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A Multi-Sensor System for Airborne Image Capture and Georeferencing

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Abstract

The development and preliminary testing of a fully digital multi-sensor system for airborne remote sensing and geographic information system (GIS) applications is described. This system was developed at The University of Calgary in collaboration with The University of California at Berkeley, with aircraft and logistics support by HJW Inc., California. It integrates a medium class inertial navigation system (INS), two low-cost Global Positioning System (GPS) receivers, and a high-resolution digital camera. During aerial image capture, camera exposure stations and INS digital records are time-tagged in real time by GPS. The INS/GPS-derived trajectory parameters describe the rigid body motion of the carrier aircraft. Thus, they are directly related to the parameters of exterior orientation. During post-processing, these parameters are extracted, eliminating the need for ground control for airborne image acquisition applications. Flight tests were performed over a part of the university campus at Berkeley, using a strip photography approach to test the integrated system performance. In this paper, the concept of direct georeferencing of digital images without ground control is presented. System calibration results are then discussed in some detail, and special attention is given to the geometrical analysis of the system imaging component. An improved imaging system is proposed and validated by computer simulations. The potential of the new system for photogrammetric use is then discussed. The major applications of such a system will be in photo ecometrics; the mapping of utility lines, roads, and pipelines; and the generation of digital elevation models for engineering applications.

Introduction

Over the past five years, the information demand for detailed forest composition and structure has increased markedly. Therefore, it became critically important to develop new remote sensing techniques that allow for the direct measurement of those parameters. Although satellite imagery is available (e.g., SPOT HRV, Landsat TM, etc.), low spatial resolution (typically, 10 to 30 m) is an obstacle to interpreting and extracting information with the required accuracy. Airborne imagery, on the other hand, resolves the low spatial resolution problem of the satellite imagery and yet provides sufficient spectral bands for remote sensing studies (Gong et al., 1998).

The main objective of this research is the development of a multi-sensor system for digital image capture and georeferencing for applications in airborne remote sensing as well as large scale digital mapping and geographic information system (GIS)

applications. The system is being developed as a joint research project between The University of Calgary and The University of California at Berkeley. Its major application will be in photo ecometrics of various vegetation species in forested areas where ground control is neither available nor needed, and where directly georeferenced digital imagery is acquired to solve the exterior orientation problem. In other words, system requirements are

- Fully digital data acquisition, and
- Direct georeferencing of the digitally acquired images without ground control points (GCPs).

Because of the advances in digital image acquisition technology, it became feasible to capture aerial or close-range images in fully digital form, which allows immediate computer access to the imagery after the acquisition process. Compared to film-based photos, digitally acquired imagery is advantageous because no time is needed for film development and image scanning.

Further, digital image processing and computer vision have been successfully utilized to facilitate automated procedures in digital aerial images such as interior orientation (Kersten and Haering, 1997), relative orientation (Schenk et al., 1991), and the generation of digital elevation models (Krzystek, 1991.) In addition, a number of sophisticated digital photogrammetric workstations are commercially available, e.g., Leica/Helava (DeVenecia et al., 1996).

Among the currently available image acquisition systems, still video digital frame cameras (DFCs), which started to emerge in the mid nineties, are the most convenient systems for aerial applications due to their freezing motion feature during exposure time. To reconstruct a three-dimensional (3D) model from 2D imagery acquired by DFCs, requires, in principle, only the modeling and estimation of the camera interior and exterior orientation parameters. DFCs have been extensively used in close-range applications utilizing self-calibration, network design optimization schemes, and sophisticated image processing techniques for target mensuration. Results have been reported by Beyer (1992), Peipe (1995), Fraser (1997), and Lichti and Chapman (1997).

In airborne applications, however, DFCs have not been frequently used due to limitations in geometry, resolution, and data rate. Current pixel resolution of commercial CCD chips is typically 7 to 15 μm, which is almost the same as that of a scanned image from a film image. DFCs performance has been analysed in tests and results have been reported in King et al. (1994), Mills et al. (1996), and Maas and Kersten (1997). Pixel resolution, on the other hand, is not a major problem for the

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applications planned at present, which are in forestry ecome-trics. Current accuracy is sufficient to capture detailed forest structure and composition and seasonal variations, which are the important factors to be studied.

