High Accuracy Autonomous Image Georeferencing Using a GPS/Inertial-Aided Digital Imaging System

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BIOGRAPHY

Alison Brown is the President and CEO of NAVSYS Corporation. She has a PhD in Mechanics, Aerospace, and Nuclear Engineering from UCLA, an MS in Aeronautics and Astronautics from MIT, and an MA in Engineering from Cambridge University. In 1986, she founded NAVSYS Corporation. Currently she is a member of the GPS-III Independent Review Team and Scientific Advisory Board for the USAF and serves on the GPS World editorial advisory board.

Dan Sullivan is a Senior Engineer at NAVSYS Corporation. He is responsible for GPS/INS Integration mission area algorithms, architecture and software. Previously he was employed as a Senior Staff Engineer with Lockheed Martin Missiles and Fire Control in Orlando, Florida, where he was responsible for systems analysis and design for image-processing, target state estimation and sensor fusion for a variety of missile, fixed-wing and rotary-wing targeting systems. He has a MS in Electrical Engineering from Columbia University.

ABSTRACT

This paper describes the implementation of a GPS/Inertial integrated navigation system, the GI-Eye, that is designed to automatically georeference imagery collected from a digital camera without requiring any ground control for registration. This is accomplished through the use of Wide-Area DGPS (WADGPS) GPS updates, combined with NAVSYS' tightly coupled GPS/inertial alignment software to provide both the precise location and the precise attitude of the digital image when the data is collected. Using this information, the GI-Eye system can georeference features extracted from airborne imagery to meter-level accuracy.

The system design has been used in both airborne and ground-based survey applications, with the resulting imagery and associated navigation data used to geolocate reference points and to produce ortho-rectified and registered airborne imagery. In this paper, flight test results of the GI-Eye are included demonstrating the precision geolocation performance and the ability to perform autonomous image rectification and georegistration without requiring any ground control points.

INTRODUCTION

This paper describes the design and implementation of a GPS/Inertial navigation system that provides a tightly coupled navigation solution time-aligned with imagery collected from a digital camera. The system design has been used in both airborne and ground-based survey applications, with the resulting imagery and associated navigation data used for target geo-location and to produce ortho-rectified and registered airborne imagery. Examples of image rectification and target geo-location performance are provided.

SYSTEM ARCHITECTURE

The GI-Eye II™ system design is an improvement and generalization of the original NAVSYS GI-Eye™ system[1]. To improve the flexibility of the system to varying user requirements, the software architecture has been redesigned to take advantage of improved user interface and software component technology available with a modern PC operating system (Windows 2000) and object-oriented language (C++). The processing consists of two main stages: real-time data logging and navigation, and a post-processing suite for exploiting the collected imagery and navigation data. Figure 1 shows these components.

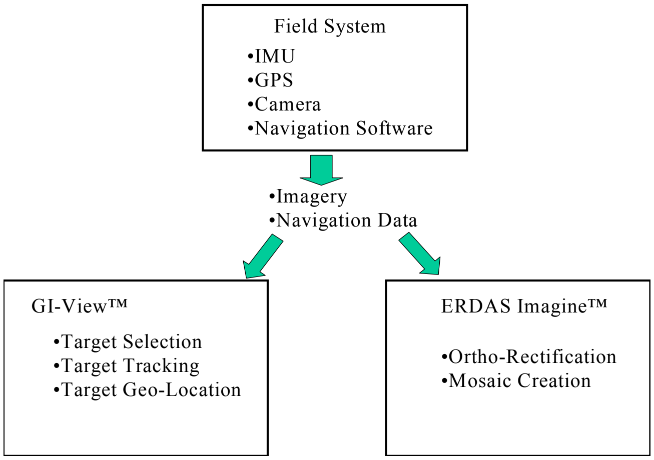

Figure 1 GI-Eye System Components

For applications that require it, an interface to the ERDAS Imagine™ software allows post-processing of collected imagery with the navigation control data attached to it. Through its OrthoBase package, Imagine can use the provided external control data associated with the imagery to rectify and geo-register the data. The availability of high-quality external control (i.e., navigation data) means that the process of rectifying and geo-registering the imagery is greatly eased.

For applications which do not require rectified imagery, but are interested in locating objects in the imagery (surveying and targeting applications), the NAVSYS GI-View™ software allows a user to browse the imagery, select desired target features, and generate geo-coordinates for them by performing a least-squares estimation process. The resulting target coordinates are output in a Microsoft Access database.

