Video Updates during GPS Dropouts using Navigation and Electro/Optic Sensor Integration Technology

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BIOGRAPHY

Shane Pinder holds a BSc in Mechanical Engineering from the Royal Military College of Canada and an MSc in Aerospace Engineering from Carleton University. His doctoral studies involved the development of a GPS-based takeoff performance monitor at the University of Saskatchewan. He is a former Lieutenant in the Canadian Forces.

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Alison Brown is the President and CEO of NAVSYS Corporation. She holds a PhD in Mechanics, Aerospace, and Nuclear Engineering from UCLA, an MSc 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.

ABSTRACT

The authors have developed Navigation and Electro/Optic Sensor Integration Technology (NEOSIT) that operates by using video navigation updates (VUPTs) to maintain inertial navigation solution accuracy during GPS dropout periods. The navigation updates are provided from object reference models downloaded pre-mission. These can include features such as buildings, road intersections, or bridges. To reduce computation, an inertial-aided model matching technique is used. The NEOSIT software includes highly efficient image processing algorithms that use the integrated navigation and optical sensor data to locate features captured within the digital image data.

In the summer of 2001, the NEOSIT system performance was demonstrated using an integrated GPS/inertial/video system to collect imagery and navigation data over Tift County, Georgia. Object models were generated from this data set, with a differential GPS (DGPS) aided navigation solution. A second set of navigation data was then generated, without the use of DGPS aiding, to simulate a GPS dropout. Using the NEOSIT model detection software, a navigation solution was computed using inertial navigation data with image aiding. The difference between the DGPS-aided truth source and the image aided navigation solution demonstrated the ability of the NEOSIT system to navigate accurately in the absence of GPS aiding.

INTRODUCTION

Several military and commercial platforms are currently installing navigation sensors concurrently with the introduction of high-quality visual capabilities and digital mapping/imagery databases. The NEOSIT software application, developed for CECOM, is designed to optimally integrate navigation data, sensor imagery, and an image or terrain database to estimate and correct for errors in each data source. The modular design is to allow the NEOSIT application to be used with sensors and navigation already installed on different host platforms and with digital mapping and imagery data sources with varying degrees of precision.

The NEOSIT software application is designed to operate in three modes. The first mode uses the precision GPS/inertial imagery metadata to extract target coordinates from the imagery[1,2]. The second mode is used to correct for offsets in the image or terrain database registration coordinates. The third mode of operation is to provide a backup navigation capability in the event of GPS dropouts by applying reference points from the imagery to update the onboard navigation solution.

NEOSIT SOFTWARE APPLICATION

The NEOSIT application is designed to interface with the following components, as illustrated in Figure 1.

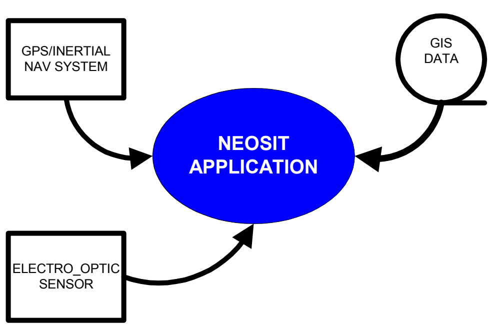

Figure 1 NEOSIT Component Interfaces

GIS Geospatial Data

The NEOSIT application can accept data from a variety of different government and commercial digital data sources. These include rectified imagery, such as the Controlled Image Base® (CIB®), Digital Precision Point Data Base (DPPDD), digital terrain elevation data (DTED®), and vector maps such as VMAP or commercial equivalents.

GPS/Inertial Navigation System

The integrated GPS/inertial navigation data are used to provide the geospatial reference data associated with the electro-optic sensor data. The results presented in this paper were generated using NAVSYS' GI-Eye product, shown in Figure 2.

