cameras.

5.3. Terrestrial versus in-flight calibration—a comparison

It is obvious that the terrestrial approach provides a higher precision calibration of the roll and pitch components of the orientation offset. However, it is the opposite in the heading component. The advan-

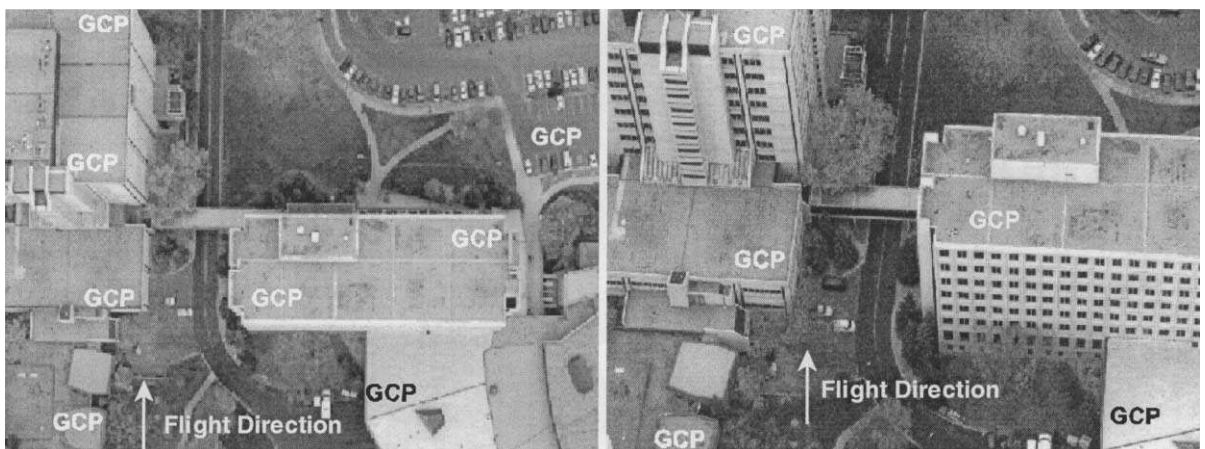


Fig. 6. A nadir digital image (left) and an oblique digital image (right), October 1998 flights.

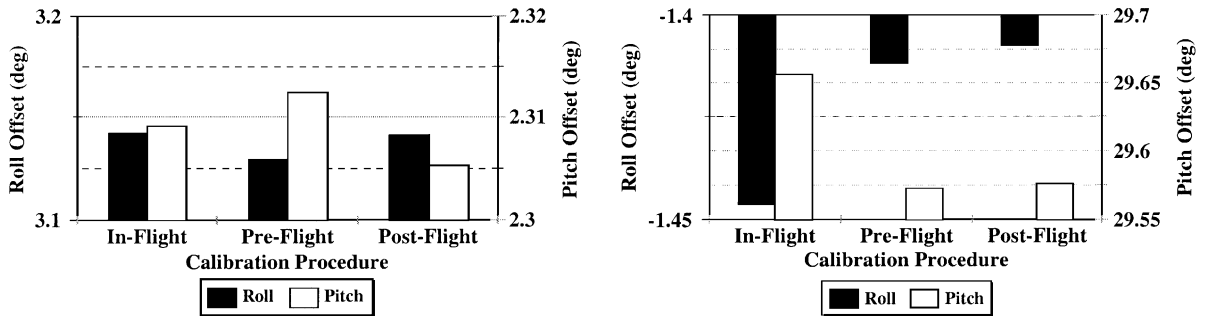


Fig. 7. Boresight roll and pitch components for INS/nadir (left) and INS/oblique (right).

tages of the in-flight approach are: the calibration process and the data acquisition process take place in the same environment; it cancels INS errors developed over time before photography, especially when having horizontal manoeuvres which improve INS-derived heading precision; and it is much more convenient if the system is used with different aircrafts. The drawbacks are: it requires special calibration field, and the calibration accuracy is dependent on the accuracy, density and configuration of the GCP calibration field, the sensor geometry (poorer results for smaller image size) and image point measurement precision.

The advantages of the terrestrial approach are: it provides stronger network geometry for aerotriangulation, higher precision target mensuration in imagery (typically 1/20–1/50 pixel), and is much more controlled than the in-flight approach. The drawbacks are: its geometry is different from that obtained during aerial image acquisition; it is not consistent with the operational environment; the INS-derived azimuth is of poorer quality than that achieved in airborne case; and any error in equipment installation would result in the loss of calibration parameters and the calibration would have to be repeated. Fig. 7 shows the calibrated boresight roll and pitch components for both cameras, while their statistics are listed in Table 1.