In the field system, a component-based software architecture allows a variety of system configurations of devices to be integrated into the same software, depending on the application requirements. Figure 2 shows the layout of the software. Each device is provided with a custom interface module, which provides a uniform data and behavioral interface to the rest of the system. It is thus a simple matter to change cameras or other external devices for a specific application's requirements.

The purpose of the system is to provide a tightly-coupled GPS/Inertial navigation solution (position, velocity and attitude). This navigation data is time-aligned to the imagery by making use of the "event-mark" capability of most GPS receivers. Most digital cameras have the capability to provide a hardware "strobe" signal, which can be sent to the GPS receiver. The receiver then produces a message with the exact GPS timestamp corresponding to the image. This allows the system to provide accurate navigation data associated with each image

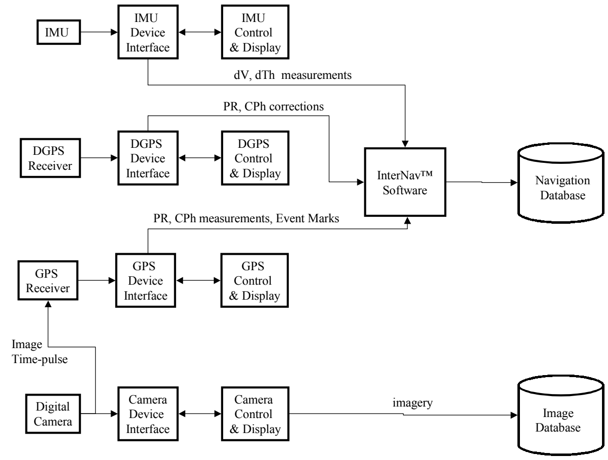

Figure 2 GI-Eye II Software Architecture

The system can process differential corrections (in RTCM SC104 format) from a variety of sources, or can be run in non-differential mode. The InterNav™ component performs the algorithm operations necessary to integrate the available measurements into a common navigation solution. It can process raw GPS range measurements or receiver-computed position and velocity, including Real-Time Kinematic (RTK) carrier-phase quality GPS position measurements.

NAVIGATION ALGORITHM DESIGN

The InterNav navigation software is responsible for combining the measurement data from the onboard IMU and GPS devices into a unified, tightly-coupled solution for position, velocity and attitude. It includes software to perform leveling and heading alignment. When initialized, the algorithms first perform a rough-leveling process, wherein they integrate the measured acceleration of the IMU to estimate the tilt (pitch and roll with respect to local-level) of the IMU. The navigation solution is initialized with the GPS position and velocity and the computed tilt. The heading of the platform is unknown at startup.

The system is mechanized as a local-level wander-azimuth terrestrial inertial navigator. Initially, the unknown heading is represented as unknown wander azimuth, with the navigation frame chosen to align the IMU X body axis with the initial navigation frame X axis. As the system moves and maneuvers, a velocity error with respect to the GPS-measured velocity (converted into the navigation frame using the erroneous wander-azimuth) builds up. This velocity difference is used in a Kalman filter to estimate the heading error of the platform. Table 1 shows the state definitions for the heading-alignment filter.

Table 1 Heading-Align Mode Kalman Filter States

State	Meaning
1-2	Tilt error (navigation frame)
3-4	Horizontal velocity error (navigation frame)
5	Error in sin(α)
6	Error in cos(α)
7-9	Accelerometer bias
10-12	Gyro Bias

When the heading-align filter converges to a solution for the wander-angle α (based on the filter covariance), the system transitions to Fine-Align navigation mode. In Fine-Align mode, another Kalman filter is instantiated. Since the navigation errors have been driven to reasonably small values during the alignment process, this filter can be implemented as a closed-loop "error state" filter integrated with the strapdown navigation system. It has additional states representing the IMU and GPS device errors; the state dynamics in the filter are linearized about the current navigation solution state for position, velocity and attitude. The estimated IMU and INS errors are fed back to the navigation system to correct both the inertial navigation solution and the incoming IMU and GPS measurement data for device biases and other errors. Figure 3 shows the operation of the navigation system once it has been aligned, and The output of InterNav is a computed solution for position, velocity and attitude of the camera platform at any desired time during the system operation. It has the capability to log all its inputs and outputs for replay, post-processing and debug. Additionally, it includes code to compute the navigation solution at a time corresponding to a collected image, convert the navigation data from the IMU body frame to the camera frame and output the image navigation data in a form suitable for later processing with GI-View, ERDAS Imagine, or custom post-processing code.
Table 2 shows the filter state-vector definition in this mode.