Electro-Optic Sensor

The NEOSIT application can be used to process data from a variety of different sensors including optical, IR, or hyperspectral devices. These sensors must only be capable of providing digital data in a standard image format to the NEOSIT application. The Hasselblad digital frame camera shown in Figure 2 was used to provide the test data presented in this paper.

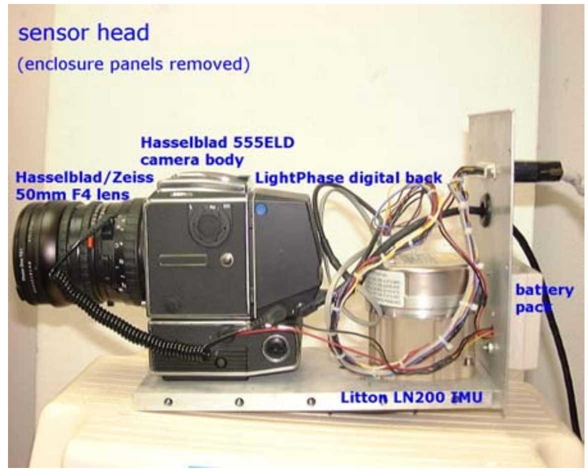

Figure 2 GI-Eye Product

GEOREGISTRATION ALGORITHM

The core algorithm for all of the modes of operation of the NEOSIT software is the georegistration algorithm shown in Figure 3. 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.

$$l^{(C)} = \begin{bmatrix} p_x & p_y & f \end{bmatrix} / \sqrt{p_x^2 + p_y^2 + f^2} \qquad \textbf{(1)}$$

$$\underline{l}^{(N)} = C_B^N C_C^B \underline{l}^{(C)} \qquad \textbf{(2)}$$

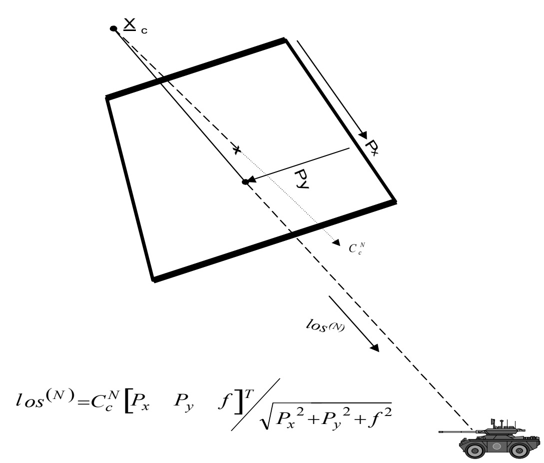

Figure 3: Measurement Geometry

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.

$$\underline{x}_T^{(N)} = \underline{x}_C^{(N)} + R\,\underline{l}^{(N)} \qquad R = \left|\underline{x}_T - \underline{x}_C\right| \qquad \textbf{(3)}$$
$$\underline{z} = \hat{\underline{x}}_T - \underline{x}_T = \hat{\underline{x}}_T - \underline{x}_C^{(N)} - R\,\underline{l}^{(N)}$$

This residual provides a measure of the following error sources:

- Error in the feature coordinates ($\hat{\underline{x}}_T$) (errors in the GIS data source)
- Error in the camera location ($\hat{\underline{x}}_C$) (errors in the navigation position solution)
- Error in the estimate of the camera attitude (C_B^N) (errors in the inertial attitude solution)

This observability is the key to the video estimation process, enabling both target location errors and navigation errors to be estimated from the integrated navigation and image data.

To evaluate the image georegistration accuracy of the NEOSIT system, imagery and navigation data were collected from an aircraft at a nominal altitude of 1000m AGL. The attitude error demonstrated from these data was well under one milliradian.

VIDEO-AIDING NAVIGATION UPDATES

Coupling video and navigation data can serve several different purposes. When a good navigation solution is available, it can be used to build new waypoint models for later use or to improve the accuracy of existing GIS-based waypoint models. It can also be used to provide target geo-coordinates for any object of interest. When GPS is denied, the system can operate in two modes. First, it can use previously stored waypoint models to provide absolute navigation updates, eliminating INS drift. Alternatively, it can create new waypoints even under GPS-denied conditions, which provide relative position aiding to reduce INS drift.