On the other hand, direct georeferencing by combining the Global Positioning System (GPS) with an inertial navigation system (INS) has received significant attention over the past few years in land-based and airborne applications. See Schwarz *et al.* (1993) for the mathematical model and proposed applications, and Lechner and Lahmann (1995), Schwarz (1995), El-Sheimy (1996), Škaloud *et al.* (1996), Cramer *et al.* (1997), Mostafa *et al.* (1997), Toth and Grejner-Brzezinska (1998), and Reid *et al.* (1998) for applications. Škaloud *et al.* (1996) demonstrated an accuracy of 0.3 m (RMS) horizontally and 0.5 m (RMS) vertically for ground points georeferenced by GPS/INS-derived position and orientation using 1:6000-scale optical photography in an aerotriangulation scheme. Lechner and Lahmann (1995) showed an agreement of 10 to 20 cm between camera exposure station positions determined independently using GPS/INS and traditional aerotriangulation by GCP using 1:2000-scale optical photography. However, careful consideration has to be given to the different geometries and resolution of digital cameras as compared to optical cameras before such an approach can be successfully implemented for digital cameras.

Recently, fully digital systems comprising GPS, INS, and digital image acquisition systems have been implemented. Independently, Cramer *et al.* (1997) and Mostafa *et al.* (1997) showed comparable results of positioning accuracy at the meter level for ground objects directly georeferenced by GPS/INS. Furthermore, The Ohio State University Center for Mapping started the development of the AIMS system for large scale mapping purposes (Toth and Grejner-Brzezinska, 1998).

Basic Concept of Direct Georeferencing

In the equations given below note that, except for orientation matrices, subscripts refer to a specific point, while superscripts account for the coordinate frame in which the coordinate component is given. Matrix subscripts and superscripts indicate the rotation from the subscript system to the superscript system. Uppercase letters refer to a mapping frame (M-frame), while lowercase letters refer to a camera frame (c-frame) as shown in Figure 1. Bold-faced lowercase letters are used for vectors, while bold-faced uppercase letters are used for rotation matrices. Furthermore, T denotes vector or matrix transposition, while *t* denotes time.

As shown in Figure 1, direct georeferencing of digital images can be described by the formula

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

where $\mathbf{r}_G^M$ is the georeferenced 3D position vector of an arbitrary object point *G* in the *M*-frame, which is expressed by

$$\mathbf{r}_G^M = (X_G^M \quad Y_G^M \quad Z_G^M)^T \tag{2}$$

while $\mathbf{r}_E^M(t)$ is the 3D position vector of coordinates of the exposure station *E*, at the instant of exposure, in the *M*-frame, represented by

$$\mathbf{r}_E^M(t) = (X_E^M(t) \quad Y_E^M(t) \quad Z_E^M(t))^T \cdot \tag{3}$$

$\mathbf{r}_g^c(t)$ is the 3D coordinate vector of the image point g in the *c*-frame, expressed by

$$\mathbf{r}_g^c(t) = (x_g^c(t) - x_o^c \quad (y_g^c(t) - y_o^c)/k_y \quad -f)^T \tag{4}$$

where $x_g^c(t)$ and $y_g^c(t)$ are the image point coordinates of the image point g corresponding to the arbitrary object point *G*; x_o^c,
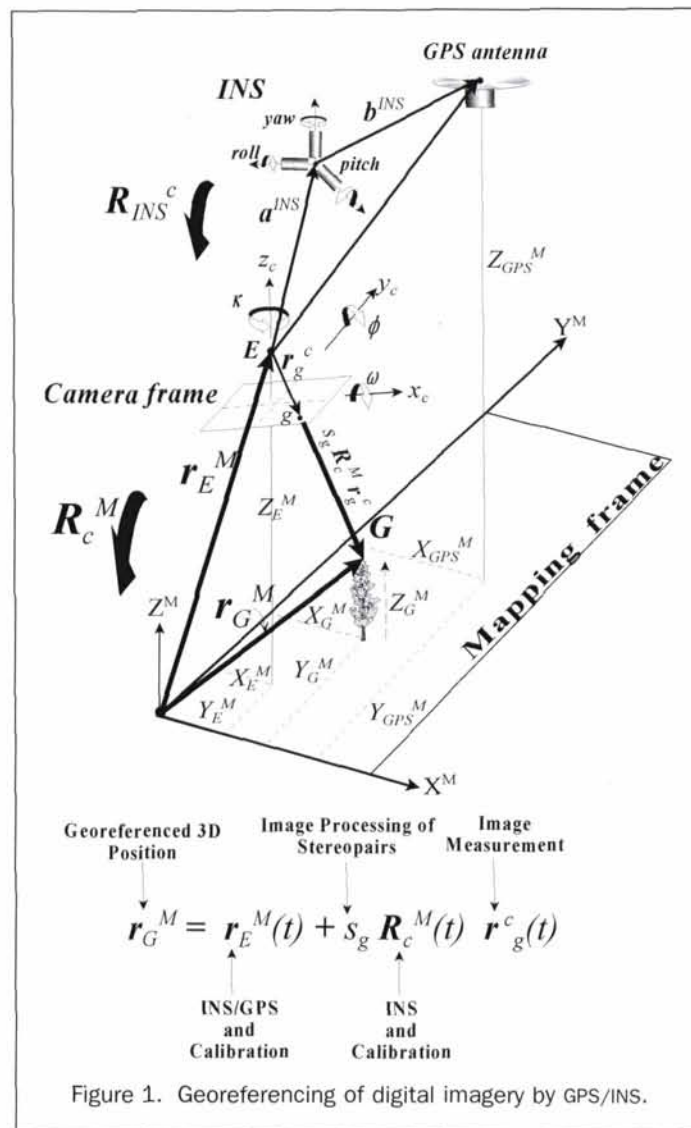

