Development and Testing of an Airborne Remote Sensing Multi-Sensor System

Mohamed M. R. Mostafa, Klaus-Peter Schwarz, and Michael A. Chapman

Department of Geomatics Engineering
The University of Calgary
Calgary, Alberta, Canada

ISPRS Commission II, Working Group 1

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ABSTRACT

This paper describes the development and testing of a fully digital multi-sensor system for remote sensing and GIS applications. 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., CA. It integrates a medium class INS, two low-cost GPS receivers, and a high resolution digital camera. The digital camera captures strips of overlapping vertical images. Camera exposure stations and INS digital records are time-tagged in real time by the GPS pulse. 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 in 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 ofdigital images without ground control is presented. System calibration results are then discussed in some detail. Geometrical analysis of the system imaging component is addressed and an improved imaging component 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, mapping of utility lines, roads, pipelines, and the generation of digital elevation models for engineering applications.

1. INTRODUCTION

Te main objective of this research is to develop a multi-sensor system for digital image capture and georeferencing for applications in Remote Sensing, Digital Mapping, and GIS. Such a system is currently developed in a joint research project between The University of Calgary and The University of California at Berkeley. Its major application will be in remote sensing of various vegetation species in 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:

1. Fully digital data acquisition; and
2. Direct georeferencing of the digitally acquired images without Ground Control Points (GCPs).

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

Further, information extraction from digital imagery is already a well established field and many sophisticated digital image processing algorithms have been successfully implemented in commercial digital photogrammetric and remote sensing software packages. Digital image acquisition using the currently available Digital Frame Cameras (**DFC**) is, therefore, an advantageous technique compared to analogue image acquisition as far as time and cost are concerned.

However, current pixel resolution of commercial CCD chips is typically 7-15 μm, which is almost an order of magnitude poorer than that of film. This is not a major problem for the applications planned at present which are in forestry ecometrics. Current accuracy is sufficient to capture seasonal variations which are the important factors to study. The system will thus be used for data acquisition for the same areas on a regular basis.

Cost-effectiveness will be achieved by eliminating the time, effort, and cost of establishing GCPs, developing photographic film, and performing the sophisticated and expensive photo measurements. It is estimated that 60% of the time, effort, and cost could be saved in this way.

Direct georeferencing by GPS/INS received significant attention over the past few years in land-based and airborne applications. (see Schwarz et al (1994) for the mathematical model and proposed applications and Schwarz (1995); El-Sheimy (1996); Skaloud et al (1996), Mostafa et al (1997), and Cramer et al (1997), for applications.)

Skaloud 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 optical photography in an aerotriangulation scheme. However, careful consideration has to be given to the different geometrical and resolution aspects 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 metre level for ground objects directly georeferenced by GPS/INS.

Furthermore, The Ohio State Center for Mapping started to develop the AIMS system for digital mapping purposes (c.f., Toth1997).

2. BASIC CONCEPT OF DIRECT GEOREFERENCING

In the sequel, note that except for the orientation matrices, any 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 an image frame (i-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 transposition, while t denotes time.

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

$$\mathbf{r}_G^M(t) = \mathbf{r}_E^M(t) + s_g\, \mathbf{M}_i^M(t)\, \mathbf{r}_g^i(t) \qquad (1)$$

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

$$\mathbf{r}_G^M(t) = \begin{pmatrix} X_G^M(t) & Y_G^M(t) & Z_G^M(t) \end{pmatrix}^T \qquad (2)$$

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:

$$\mathbf{r}_E^M(t) = \begin{pmatrix} X_E^M(t) & Y_E^M(t) & Z_E^M(t) \end{pmatrix}^T \qquad (3)$$