The required pixel measurements for the video aiding process can come from manually-cued objects in the scene or from a waypoint detection algorithm, which automatically detects and localizes waypoint objects. The following sections describe an automated approach to waypoint modeling and detection and describe the method used to apply these measurements for navigation updating.

Estimates are obtained by automatically localizing a model of a scene object, or landmark, in the image data. Accurate scene coordinates for the landmarks are required to generate absolute position estimates. These may be obtained from map data, or from the platform at times when accurate image sensor position and attitude estimates are available. For relative position estimates, the landmark is selected in one image, automatically modeled, and localized in subsequent images.

MODEL GENERATION

For position aiding, the operation of the system depends on the availability of a database of three-dimensional object models. These models can be generated using GIS data (vector maps, CIB, or digital orthoquad (DOQ) imagery as in Figure 4) in conjunction with DTED or imagery collected from a platform with accurate navigation equipment when GPS is not denied. Figure 5 shows a block diagram of the Model Generation process.

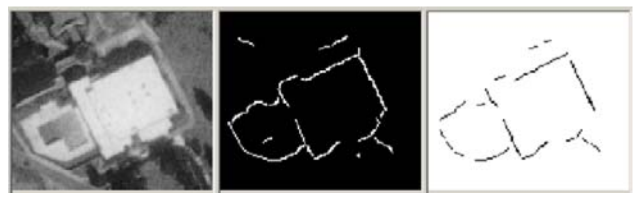

Figure 4 Model Generation from DOQ

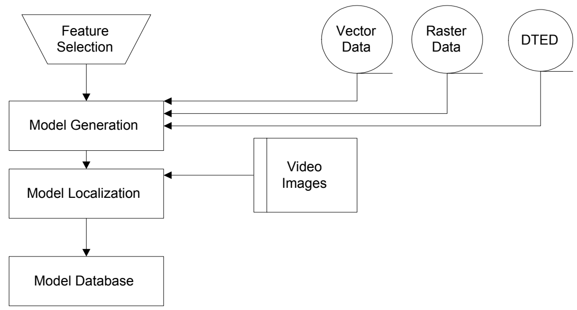

Figure 5 Model Generation Process

Model generation begins with the selection of a feature. From the GPS/inertial reference data, it is possible to estimate the viewing parameters of the imaging sensor. These meta-data can be used to compute the geographic region that is in the field view of the sensor. A query is then performed on the GIS data to aid in the determination of the range to the selected feature.

As shown in Figure 6, this approach results in a model that may have a large position uncertainty along the line-of-sight, depending on the accuracy of the information used to estimate the range to the feature. This error can be reduced by combining data from multiple images as discussed below.

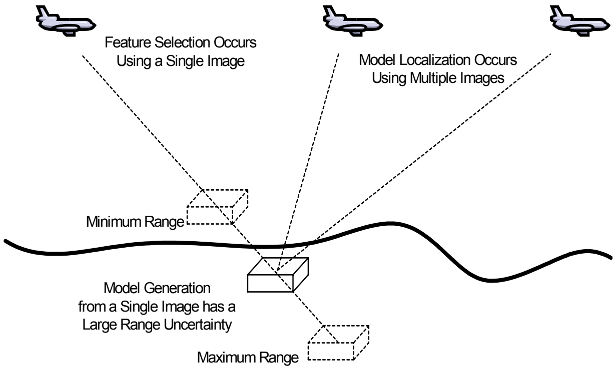

Figure 6 Model Generation and Localization

When an accurate navigation solution is available, the offset between the predicted feature location based on the GPS/inertial data and the actual location observed from within the video frame is a function of the error in the recorded location for that feature within the model database.