Figure 1. Georeferencing of digital imagery by GPS/INS.

y_o^c are the principal point offsets from the CCD format center; k_y is a factor accounting for the non-squareness of the CCD pixels; *f* is the calibrated focal length of the lens in use; s_g is an image point scale factor implicitly derived during the 3D photogrammetric reconstruction of objects using image stereopairs; and $\mathbf{R}_c^M$ is the orientation matrix rotating the *c*-frame into the *M*-frame utilizing the three *c*-frame orientation angles ω, ϕ, and κ, shown in Figure 1 (Moffit and Mikhail, 1980).

When using the direct georeferencing approach, the image plane orientation angles are independently computed by INS and, thus, the INS-derived attitude angles must be transformed to those angles using the formula

$$\mathbf{R}_c^M(t) = \mathbf{R}_{INS}^M(t) \, R_c^{INS} \tag{5}$$

where $\mathbf{R}_c^M(t)$ is previously defined; $\mathbf{R}_{INS}^M(t)$ is the INS-derived rotation matrix rotating the INS body-frame into the *M*-frame; R_c^{INS} is a transformation matrix which rotates the INS body-frame into the *c*-frame and will be called the INS/camera orientation offset from now on. $\mathbf{R}_{INS}^M(t)$ contains the attitude angles (roll, pitch, and yaw), derived from the INS/GPS integration scheme shown in Figure 2, using the KINGSPAD software of The University of Calgary. For details on the strapdown INS mechanization and GPS/INS integration modeling and error estimation, see Wei and Schwarz (1990) and Schwarz (1998), respectively.
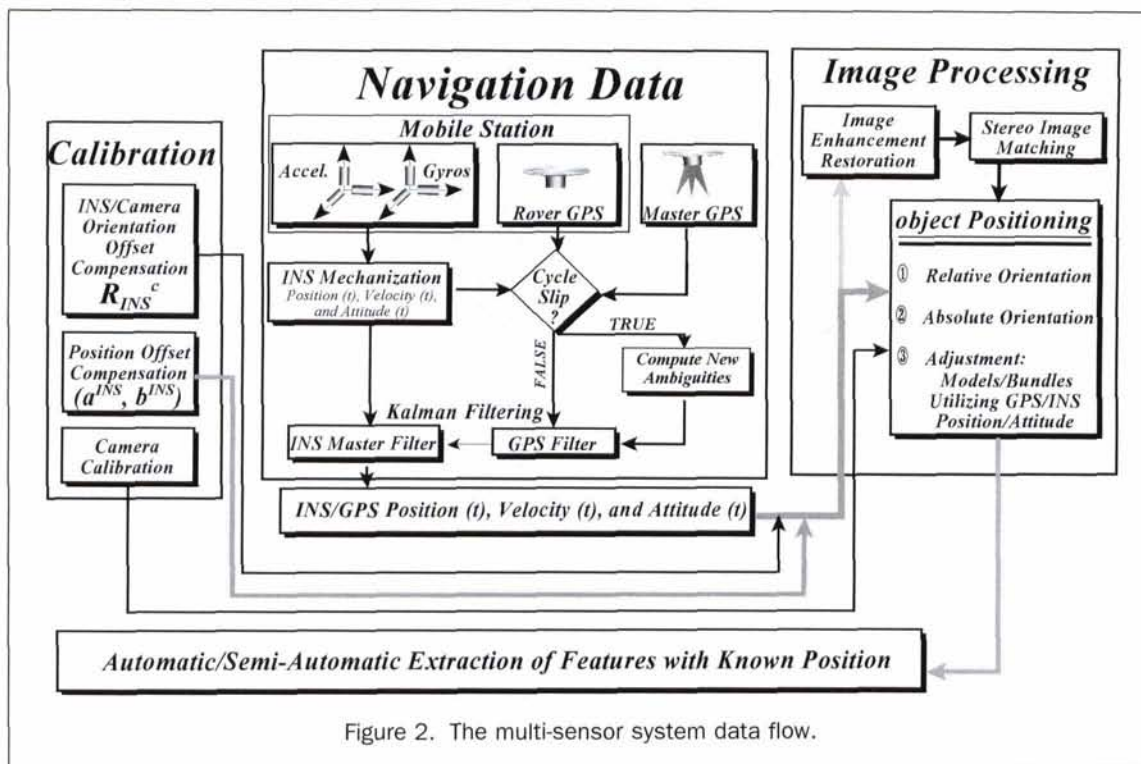
Figure 2. The multi-sensor system data flow.