$\mathbf{r}_g^i(t)$ is the 3D position vector of coordinates of the image point g in the i-frame, expressed by:

$$\mathbf{r}_g^i(t) = \begin{pmatrix} x_g^i(t) - x_o^i & (y_g^i(t) - y_o^i)/k_y & -f \end{pmatrix}^T \qquad (4)$$

where $x_g^i(t)$ *and* $y_g^i(t)$ are the image point coordinates of the image point g corresponding to the arbitrary object point G; x_o^i, y_o^i 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 $\mathbf{M}_i^M$ is the orientation matrix rotating the i-frame into the M-frame utilizing the three i-frame orientation angles ω, ϕ, and κ, shown in ***Figure 1*** (cf., 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:

$$\mathbf{M}_i^M(t) = \mathbf{R}_{INS}^L(t)\, \mathbf{M}_i^{INS} \qquad (5)$$

where $\mathbf{M}_i^M(t)$ is previously defined; $\mathbf{R}_{INS}^L(t)$ is the INS-derived rotation matrix rotating the INS body-frame into the local level frame; $\mathbf{M}_{INS}^i$ is a transformation matrix which rotates the INS body-frame into the i-frame and will be called the INS/Camera orientation offset in the sequel. $\mathbf{R}_{INS}^L(t)$ 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.

Two methods can be used to compute the INS/Camera orientation offset, $\mathbf{M}_{INS}^i$. One approach is to measure such an offset using an additional onboard sensor (Schwarz et al, 1994).

This way, ***Equation** 5* can be modified to accommodate $\mathbf{M}_{INS}^i$ 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 and, thus, their orientation offset can be held fixed over time.

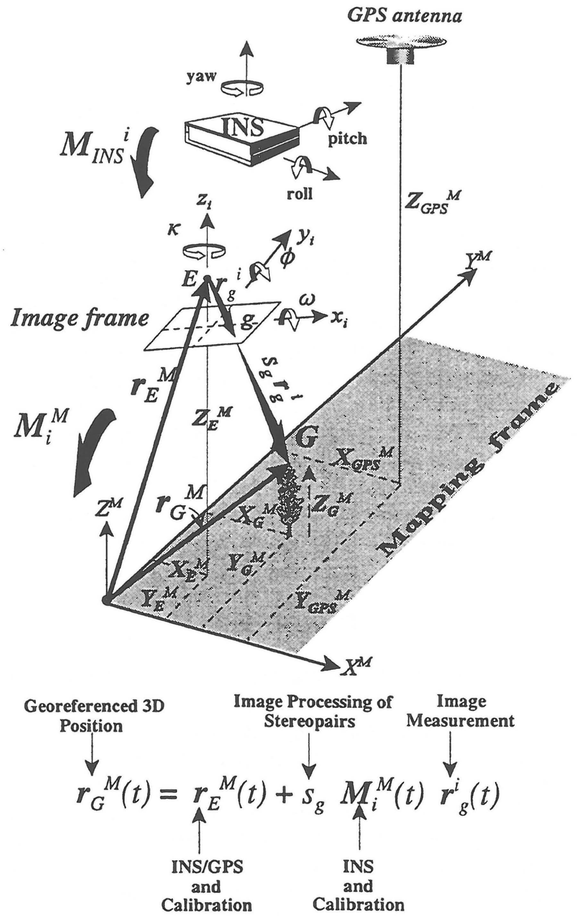

Figure 1. Georeferencing of a Digital Image by GPS/INS

Then, the orientation offset can be computed once per flight using a target field, if the INS and the camera are detached from their frame between flights. If the two sensors are permanently attached to their metal frame, such an offset is required to be computed only once after equipment installation and could be checked on a yearly basis. This method is advantageous since 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 of in-flight calibration using GCPs. This method was implemented to compute the INS/Camera orientation offset and ***Equation** 5* will apply.

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 in 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 vibrational environment.

