Precision Kinematic Alignment Using a Low-Cost GPS/INS 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 Interagency GPS Executive Board Independent Advisory Team and Scientific Advisory Board for the USAF and serves on the GPS World editorial advisory board.

Dan Sullivan is a Senior Scientist 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

Tight GPS/INS coupling has been shown to be an effective way of providing accurate position, velocity and attitude information using low-cost components. This paper describes test results for a system that uses an improved kinematic alignment algorithm suite that provides a high-quality navigation solution using direct carrier-phase and pseudo-range GPS measurements tightly coupled with measurements from a low-cost IMU system. The test data shows the utility of an airborne and ground based version of this system for use in precision registration of video imagery. This has applications for generating target coordinates and also for use in mapping and navigation for a variety of military and civilian applications.

INTRODUCTION

Achieving precision attitude is an enabling capability for military and commercial applications that use digital imagery for applications such as digital mapping, target registration or GIS data collection. To register airborne imagery today, georegistration is accomplished by using surveyed features selected from within the digital images. This is currently time intensive and expensive to implement as it relies on establishing ground truth over the area of interest.

NAVSYS has developed a precision, autonomous georegistration system, the GI-Eye that uses GPS and inertial technology to provide meta-data linked to the digital images, as they are collected. This capability avoids the need for requiring any ground truth. As illustrated in Figure 1, the accuracy level of the georegistration solution is dominated by the precision to which the camera alignment can be observed.

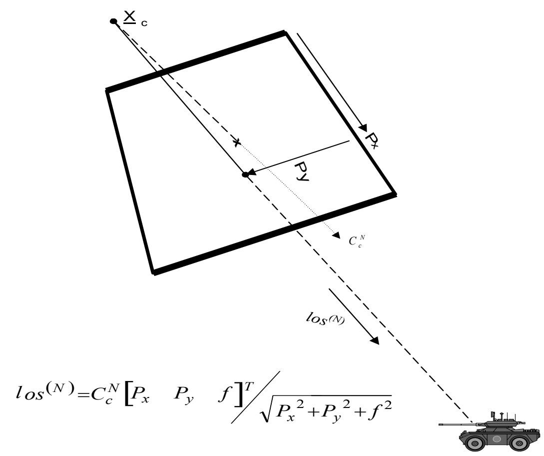

Figure 1 GPS/Inertial Georegistration

IMAGE GEOREGISTRATION ACCURACY

The estimated line-of-sight to any feature in the video image, derived in the navigation (North, East, Down) frame, can be computed by transforming the pixel derived line-of-sight vector in camera axes to the navigation frame using the inertial attitude data.

$$\underline{l}^{(C)} = [p_x \quad p_y \quad f] / \sqrt{p_x^2 + p_y^2 + f^2}$$

where p_x and p_y are the target pixel coordinates derived from the image data, and f is the focal length of the camera (in pixel units).

The alignment between the camera frame and the inertial body frame is fixed and is defined by the matrix C_C^B. The direction cosine matrix derived from the inertial data to transform from body to navigation frame coordinates (C_B^N) can be used to compute the line-of-sight from the camera location to the target location in navigation frame coordinates.

$$\underline{l}^{(N)} = C_B^N C_C^B \underline{l}^{(C)}$$

Since the camera location is known ($\underline{x}_C$), the target coordinates can be calculated through a least squares solution from multiple image data. The observed line-of-sight to the target provides a measure of the offset between the estimated target location and the observed target location through the following equation.

$$\hat{\underline{x}}_T{}^{(N)} = \underline{x}_C{}^{(N)} + R\,\underline{l}^{(N)} \qquad R = |\hat{\underline{x}}_T - \underline{x}_C|$$

The accuracy to which the feature coordinates can be estimated is a function of the following errors.

1. Error in the estimate of the camera location ($\underline{x}_C$)

This will be dominated by the GPS performance. With kinematic GPS positioning, the camera location can be determined to an accuracy of better than 0.1 meters.

2. Error in the estimate of the camera attitude (C_B^N)

This corresponds to errors in the inertial alignment and misalignment angle errors between the inertial system and the video camera.