The filter works by correlating position and velocity differences between the INS solution and the GPS pseudo-range and delta-range measurements (suitable corrected for GPS antenna lever-arm effects), with errors in both the navigation solution and in the IMU device errors that caused the errors in the first place. This "tight coupling" between the IMU and GPS data means that the navigation solution has lower error overall, while maintaining the high-dynamics navigation capability of the INS solution.

When carrier-phase-derived GPS position measurements are available, the InterNav Kalman filter can exploit the extremely low measurement noise (~1 cm 1σ) of the GPS Real-Time Kinematic (RTK) data to further tighten the navigation solution. This improved attitude accuracy (due to the coupling between position/velocity accuracy and attitude accuracy), coupled with a highly accurate position solution, is suitable for survey applications.

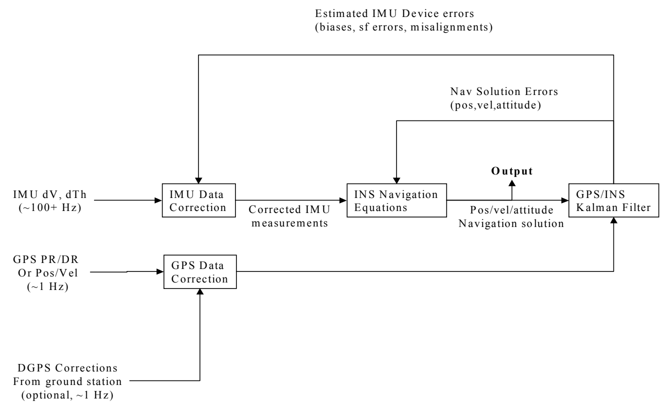

Figure 3 Fine-Align Mode Navigation Architecture

The output of InterNav is a computed solution for position, velocity and attitude of the camera platform at any desired time during the system operation. It has the capability to log all its inputs and outputs for replay, post-processing and debug. Additionally, it includes code to compute the navigation solution at a time corresponding to a collected image, convert the navigation data from the IMU body frame to the camera frame and output the image navigation data in a form suitable for later processing with GI-View, ERDAS Imagine, or custom post-processing code.

Table 2 Fine-Align Kalman Filter States

State	Meaning
1-3	Position Error (navigation frame)
4-6	Velocity Error (navigation frame)
7-9	Body Attitude Error (navigation frame)
10-12	Accelerometer bias error
13-15	Gyro bias error
16	GPS Clock bias error
17	GPS Clock frequency error
18-26	Accelerometer misalignment & sf error
27-32	Gyro misalignment & sf error

IMAGE RECTIFICATION RESULTS

In the summer of 2001, a GI-Eye II system was used to collect imagery and navigation data over Tift County, Georgia. The data was collected from an aircraft at a nominal altitude of 1000m AGL. Figure 4 shows the components of the flight system.

The camera field-of-view was 28 degrees, and the image resolution was 2032x3056, yielding a ground pixel resolution of about 23 cm/pixel. The collected imagery and associated navigation data were rectified and geo-registered using the ERDAS OrthoBase package in the Imagine™ software. The navigation data was used "as is", and no image tie-point processing was performed to improve the registration and rectification process. A portion of a rectified mosaic (with UTM coordinates) is shown in Figure 5. A sample region containing three image-boundaries from the mosaic is shown Figure 6. (Although the quality of the image reproduction in this document is limited, it is hoped the reader can see that the mis-registration is on the order of a pixel). This result is useful in that it indicates an ability to ortho-rectify airborne imagery with **no image tie-points** and **no image manipulation** in producing the rectified results.

Figure 4 Flight System (clockwise from upper left: aircraft, sensor head with camera and IMU, data logger with display and keyboard, data logger).