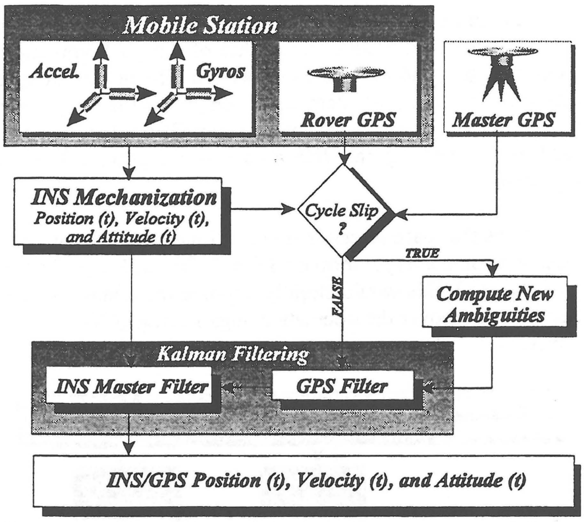

Figure 2. GPS/INS Loosely Coupled Integration Scheme implemented in The KINGSPAD Software of The University of Calgary

3. EQUIPMENT SELECTION FOR DATA ACQUISITION

The current system design is for a low cost system. Therefore, two low-cost Ashtech SCA12 GPS sensors 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. It will be replaced by a low-cost INS in the future. Onboard the fixed wing airplane, one of the GPS receivers, the INS, and the digital camera were interfaced to two PCs, which control the different tasks required for data acquisition, using data logging software developed at The University of Calgary.

4. 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 is calibrated at The University of Calgary using a self-calibrating free-network bundle adjustment software (Lichti and Chapman, 1996) 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 kinematic tests were conducted in Calgary to analyze their performance. As shown in ***Figure 1***, the INS, the GPS antenna, and the digital camera cannot occupy the same spot in three dimensional space. Further, the INS derived attitude angles (roll, pitch, and yaw) are coordinatized in the INS body-frame and they should be related to the image plane orientation angles (ω, ϕ, and κ) for using ***Equation 1***.

Thus, before testing the system in flight, the GPS/INS/camera position offsets were surveyed at the HJW 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 Digital Photogrammetric Workstation (DPW 77) utilizing 18 GCPs and 32 tie points in a small block of 4 x 4 images. Tie points were selected as building rooftops and road intersections to have an elevation variations of up to 7% to be able to recover the ω and ϕ angles with higher precesion than that of using a flat terrain. The DPW 77 was able to mensurate the image targets with an accuracy of 0.1 pixel.

5. 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 3*** shows the physical pixel resolution of the CCD chip in use (corresponding to 9 µm) for different flight heights and different mean elevation of ground objects.

Two different spatial resolutions were therefore tested, namely, one at 500 m and the other at 1000 m flying height which yielded an image scale of 1:19,000 (approx. 15 cm pixel resolution) and 1:38,000 (approx. 30 cm pixel resolution), respectively.

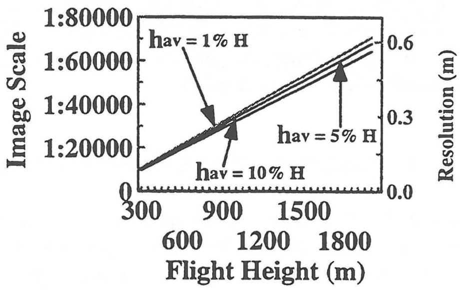

Figure 3. The DCS 420 Digital Camera Average Image Scale and Physical Resolution for Different Flying Heights and Mean Terrain Elevations

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 4***.