Two methods can be used to compute the INS/Camera orientation offset, $\mathbf{R}_{INS}^c$. One approach is to measure such an offset using an additional onboard sensor. In this way, Equation 5 can be modified to accommodate $\mathbf{R}_{INS}^c$ as a function of time, and, thus, the INS and the camera can be allowed to mutually rotate. The second method is to ensure tight coupling of the INS and the camera during photography, thus keeping their orientation offset fixed over time. The orientation offset can be computed once per flight using a target field on the ground. If the INS and the camera are detached from their frame between flights, then the offset has to be computed for each flight. If the two sensors are permanently attached to their mount, such an offset is required only once after equipment installation and could be checked on a regular basis. This method is advantageous because the orientation offset is constant over time, which facilitates the ease of the photogrammetric 3D object reconstruction using the INS-derived attitude and such a constant offset. Its main drawback, however, is the need for in-flight calibration when using GCPs. This method was implemented to compute the INS/Camera orientation offset, and Equation 5 applies.

To be able to test the second method, special shock mounts were designed according to the idle, cruise, and climb RPM of the engines of the Cessna 310 airplane used in the flight tests. These shock mounts were installed on the plywood frame which connects the INS/Camera carrier rigid metal frame to the aircraft platform. Thus, the INS and the camera are tightly attached mutually but loosely attached to the aircraft platform. The shock mounts also helped to isolate the fragile camera from the strong aircraft vibrations.

Equipment Selection for Data Acquisition

The current system design is for a low-cost system. Therefore, two low-cost Ashtech SCA12 GPS receivers and a Kodak DCS 420m digital camera were selected as system components. Currently, The University of Calgary's Litton LTN 90-100 INS is used as the inertial component. Onboard the fixed wing airplane, the GPS receivers, the INS, and the digital camera were interfaced to two PCs, which control the different tasks required for data
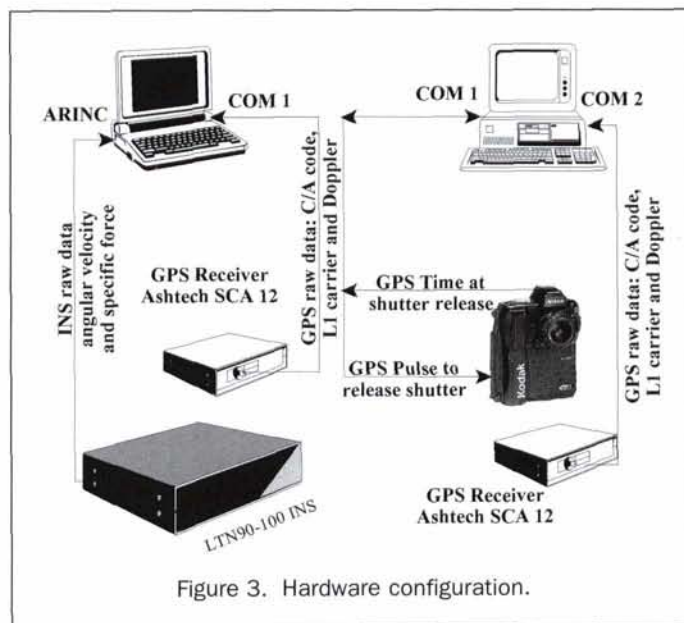

Figure 3. Hardware configuration.

acquisition, using data logging software developed at The University of Calgary, as shown in Figure 3.

The Multi-Sensor System Calibration

The overall system calibration is required to relate GPS-derived positions, INS-derived attitude parameters, and imagery-derived object point coordinates. In addition, the digital camera was calibrated at The University of Calgary using a self-calibrating free-network bundle adjustment software (Lichti and Chapman, 1997) to determine the camera interior geometry and the distortion parameters of the lens in use. Due to the lack of information about the low cost GPS receivers, a few static and
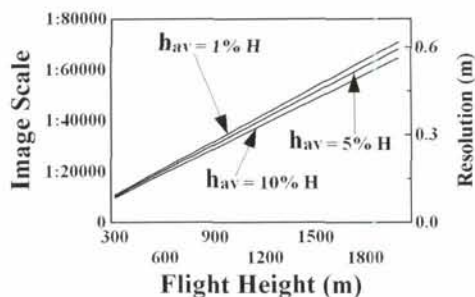
Figure 4. The DCS 420 digital camera average image scale and physical resolution for different flying heights and mean terrain elevations.