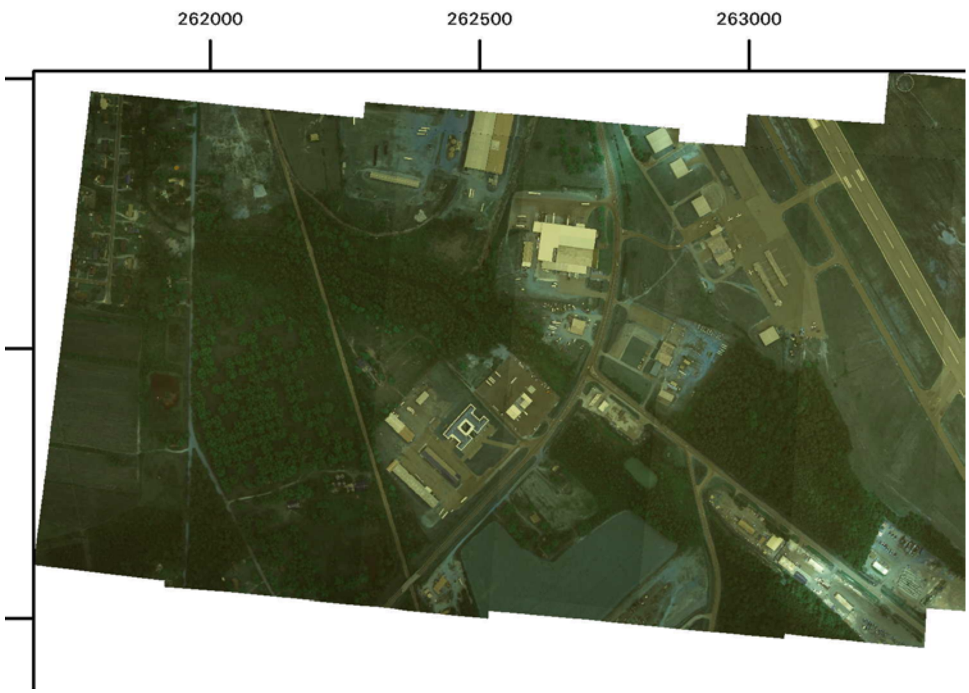

Figure 5 Rectified Mosaic Example

Figure 6 Example of Rectified Image Boundaries

GEO-LOCATION RESULTS

Using the same flight data as referenced in the previous section, a series of surveyed targets had their geo-coordinates computed. These coordinates were derived by simply reading the latitude and longitude values in the rectified image mosaics. Table 3 summarizes the target geo-location performance of the system. In this configuration, the system was using a WAAS DGPS receiver system to provide RTCM pseudo-range correction data for input into InterNav. The targets were accurately surveyed with carrier-phase GPS, so the resulting targeting error is principally a combination of ownship position error and attitude error. Since the absolute position accuracy of DGPS is on the order of 1-1.5 meters, the 0.92 meter CEP from 1000m+ range indicates that, not only is the position solution good, but the attitude error is extremely small, clearly well under one mrad.

Table 3 Geo-Location Performance from Rectified Imagery

Point	Avg East Error (m)	Avg North Error (m)	Avg dist (m)
NSPL01	-0.11	-0.35	0.37
CPES Blueberry	0.43	-0.87	0.97
CPES Hort Hill	-0.49	-0.32	0.58
Tifton A – CoC	-0.35	-2.23	2.26
FAA TMA	0.20	1.14	1.16
Tifton CBL 150	-0.31	0.20	0.37
Tifton CBL 0	-0.15	0.28	0.32
Tifton CBL 100	-0.24	0.20	0.31
Excelsior reset	0.48	-1.77	1.83
M 157	0.65	1.80	1.91
Total RMS	0.47	1.27	0.92

SUMMARY

An architecture for performing tightly-coupled GPS/INS navigation has been described. The resulting system, using standard commercial devices and computers, has been field-tested in both ground-based and airborne applications. Image rectification results indicate that total position error (when using Wide Area DGPS corrections) is under one meter, and attitude error under one mrad absolute. Using a GPS RTK solution, the position error can be reduced to within a few centimeters.

ACKNOWLEDGMENT

Ground reference point coordinates were compiled and made available by Tasha Wells of the National Environmentally Sensitive Agriculture Laboratory (NESPAL) in Tifton, Georgia. NESPAL also laid out the reference point markers and paid for the aircraft services involved in the data acquisition.

REFERENCES

[1] Brown, Zhang, Reynolds. “Precision Targeting Using GPS/Inertial-Aided Sensors,” ION Proceedings 55th Annual Meeting, 1999.