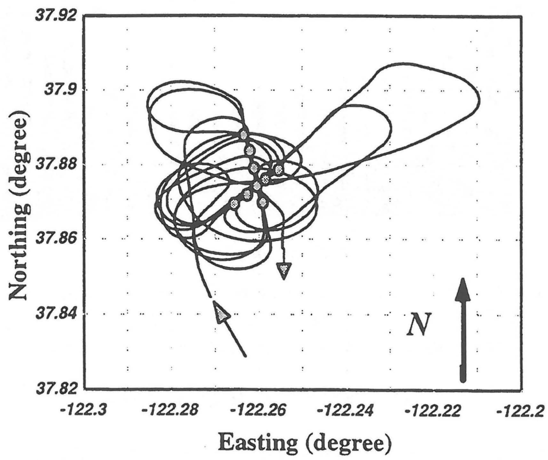

Figure 4. GPS/INS-derived Flight Test Trajectory over Berkeley Campus, California, January, 1997

Ground control information were extracted from HJW 1:2400 aerial optical photography and with an accuracy of 20 cm (std. dev.) in the planimetry and 30 cm (std. dev.) in the vertical, respectively.

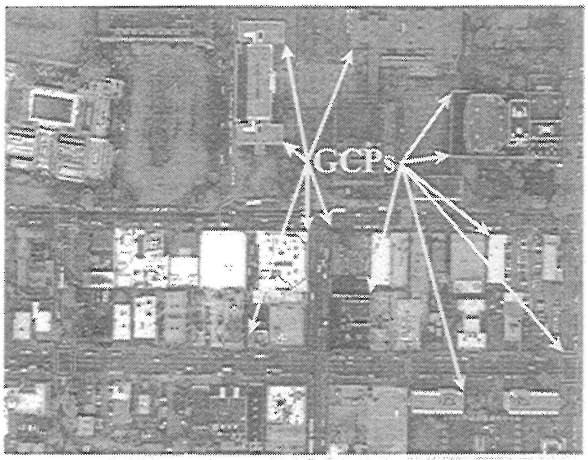

Figure 5. A Digital Image Acquired over Berkeley Campus and its vicinity (Strip #3, Image#5)

6. MULTI-SENSOR SYSTEM PERFORMANCE

To test the direct georeferencing approach, 24 points of the available GCPs have been independently positioned using the exterior orientation parameters extracted from the INS/GPS-derived trajectory. 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 block of 4 x 4 images, along with their associated statistical measures, to independently compute the coordinates of those GCPs. The positioning accuracies for the 24 points are shown in ***Figure 6.***. The stadndard deviation for horizontal coordinates is 0.9 m and 1.8 m for height. The interior orientation parameters were solved for during the adjustment.

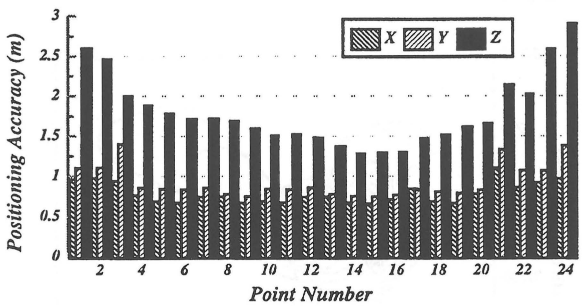

Figure 6. The Multi-Sensor System Overall Accuracy derived from comparing the coordinates of known 24 GCPs with those obtained from direct georeferencing by GPS/INS

7. SYSTEM ERROR ANALYSIS

The accuracy level shown in ***Figure 6*** 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; namely, the accuracy of the navigation component, the resolution and geometry of the imaging component, and the overall system calibration. ***Figure 7*** depicts those factors in some detail.

The imaging component and the system overall calibration are largely responsible for the deterioration of the positioning accuracy shown in ***Figure 6***. This is due to the fact that the small format of the DFC affects the quality of the photogrammetric space resection and the 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 will be used (e.g., 2k x 2k, 2k x 3k, etc.) This would slightly improve the quality of space resection to recover the orientation angles using GCPs of higher precision.