For GIS-base models, the location and attitude of each sensor image is used to compute a projection of the image onto the map and identify a region of interest within the database. A query is performed on the GIS data to identify any features that fall within this region. The features that are returned from this query are then processed by a feature extraction algorithm where their precise coordinates are detected within the image data.

To generate a model, a series of image-processing operations are performed which extract edges from the region of interest and look for salient line features. Figure 7 shows an example of the model extracted from a building. The model is stored on-board as a simple list of line segment (lat/lon/alt) coordinates, greatly reducing storage requirements compared with image-based correlation approaches.

Models can also be extracted directly from GIS vector products, bypassing the need for airborne reference data.

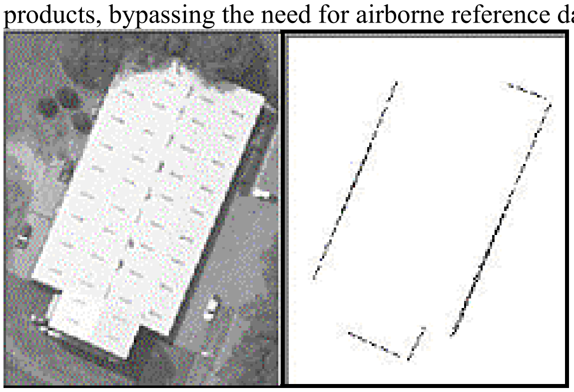

Figure 7 Model Extraction

MODEL DETECTION

Given a pre-loaded or dynamically-extracted model, the navigation aiding process must then be able to localize that model within a scene. Based on the current navigation (position and attitude) and model uncertainty, a region of interest (ROI) is selected which should contain the waypoint object. Figure 8 shows an example of the results obtained from running the Model Detection function with an initial navigation error. The blue model denotes the expected model location at the center of a yellow uncertainty box derived from the model and navigation uncertainty. The red outline shows the minimum-error match location.

Figure 8 ROI and Detected Model

A similar example using a model generated from a vector road database is shown in Figure 9.

NAVIGATION ERROR ESTIMATION

The pixel observation residual between the expected and measured model position can be used to observe both the target coordinate error and the navigation error. Observability of the navigation error requires multiple observations, either from multiple waypoints or to the same waypoint at different times during aircraft maneuver. To enable updates to be applied correctly from pixel observations taken at different times, the update equation takes into account the error propagation of the inertial error states between times, using standard state-transition matrix techniques. The internal navigation states that can be observed using this equation include the navigation solution errors and instrument errors. A minimum implementation would include three position states, three velocity states and three alignment error (ψ) states, or a total of N=9 states. Additional states are also included in the inertial Kalman Filter for accelerometer and gyroscope bias, scale factor and misalignment errors.

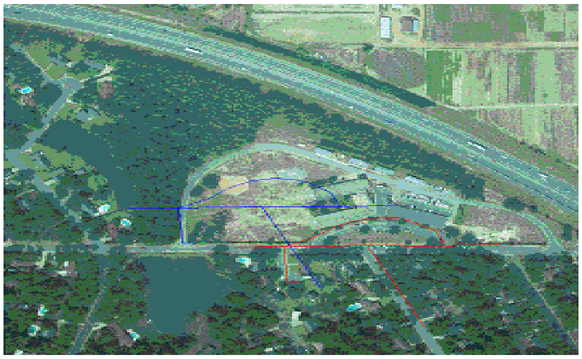

Figure 9 Detection of VMAP Model

AIRBORNE TEST RESULTS

The aerial data shown earlier[1] was also used to test the Model Detection and Navigation Update algorithms. Models were generated of suitable landmarks in this area and the model update function was then used to localize the models using multiple images using the NEOSIT Target Geolocation capability. A second set of navigation data was then generated, without the use of GPS aiding, to emulate the effect of navigating through the same are in the event of GPS jamming.

Using the model detection algorithms described above, a navigation solution was computed using only INS data with image aiding. The NED-frame difference between the DGPS navigation solution and the image-aided navigation solution is shown in Figure 10.