INERTIAL ALIGNMENT TECHNIQUES

Prior to the development of tightly integrated GPS/inertial systems, inertial alignment was accomplished through a technique termed gyrocompassing. This mode depended on the observability of heading through earth rate (Wx, Wy) and, as illustrated in Figure 2, the resulting heading accuracy was a function of the gyro bias error. To achieve 1 mrad alignment accuracy, for example, using gyrocompassing would require a 0.01 deg/hr gyroscope.

$$\tilde{\theta} = \frac{B_G}{W}$$

When using a tightly coupled GPS/inertial Kalman filter solution, the observability of the heading error propagates through the delta-range updates, which provide a direct observation of the velocity error. This observability couples through the heading propagation into delta-position (navigation frame) through the sensed body-frame velocity. To separate out heading errors from the tilt and accelerometer error propagation, change in the velocity vector is needed. The accuracy of this delta-range alignment mode is therefore a function of the vehicle dynamics (the higher the acceleration, the better the observability) and the delta-range measurement noise. As demonstrated by the test results included in this paper, alignment accuracies of 1 mrad are possible using this technique for airborne applications. For man-portable or land mobile applications though, where the dynamics experienced are smaller, the alignment quality using the delta-range updates is poorer.

The best quality alignment accuracy can be achieved using a kinematic alignment mode. In this mode, the full carrier phase observations are applied as updates to the Kalman filter in place of the delta-range observations. In this mode the heading observability occurs from the full change in position of the platform while coherent carrier lock is maintained. The integrated GPS/inertial solution position accuracy is also improved by applying kinematic GPS position updates, which allows for sub-meter precision relative to a reference station.

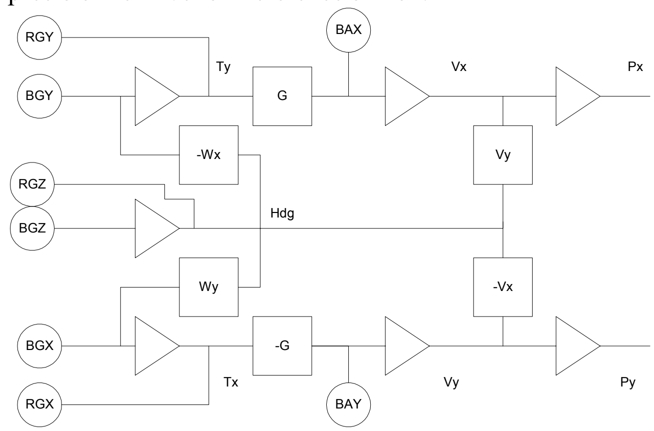

Figure 2 Inertial Error Propagation

INTERNAV SOFTWARE

The kinematic alignment algorithms were implemented as an extension of the NAVSYS' InterNav integrated GPS/inertial software product [1]. InterNav is used as an embedded software module for integrated GPS/inertial applications to process the raw IMU data and produce an inertial navigation solution. The software includes the functions illustrated in Figure 3. InterNav is designed to operate with both high quality inertial data, such as could be provided by an Enhanced GPS-Inertial (EGI) navigation system, or low grade data, such as is available from a Fiber Optic Gyro (FOG) or MEMs IMU, through changing keywords to specify the quality of the raw IMU (delta-theta, delta-V data inputs).

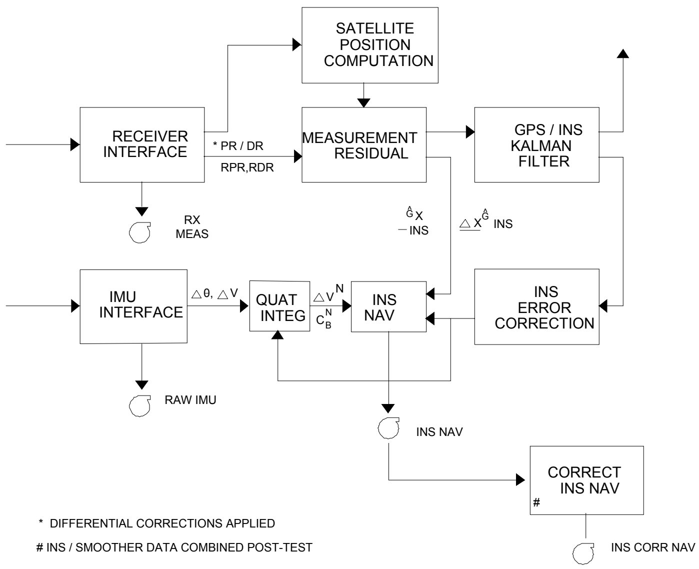

Figure 3 InterNav Software Architecture

Table 1 InterNav Kalman Filter Navigation 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