6. Multi-sensor system testing in flight

In October 1998, a test flight was conducted over The University of Calgary (U of C) campus for two consecutive days. The campus was chosen because it

covers an area of about 150 ha where GCPs could be easily established and because it has a detailed urban character. The hardware configuration described in Section 3 is used in this test flight as shown in Fig. 8. The dual-camera system introduced in Section 4 was used in these flights because it allows a direct comparison between a single-camera system and a dual-camera system. The flight altitude was chosen at 400–500 m, and the flight pattern was designed to cover the entire campus by a block of 50–60% endlap and 30–40% sidelap, using repeated west-to-east flight lines and a single flight per strip in the opposite direction. Two cross strips were also flown from south to north and vice versa. The flight pattern is partially shown in Fig. 9.

Almost 100 GCPs were painted all over the campus. They are needed to provide an independent reference to test the overall system performance when using the airborne data (GPS, INS, and nadir



Fig. 8. The multi-sensor system used in the October 1998 test flights.

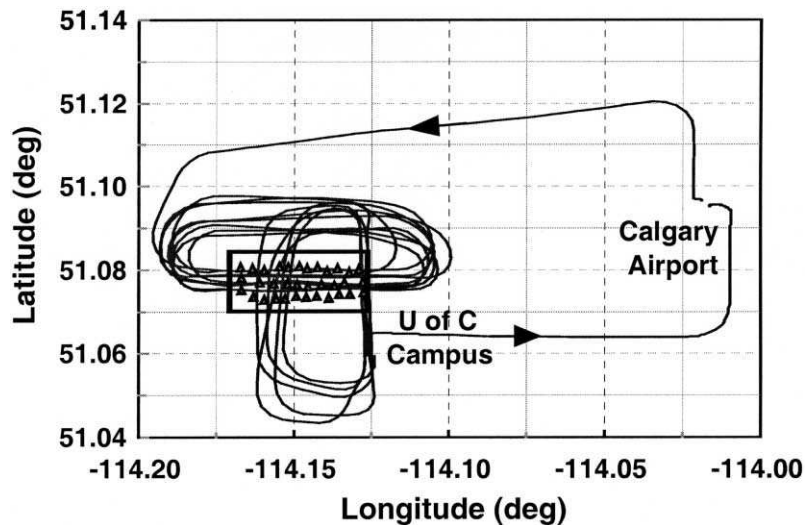


Fig. 9. Partial GPS/INS-derived trajectory of the Calgary test flight.

and oblique images) for positioning objects on the ground. In addition, the in-flight aerial calibration of the entire system, as discussed in Section 5.2, can be tested in this way. Fifty-three percent of the GCPs were placed on roads and parking lots, 27% on medium-height building rooftops, and 20% on highest building rooftops, to end up with a 67-m maximum elevation above the ground. This is to obtain large height differences between adjacent points (e.g., on the ground and on building rooftops) to be able to calibrate the digital cameras and the entire system in-flight, as for example, shown in Fig. 6. All GCPs were surveyed using GPS utilizing multiple master stations. A network adjustment was finally performed to double-check the GPS-fixed baselines. The network adjustment yielded GCP coordinate precision at the level of about 1 cm (1σ) in planimetry and 2.0 cm (1σ) in height.

The flight was done with wide turns to avoid signal blockage by aircraft banking and, thus, the roll angle was typically smaller than 15° . Further, mission planning was done to ensure a good sun angle and good satellite sky distribution. Two master stations were kept running during the test period. One was located close to the airport and was occupied by a Trimble 4000 SSI, the other was on the rooftop of the engineering building and was occupied by an Ashtech Z XII receiver. This resulted in two inde-

pendent GPS trajectories which, when compared, agreed to be better than 10 cm, which is typical for a 2–8-km baseline. These values indicate that each of the two independent solutions provides sufficiently high-precision camera exposure station position. The Ashtech GPS raw data together with the INS measured specific force and angular velocity raw data were processed using the KINGSPAD software. The Kalman filter-derived estimates of the positioning precision are 0.04, 0.05 and 0.09 m, for latitude, longitude and height, respectively. For attitude, they are 0.0075° , 0.0097° and 0.0152° , for roll, pitch and yaw, respectively.

The GPS/INS interpolated position and attitude angles at each exposure station were used together with the imagery to analyse the system performance when using nadir plus oblique images. After pre-processing the GPS/INS data to compensate for the position and orientation offsets between the navigation and imaging sensors, the compensated position and attitude parameters were used as observable exterior orientation parameters (in M-frame) together with their standard deviations and the image point measurements from the commercial software package PCI OrthoEngine.