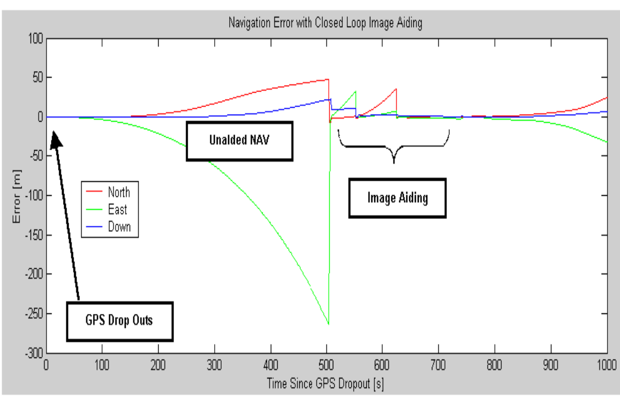

Figure 10 Airborne Navigation with Image Aiding

For the first 500 seconds, no object models were in view, and the free-inertial navigation solution drifted away from truth. Once a model was visible, the estimation software applied a correction to the navigation solution. Note that, after this correction was applied, the error again began to accumulate but that the growth of the error with respect to time was reduced, indicating that position, velocity and attitude error were observed and reduced. As more models came into view, the error was better observed. At t=650 seconds, the error even approached the accuracy of the original DGPS-aided navigation solution despite having no GPS data for over ten minutes and image aiding in only the previous three minutes. In this test, no models were available after t=750 seconds, so the inertial solution again began to degrade after that time.

GROUND-BASED TEST RESULTS

A similar test was conducted with ground-based data. Figure 11 shows examples of the regions-of-interest and measured detection image models, in this case a signpost and a house.

Figure 11 Ground-based Image Aiding Test

These models were used for navigation updates during a period spanning the collection of twelve images. The result of this test is shown in Figure 12. Note that image updates were able to maintain the navigation error to meter level accuracy while the object model was in view. At t=100 seconds, the model was no longer in view and the navigation error again began to accumulate.

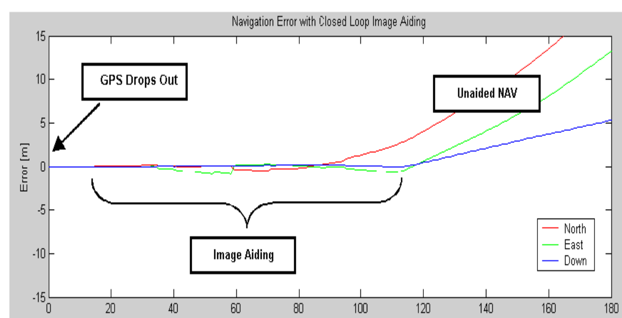

Figure 12 Terrestrial Navigation with Image Aiding

SUMMARY

The NEOSIT software application includes a combination of GPS/inertial navigation, image-processing and georegistration and navigation update functions that provides the ability to couple image measurements into the navigation solution to bound the inertial navigation solution drift when GPS dropouts occur. The results using both terrestrial and aerial systems clearly demonstrate the ability of the system to observe the error present in the navigation solution using imagery and correct the navigation solution for the observed error. With as few as two or three video navigation updates per minute, an accurate navigation solution can be maintained using images that were previously registered with the GPS/inertial targeting system. Navigation updates can also be applied using models generated from CIB imagery or VMAP registered models.

The NEOSIT software can be used to provide augmented navigation for aircraft, UAVs and UGVs by integrating the information from their on-board inertial and video sensors. This provides a robust navigation capability in the event of GPS jamming. With the advent of low cost, miniaturized Micro-Electro-Mechanical (MEMS) inertial sensor, the NEOSIT navigation solution could also be extended to man-portable operations providing alternative means for urban navigation and in buildings where the GPS signals are unavailable.

ACKNOWLEDGEMENTS

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