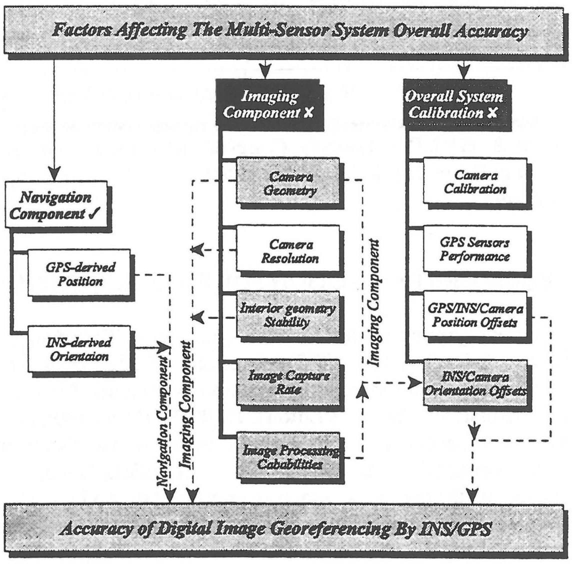

Figure 7. Factors Affecting the Multi-sensor System Overall Accuracy

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 convergence between individual camera exposure stations and an arbitrary single ground object as shown in ***Figure 8.***

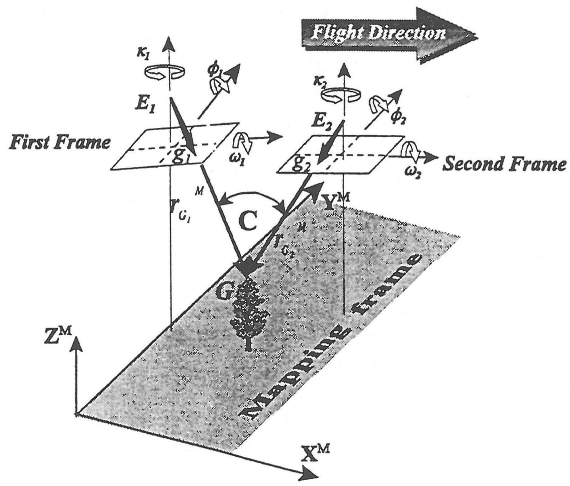

Figure 8. Angle of Convergence between two overlapped frames and an arbitrary ground object (separation between the two frames is exaggerated for purpose of illustration)

The wider the convergence angle the better the geometry of space intersection, the higher the precision of position determination, especially for the height component. ***Figure 9*** shows a comparative study between the Kodak DCS 420m used in the current system design (1524 x 1012 pixel format size and 28 mm focal length) and a typical aerial optical camera (9" x 9" format size and 6" focal length) for stereopairs and strips of 3 and 4 images, respectively. It is obvious that the large format optical camera yields much wider convergence angle and, thus, much better geometry. In specific cases, the Base/Height ratio can be even >1.0. 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.

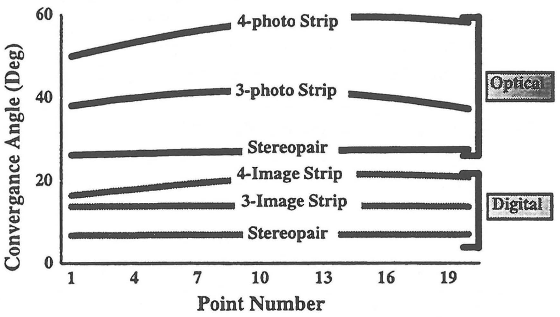

Figure 9. A Comparison Between The Angle of Convergence in Case of DS 420m and typical aerial Large format Camera

8. IMPROVED IMAGING COMPONENT DESIGN AND VALIDATION USING COMPUTER SIMULATIONS

Section 7 addressed the poor geometry of the small format DFCs. To resolve such a geometric problem, a much wider convergence angle than that shown in ***Figure 9*** is required. Using the largest format DFC commercially available (e.g., 4k x 4k) for vertical image capture will gain a slightly stronger geometry since it strengthens both space resection and intersection. However, it will not result in a performance that matches that of the optical cameras, especially for height determination.