The resulting GCP coordinates from processing stereopairs in direct georeferencing mode, or adjusting strips or blocks, were compared to the reference

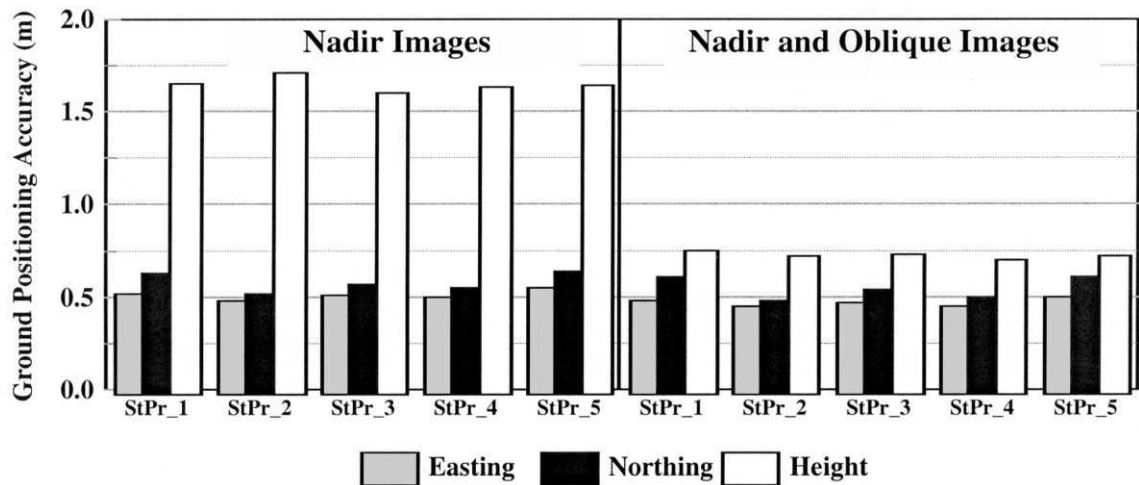


Fig. 10. Positioning accuracy for five stereopairs using nadir images (left) or nadir and oblique images (right).

values on the ground, to analyse both the direct georeferencing approach using stereopairs or GPS/INS-assisted strip or block aerotriangulation. The analysis was done as follows: using a stereopair of nadir images; using a stereopair of nadir images plus an extra oblique image; using a strip of five nadir images; using a strip of five nadir images plus extra oblique images as available; using a block of 3×3 nadir images; and using a block of 3×3 nadir images and oblique images in addition to cross strips in both directions.

Fig. 10 shows the RMS of the differences between the GCP coordinates as determined by GPS/INS/imagery data using direct georeferencing and the GCP determined by the land survey, for five stereopairs (StPr_1 to StPr_5). Each stereopair had four to seven targeted points. Fig. 10 shows the results when using nadir images (left panel) and when using the nadir and oblique images (right panel). From Fig. 10, it is clear that the ground coordinate determination accuracy is consistent in all stereopairs and according to the expectations. The

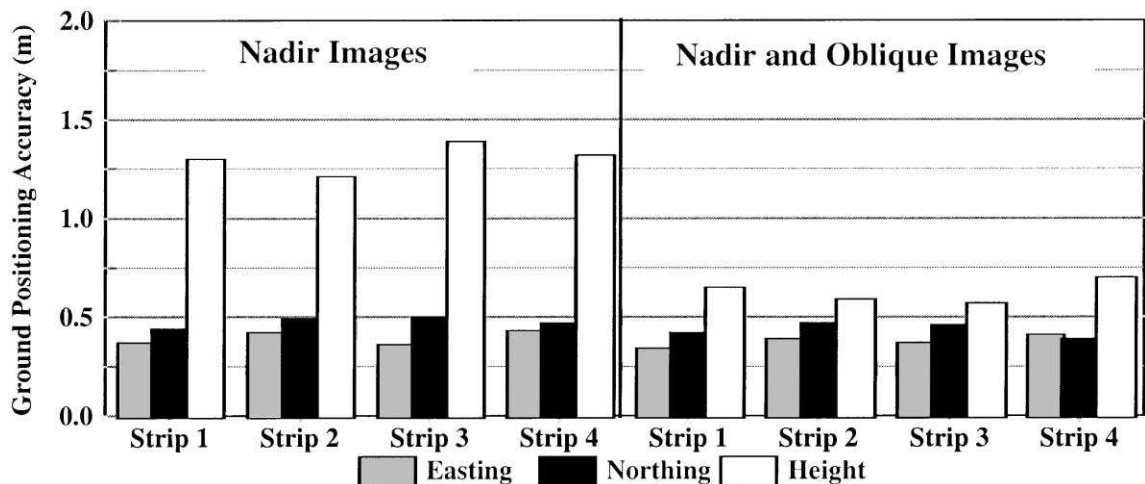


Fig. 11. Positioning accuracy for four strips using nadir (left) and nadir and oblique images (right).