Figure 5. A Digital image acquired over the Berkeley Campus and its vicinity (Strip #3, Image #5).

kinematic tests were conducted in Calgary to analyze their performance; for details, see Mostafa *et al.* (1998a).

As indicated in Figure 1, the INS, the GPS antenna, and the digital camera cannot occupy the same spot in three-dimensional space. Furthermore, the INS-derived attitude angles (roll, pitch, and yaw) are in the coordinate system of the INS body-frame and they should be related to the image plane orientation angles (ω, ϕ, and κ) for use in Equation 1. Thus, before testing the system in flight, the GPS/INS/camera position offsets were surveyed at the HJW, Inc., hangar at the Oakland airport.

The aircraft was jacked up to obtain a leveled camera image plane, and a series of measurements were taken relative to that plane. The INS/Camera orientation offset was computed using the Leica/Helava Digital Photogrammetric Workstation (DPW) utilizing 18 GCPs and 32 tie points in a four by four block of images. Tie points were selected at building corners and road intersections. Elevation variations of 7 to 10 percent improved the recovery of the ω and ϕ angles as compared to using flat terrain. The Leica DPW allowed measurement of the image targets with an accuracy of 0.1 pixel.

Testing the Multi-Sensor System

Due to the small format size of the digital camera and its associated 28-mm lens, the average image scale is much smaller than that usually obtained using aerial optical photography for the same flying conditions. Figure 4 shows the physical pixel resolution of the CCD chip in use (corresponding to 9 μm) for different flight heights and different mean elevation (h_{av}) of ground objects. Two different spatial resolutions were therefore tested—one at a 500-m flying height and the other at a 1000-m flying height—which yielded image scales of 1:19,000 (approx. 15-cm pixel resolution) and 1:38,000 (approx. 30-cm pixel resolution), respectively. Three test flights were completed over two small areas of the Berkeley campus in January, 1997. The first area has a good distribution of GCPs (building corners, road intersection, etc.) as shown in Figure 5. This area has been mainly used for system calibration.

The second area has variable vegetation species and has been used in testing the system performance in the field of photo ecometrics. The flight test pattern is partially shown in Figure 6. Ground control information was extracted from HJW, Inc., 1:2400-scale aerial optical photography with an accuracy of 20 cm (std. dev.) in planimetry and 30 cm (std. dev.) in height, respectively.

Multi-Sensor System Performance

To test the direct georeferencing approach, 24 of the available GCPs were independently positioned using the exterior orientation parameters extracted from the INS/GPS-derived trajectory.
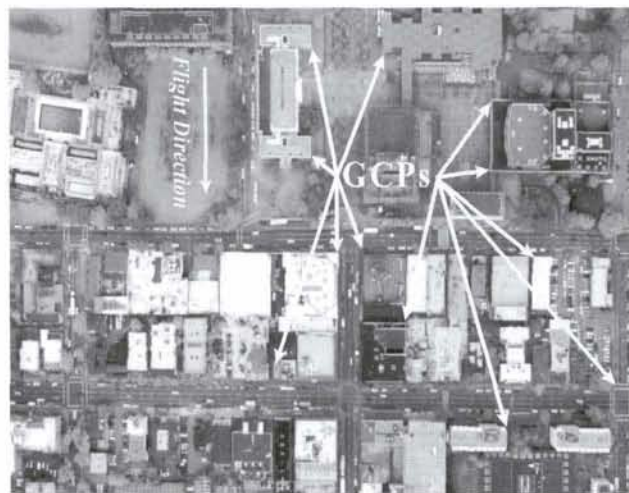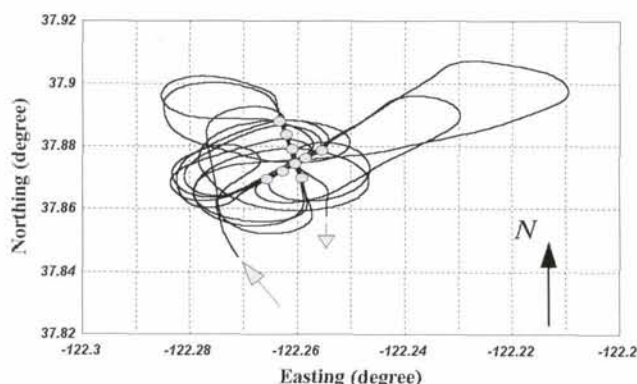

Figure 6. GPS/INS-derived flight test trajectory over the Berkeley Campus, January, 1997.