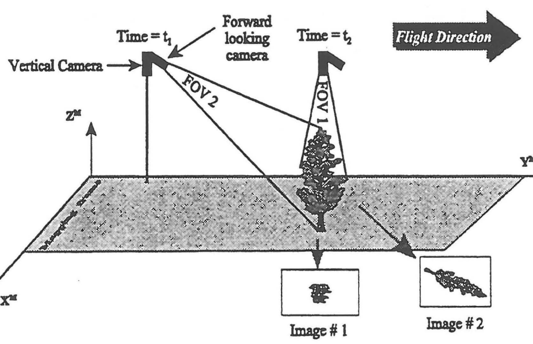

Figure 10. Vertical and Forward Looking Imaging Component

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 of a vertical image and an oblique image is to achieve wider convergence between the camera exposure stations and ground objects. Rapid convergence could not be achieved in vertical images unless a very large format such as a digitized analogue diapositive (e.g., 15k x 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), shown in ***Figure 10***. Vertical imagery, in this case, will be processed as stereopairs, strips, or blocks using an available workstation such as Leica DPW 77.

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 10***, 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 captured 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 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 any stereo matching process using this imagery. 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

flight height	*300, 350, 400, ...2000 m*
DFC format size	*3048 x 2036 (vertical)* *1524 x 1012 (oblique)*
average image scale	*1:10 000 - 1: 70 000*
focal length	*28 mm (vertical and oblique)*
overlap	*60%, 70%, 80%, and 85%*
sidelap	*40%, 50%, 60%, and 65%*
# of GCPS	*81 (9 x 9)*
average # of points/image	*6 - 9*
mean elevation	*1%, 5%, 10%, 15% of flight height*
# of exposures	*lap-dependent*
obliquity angle	*10°, 15°, 20°, 25°, 30°, and 40°*
image measurement precision	*0.1 pixel (vertical imagery)* *0.289 pixel (oblique imagery)*

Table 1. Simulated Data Parameters

As a sample of this computer simulation, a small block of 6 x 6 images was simulated with standard lap of 60% endlap, and 40% sidelap. Mean elevation variation was simulated as 10% of the flight altitude (1000 m) to enhance the geometry for recovering ω and ϕ angles, which could be easily attained in urban areas (e.g., downtown in large cities).

Oblique imagery with an obliquity angle of 20° was simulated to be available where every two or three vertical imagery has been taken. Two cross strips were also simualted with 6 vertical images and 3 oblique images per strip. They were added to enhance the geometry (space intersection) perpendicular to the direction of flight. 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 to the bundle adjustment program (Lichti and Chapman, 1996) to solve for the GCPs. ***Figure 11*** shows the estimated GCP accuracies. It is obvious that the height component of GCPs dramatically improved by a factor of 3.5. The horizontal (easting and northing) were also improved by a factor of 2.

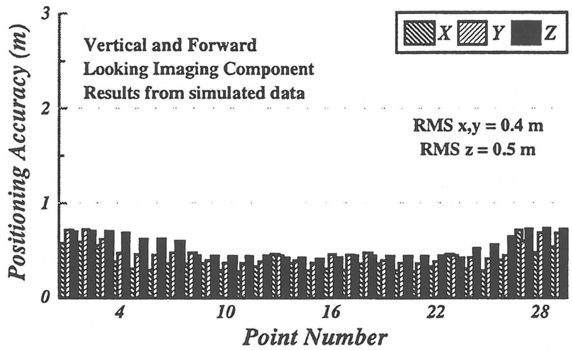

Figure 11. Positioning Accuracy using the vertical and forward-looking imaging component

9. CONCLUSIONS AND FUTURE WORK

The design and testing of an airborne fully digital 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 untargetted ground points (road intersection, building corners). The error analysis showed that major improvement in the system overall accuracy can be obtained 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 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 orientaion constraints between vertical and oblique imagery on the adjustment process, etc. Flight tests with the new system are planned for later this year.

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