Table 2
Positioning accuracy for nadir and oblique imagery using block configuration

Easting (m)			Northing (m)			Height (m)		
Max.	σ	RMS	Max.	σ	RMS	Max.	σ	RMS
<i>Nadir image block results</i>								
0.69	0.3	0.31	0.71	0.3	0.3	1.93	0.79	0.8
<i>Nadir and oblique and cross strips image block results</i>								
0.54	0.2	0.22	0.61	0.2	0.24	0.86	0.3	0.34

improvement in accuracy due to incorporating the oblique imagery in the processing is minimal in the horizontal components while it is major in the height. The horizontal accuracy improved by only a factor of 1.1. The height accuracy is improved by a factor of about 2.3.

Fig. 11 shows the RMS of the differences between the ground coordinates as determined by GPS/INS/imagery data and the land-surveyed reference coordinates, for four strips. GPS/INS-assisted strip triangulation is used to determine ground point coordinates without the use of ground control. The left panel of Fig. 11 shows the accuracy when using the nadir images only, while the right panel shows the accuracy when using nadir and oblique images. The first three strips were collected in the first day of flight (October 8th) while the fourth strip was collected in the second flight (October 9th) using the same calibrated parameters of the first day. It is clear that the absolute accuracy is consistent between different days of flight.

Table 2 shows the 3D ground positioning accuracy statistics when processing all the available imagery in block mode.

7. Summary and outlook

This paper described the development and testing of an integrated airborne imaging/navigation system for digital mapping. The major research and development component in this project is the integrated system design and software development. The multiple camera system developed here can overcome some of the inherent geometric limitations of small

format digital cameras. They are the key to accuracy improvement in such systems. The system performance has been analysed by comparing the ground point positions using GPS/INS/image data without GCP to the land-surveyed coordinates of such points. At an average image scale of 1:12,000, the achievable ground point positioning accuracy in the direct georeferencing mode using stereopairs is 0.5 m in planimetry (1σ) and 1.6 m in height. Adding one extra oblique image to a nadir stereopair improved the height accuracy to 0.7 m. Using GPS/INS-aided single strips of nadir imagery, the system accuracy is 0.4 m in planimetry (1σ) and 1.3 m in height. Adding the available oblique imagery to those image strips resulted in improved height accuracy of 0.6 m. Using GPS/INS-aided block triangulation with the nadir imagery only resulted in ground positioning accuracy of 0.3 m in planimetry (1σ) and 0.8 m in height. Adding available oblique images to the block improved the ground positioning accuracy to 0.2 m in planimetry (1σ) and 0.3 m in height.

Replacing the initial one-camera system by a dual-camera system improved the overall accuracy by factor of 2.3 when using stereopair processing. Using a block of vertical and nadir images and longitudinal and cross strips improved the overall accuracy by a factor of 4.8. Consistently repeatable results were achieved when testing the system in flight over the campus on two different days in October 1998. The internal consistency of the system is higher than the absolute accuracy with respect to reference ground truth. Since system calibration is a major contributor to the overall system error, especially for multi-sensor systems, two approaches have been used, an in-flight approach and a terrestrial one. In the terrestrial calibration, the environment is very well controlled and repeatable, especially for camera calibration. It is well suited to study different factors affecting system accuracy. In the in-flight calibration, the separation of error sources becomes a more complex task; yet it yields more accurate boresight determination. In-flight and terrestrial calibration methods have advantages and disadvantages. The two different methods provide good enough boresight determination for some mapping applications. A comparison between the two approaches needs further tests and detailed discussion, possibly in a future paper.

The system developed here is at the prototype level and, thus, data acquisition was also implemented at the prototype level. For example, the multi-camera system containing two cameras for testing was implemented using two separate laptops and a GPS receiver to synchronise the acquired imagery to the GPS time frame. In addition, the navigation data was collected using a different host computer with a different GPS receiver. Further, a full inertial system and GPS receivers were used to acquire only the raw data from the IMU and the GPS cards. This significantly adds to the system budget and reduces system portability. It is, therefore, recommended to design an industrial computer system that can accommodate the necessary boards for simultaneous navigation and image data acquisition. This would greatly improve system portability and cost. Besides the work presented here, map production using the Kodak DCS series has been reported (cf. Congalton et al., 1998). However, since these cameras are not designed for aerial surveys, the long-term stability of their calibration could be problematic and has to be well studied before using them in mapping.

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