The system calibration parameters were applied to compensate for the camera interior geometry, camera lens distortions, GPS/INS/camera spatial position offsets, and INS/camera orientation offset. The reduced exterior orientation parameters where then introduced to a four by four block of images, along with their associated statistical measures, to independently compute the coordinates of those GCPs. The positioning accuracy for the 24 points is shown in Figure 7. The standard deviation for horizontal coordinates was 0.9 m and for height was 1.8 m. The interior orientation parameters were solved for during the adjustment to double check their stability after shipping the camera from Calgary (after camera calibration) to Berkeley (to conduct test flights).

System Error Analysis

The accuracy level shown in Figure 7 is poorer than the physical resolution (30 cm) of the pixel size of the sensor in use. There are three sources of errors which strongly affect the overall system accuracy: the accuracy of the navigation component, the resolution and geometry of the imaging component, and the overall system calibration. Figure 8 depicts those factors in some detail. The imaging component and the system
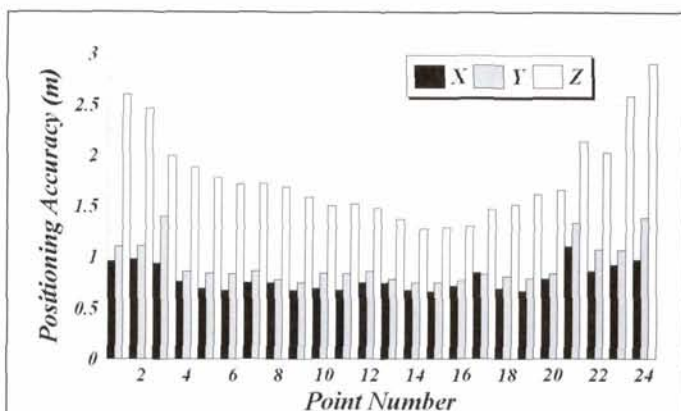
Figure 7. The multi-sensor system overall accuracy derived from comparing the coordinates of 24 known GCPs with those obtained from direct georeferencing by GPS/INS.

overall calibration are largely responsible for the deterioration of the positioning accuracy shown in Figure 7. This is due to the fact that the small format of the DFC affects the quality of the photogrammetric space resection and space intersection.

The quality of space resection becomes a problem when computing the image plane orientation angles of a small block using GCPs that have been used for computing the INS/camera orientation offset (see Equation 5). To resolve the space resection problem (due to the narrow space resection cone), a larger format DFC should be used (e.g., 2k by 2k, 2k by 3k, etc.). This would slightly improve the quality of space resection to recover the orientation angles using GCPs of higher precision. The quality (e.g., geometry, measurement accuracy) of space intersection, on the other hand, directly affects the accuracy with which ground object positions are determined. This is dependent on the base/height ratio, or, in other words, on the angle of intersection (I) between individual camera exposure stations and an arbitrary single ground object as shown in Figure 9. The wider the intersection angle, the better the geometry of space intersection, and the higher the precision of position determination, especially for the height component. Figure 10 shows a comparative study between the Kodak DCS 420m used in the current system design (1524- by 1012-pixel format size and 28-mm focal length) and a typical aerial optical camera (9- by 9-
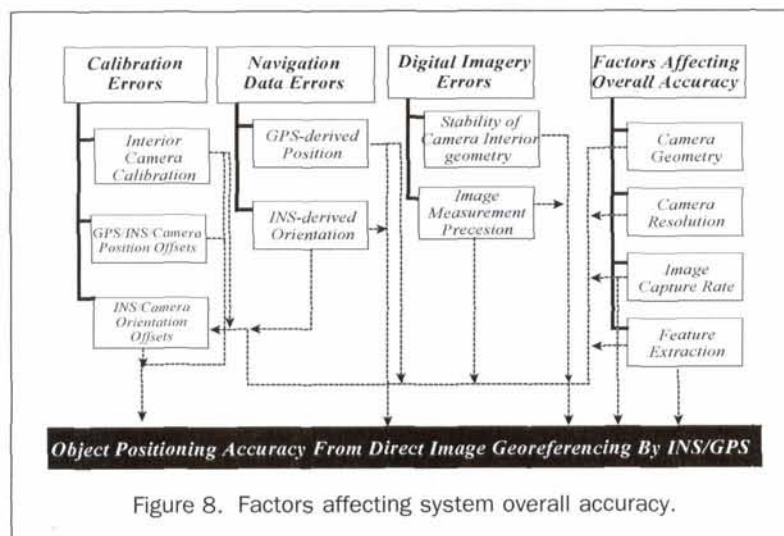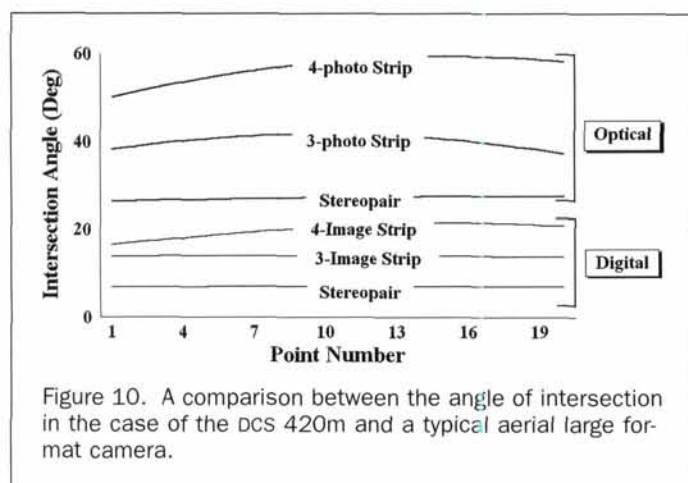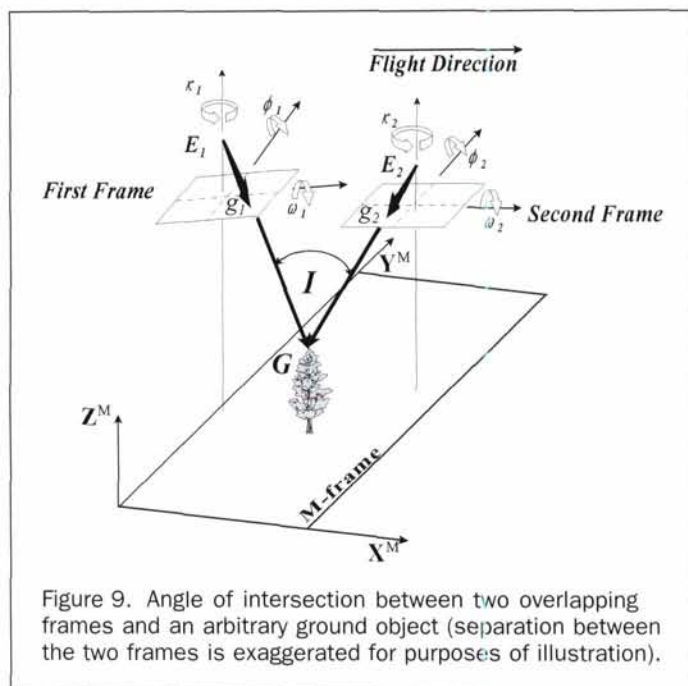
inch format size and 6-inch focal length) for stereopairs and strips of three and four images, respectively. It is obvious that the large format optical camera yields a much wider convergence angle and, thus, much better geometry. In the case of a DFC, however, the convergence angle is much narrower and its maximum is 20°, which yields a very narrow cone of space intersection.