The base InterNav filter states are shown in Table 1. In the conventional alignment mode, the pseudo-range and delta-range updates are applied to align the Kalman filter. In the kinematic alignment mode, the updates are changed to pseudo-range and carrier-phase. When ambiguity resolution has been accomplished and a kinematic position solution is available, this is applied as a position update in place of the pseudo-ranges.

When the above filter is integrated with the IMU, the inertial navigation solution is used to propagate the position and velocity navigation states and the pseudo-range and carrier-phase observations are applied to estimate the navigation error. The benefit of this approach is that the filter can be tightly tuned to track slowly varying GPS errors and improve both the positioning and alignment accuracy.

GI-EYE SYSTEM CONFIGURATIONS

The kinematic GPS alignment algorithms have been implemented in NAVSYS integrated GPS/inertial/video precision georegistration system, the GI-Eye [2,3]. The GI-Eye integrates GPS, inertial, and video components to derive the precise position and 3-D attitude of the optical sensor. This enables the target coordinates to be extracted from the digital images as described in Figure 1. This system concept allows for rapid and accurate geo-registration of objects remotely without the need for any known registration points to be within the image.

The GI-Eye adopts a component-based software architecture, which allows a variety of different system configurations and devices to be integrated into the same software, depending on the application requirements. Figure 4 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 GPS/inertial integrated navigation solution is computed using our InterNav integrated navigation software.

Testing of the GI-Eye precision alignment performance was performed using both an airborne configuration and a land-based configuration of the GI-Eye system. A description of these systems and the test data collected is described in the following sections of this paper.

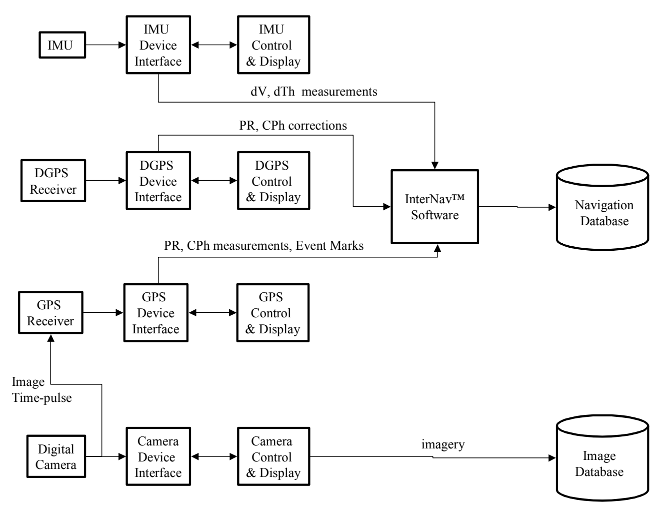

Figure 4 GI-Eye Software Architecture

GI-EYE AIRBORNE TESTING

The airborne GI-Eye configuration used to evaluate the alignment performance included a Wide Area

Augmentation System (WAAS) receiver to provide differential corrections to the GPS pseudo-ranges. The system time synchronizes the IMU, GPS and imagery by exploiting the event-mark capability of the Novatel receiver. When the camera is commanded to take a picture, the strobe pulse from the camera is used as an event-mark input to the GPS receiver, which then produces an output message containing the exact GPS time of the collected frame. To synchronize the IMU, the GPS 1 Pulse-Per-Second (1 PPS) output is aligned with the incoming IMU data. The hardware configuration used to perform the testing is shown in Figure 5. An LN-200 FOG IMU was used to observe the camera alignment.

The inertial alignment performance was tested by collecting imagery and navigation data during a flight test over Tift County, Georgia. The data was collected from an aircraft at a nominal altitude of 1000m AGL. 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 6. A sample region containing three image-boundaries from the mosaic is shown Figure 7. (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.