Improved Imaging Component Design and Validation Using Computer Simulataions

The previous section addressed the poor geometry of the small format DFCs. To resolve such a geometric problem, a much wider intersection angle than that shown in Figure 10 is required. Using the largest format DFC commercially available (e.g., 4k by 4k) for vertical image capture will give a fairly stronger geometry because it strengthens both space resection and intersection. However, it will not result in a geometry that matches that of the optical cameras, especially for height determination.

Besides using a higher resolution digital camera, the imaging component of the system can be improved by including more than one digital camera. This solution will not only improve the data rate, but will also dramatically improve the geometry, especially when one of these cameras is mounted forward or aft looking. For forestry applications, the number and height of the trees will be recovered more accurately using low-oblique imagery in conjunction with near-vertical imagery. The main idea of using a stereopair consisting of a vertical image and an oblique image is to achieve a wider intersection between ground objects and the camera exposure stations. Such a wide intersection cannot be achieved in vertical images unless a very large format such as a scanned analog diapositive (e.g., 15k by 15k) is used. A two-camera imaging component with vertical and forward-looking camera consists of a master and a slave camera. The master camera will be taken as the vertical camera. Its imagery will be used in routine work, such as 3D positioning of objects in its field of view (FOV #1), as shown in Figure 11. Overlapping vertical imagery, in this case, processed as stereopairs, strips, or blocks using an available workstation such as the Leica DPW. The main function of the slave camera imagery is to enhance the geometry for positioning of objects that appear in both vertical and oblique imagery.

As shown in Figure 11, images from the master and the slave cameras, over two epochs of time, will be combined during processing. At time t_1, a ground object (e.g., a tree) will appear in the slave camera field of view (FOV #2) and thus will be cap-

Figure 8. Factors affecting system overall accuracy.

Figure 9. Angle of intersection between two overlapping frames and an arbitrary ground object (separation between the two frames is exaggerated for purposes of illustration).

Figure 10. A comparison between the angle of intersection in the case of the DCS 420m and a typical aerial large format camera.

Figure 11. Vertical and forward looking imaging component.