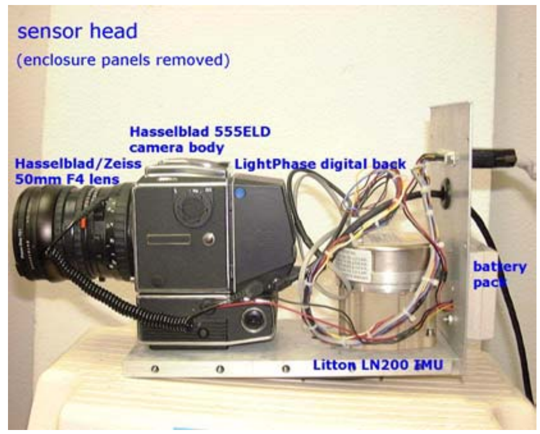

Figure 5 Airborne GI-Eye GPS/Inertial/Video System

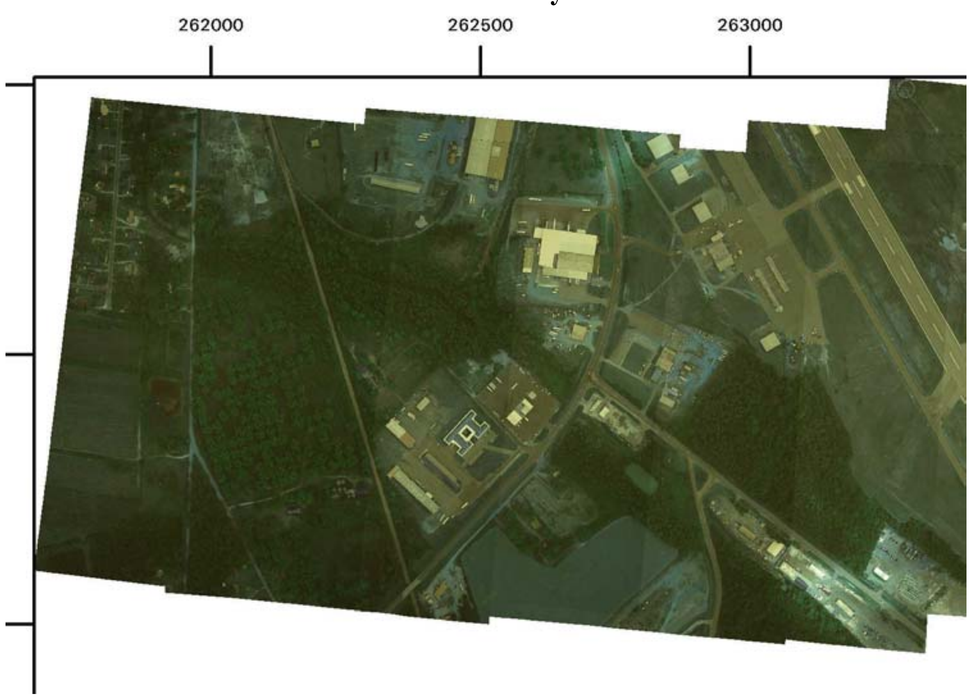

Figure 6 Rectified Mosaic Example

Figure 7 Example of Rectified Image Boundaries

Table 2 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

To verify the alignment accuracy, 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 2 summarizes the target geo-location performance of the system. The targets were accurately surveyed with carrier-phase GPS, so the resulting targeting error is principally a combination of ownship position error from the WADGPS corrected solution and the alignment attitude error. Since the absolute position accuracy of WADGPS is on the order of 1 to 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.

GI-EYE GROUND-BASED TESTING

To further test the kinematic alignment accuracy, ground tests were performed using the terrestrial GI-Eye system configuration shown in Figure 8. This includes a Novatel, codeless, dual frequency provides L1 and L2 observations to allow both real-time kinematic (RTK) positioning and alignment to be performed. An LN-200 FOG IMU was again used to perform the camera alignment.

To verify the alignment accuracy of the GI-Eye system, surveyed test markers at known locations were used as “targets.” These targets were precisely surveyed relative to the NAVSYS reference antenna using kinematic GPS.

The “true” target bearing for each image was determined post-test by computing the bearing from the known sensor position (from the RTK-computed position solution) and the surveyed target position. If the range-to-target is large enough (>100 meters for this 2 cm RTK system), then the position error contributes a negligible amount to the computation of “true” bearing. The “true” bearing was then compared with the measured bearing from the sensor system. These results were repeated using the camera alignment computed post-test using conventional delta-range updates and also with the more precise kinematic alignment updates.

Table 3 summarizes the results for those targets that were at sufficient range from the GI-Eye test system to provide a good measure of the alignment attitude accuracy. The average alignment error when using delta-range updates in the conventional tightly coupled GPS/inertial Kalman filter mode was 1.3 mrad. With the kinematic alignment filter using the carrier phase updates, the average alignment error was reduced to below 0.5 mrad, a factor of two improvement.

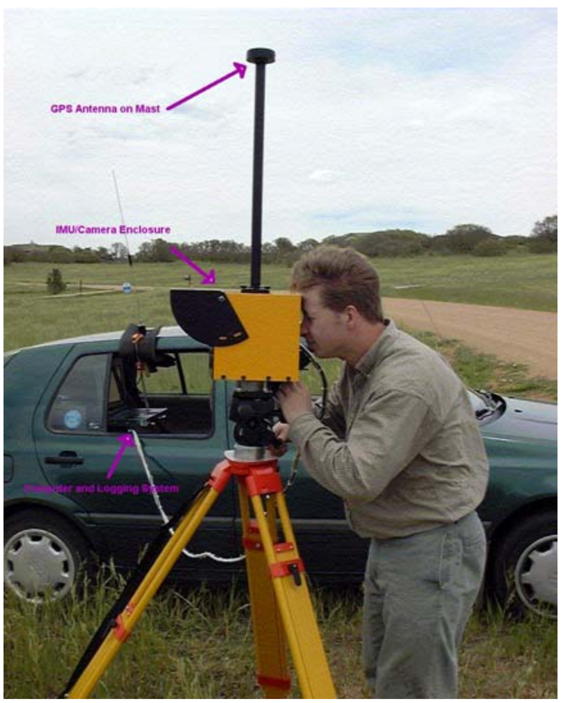

Figure 8 Terrestrial GI-Eye Hardware

CONCLUSION

The results of the flight and ground-based testing with the GI-Eye integrated GPS/inertial navigation system has shown that the average inertial alignment error can be reduced to within 0.5 mrad. The use of the improved kinematic alignment algorithm has reduced the heading error by more than a factor of two over “standard” GPS/inertial tight coupling using pseudo-range/delta-range measurements. Moreover, the kinematic alignment algorithm was able to provide this high level of precision without requiring any significant vehicle dynamics to provide heading observability. By also providing kinematic position updates to the integrated GPS/inertial solution, the combined precision positioning and alignment capability provided by our GI-Eye hardware and InterNav software can support sub-meter image georegistration without requiring the use of any ground registration points within the imagery. This capability has applications for extracting precision target information and for streamlining and reducing costs for generating digital maps from overhead imagery.

Table 3 Kinematic Alignment Heading Error

Target	Range (m)	DR Filter Error (rad)	Kinematic Filter Error (rad)
Utility box	144.24	0.002967	0.001047
Utility box	105.79	0.001745	0.000175
Utility box	86.89	0.001571	0.000000
Intersection sign	202.67	0.000873	0.000349
Intersection sign	153.32	0.001920	0.000000
Intersection sign	148.83	0.001047	0.000698
Intersection sign	129.4	0.001396	0.000349
Intersection sign	108.8	0.002618	0.000175
Hay Creek Bridge	139	0.000000	0.000698
Hay Creek Bridge	120.97	0.000175	0.000698
Hay Creek Bridge	91.24	0.000524	0.001047
Hay Creek Bridge	112.78	0.001571	0.000873
Stop-ahead sign	326.85	0.001047	0.000524
Stop-ahead sign	293.86	0.001745	0.000698
Stop-ahead sign	257.88	0.001222	0.000175
Stop-ahead sign	221.99	0.001571	0.001047
Stop-ahead sign	186.52	0.000873	0.000000
Stop-ahead sign	151.86	0.000698	0.000175
Stop-ahead sign	117.19	0.000349	0.000175
Average Error		**0.001258**	**0.000468**

ACKNOWLEDGEMENTS

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