Figure 12. Positioning accuracy using the vertical and forward-looking imaging component.

tured in an oblique image shown in image #2. At time t_2, the same ground object will appear in the field of view of the master camera (FOV #1) and thus will be captured in a near vertical image shown in image #1. In post-processing mode, both images can be used to recover any metric information concerning the imaged scene such as tree height, stem thickness, and other classification aspects. The master camera should provide a higher resolution and better data rate than the slave camera. This is due to the fact that the oblique imagery is only needed for point-based processing because of the difficulty of stereo matching; for details, see Shufelt (1996.) The vertical imagery, however, will be used in stereo operations and should have good overlap and be of higher resolution and greater bit quantization. Computer simulations were done to validate this idea. Table 1 shows the different parameters involved in the simulations.

As a sample of this computer simulation, a small 6 by 6 block of images was simulated with a standard forwardlap of 60 percent and sidelap of 40 percent. Mean elevation variation was simulated as 10 percent of the flight altitude (1000 m) to enhance the geometry for recovering ω and ϕ angles. It was
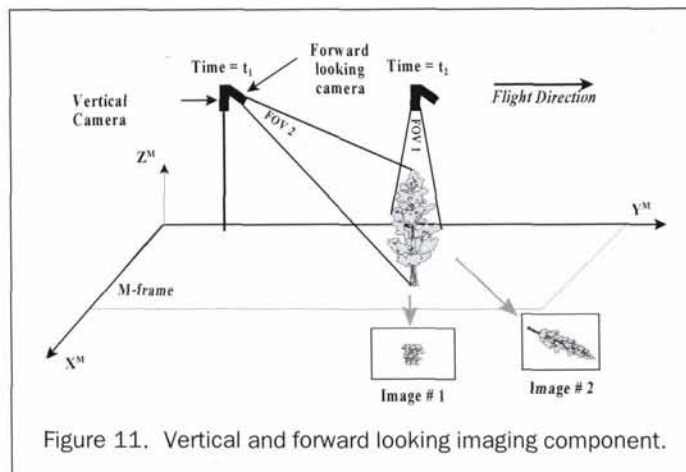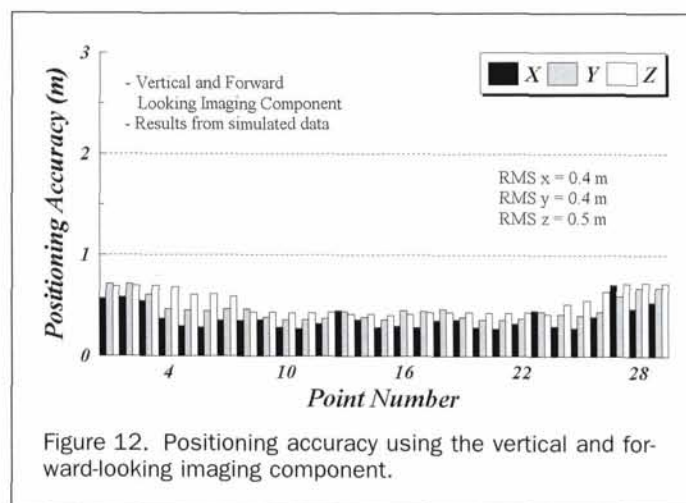
assumed that oblique imagery with an obliquity angle of 20° was available for each second or third vertical image. Two cross strips were also simulated with six vertical images and three oblique images per strip. They were added to enhance the geometry (space intersection) perpendicular to the direction of flight. In this way, the entire block is covered by vertical and oblique imagery along and across the flight direction. GPS/INS statistical measures together with the simulated exterior orientation parameters, GCPs, and image point measurements were introduced into the bundle adjustment program (Lichti and Chapman, 1997) to solve for the GCPs. Figure 12 shows the estimated GCP accuracies. It is obvious that the height component of GCPs

dramatically improved by a factor of 3.5, while the horizontal (easting and northing) were improved by a factor of 2.

Summary and Future Work

The design and testing of a fully digital airborne system integrating INS/GPS/Digital camera has been described and preliminary test results have been discussed. Accuracies currently achieved are at the level of 0.9 m (horizontal) and 1.8 m (vertical) for untargeted ground points (road intersection, building corners). The error analysis showed that a major improvement in the system overall accuracy can be obtained by using an additional forward-looking camera to strengthen the geometry of the photogrammetric space intersection and, thus, improve the ground point positioning accuracy, especially for elevations. Computer simulations show that submeter accuracy for all coordinates can be achieved when using the proposed imaging component. Further investigations are needed to determine the best obliquity angle, overlap, sidelap, mean terrain elevation, the effect of imposing relative orientation constraints between vertical and oblique imagery on the adjustment process, etc. Flight tests with the proposed system have recently been conducted over The University of Calgary campus and are currently being evaluated.

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