

Video-aided GPS/INS Positioning and Attitude Determination

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BIOGRAPHY

Alison Brown is the President and CEO of NAVSYS Corp. 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 Univ. In 1986 she founded NAVSYS. Currently she is a member of the GPS-III Independent Review Team for the USAF and serves on the GPS World editorial advisory board.

Randy Silva is the lead software architect at NAVSYS Corporation for our integrated GPS products. He has experience developing real-time and Windows-based applications and has over eight years experience with GPS navigation systems. Mr. Silva received his Bachelors Degree from the University of Colorado at Boulder.

ABSTRACT

NAVSYS have developed a GPS/inertial/video integrated system, the GI-Eye that is designed to provide precision 3-D mapping and modeling data. For both military and commercial applications, there is a need to have a robust method of continuing operation during periods of GPS drop-outs. When the GPS satellite signals are denied, either through intentional jamming or by natural conditions such as urban or terrain masking, the positioning and attitude performance will rapidly degrade due to error growth in the un-aided inertial solution. NAVSYS have developed a video-update technique for the integrated GPS/inertial/video sensor that allows precise positioning and attitude information to be maintained, even during periods of extended GPS drop-outs. This relies on information extracted from the video images of reference points and features to continue to update the inertial navigation solution. In this paper, the principles of the video-update method are described.

1 INTRODUCTION

The video-aided GPS/INS positioning system described in this paper leverages a system architecture developed at NAVSYS for optimally combining data from navigation, electro-optic sensors and geographic data sources. This Navigation/Electro-Optic Sensor Integration Technology (NEOSIT) software application is being developed under contract to the U.S. Army.

The NEOSIT application is designed to optimally integrate navigation data, sensor imagery and image or terrain database to estimate and correct for errors in each data source. The design is highly modular and based on commercial off-the-shelf tools to facilitate integration with a variety of different navigation and electro-optic sensors and with different sources of digital mapping and imagery databases. The modular design allows the NEOSIT application to be used with sensors and navigation systems already installed on different host platforms and to be integrated with digital mapping and imagery data sources with varying degrees of precision.

This paper describes the method applied by the NEOSIT application to integrate the inertial measurements, sensor imagery and GIS data to apply navigation updates to provide precise positioning and attitude data during periods when GPS observations are not available.

2 SYSTEM COMPONENTS

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

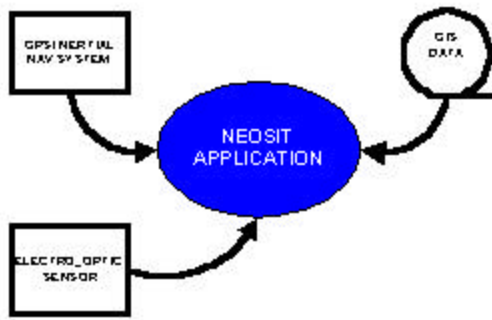


Figure 1 NEOSIT Component Interfaces

GPS/Inertial Navigation System

The NEOSIT uses integrated GPS/inertial navigation data from the host platform to provide the geospatial reference data. Integrated GPS/inertial navigation systems are the core reference for most military aircraft today. The initial NEOSIT testing is being performed using NAVSYS GI-Eye integrated GPS/inertial/video targeting system shown in Figure 2¹.

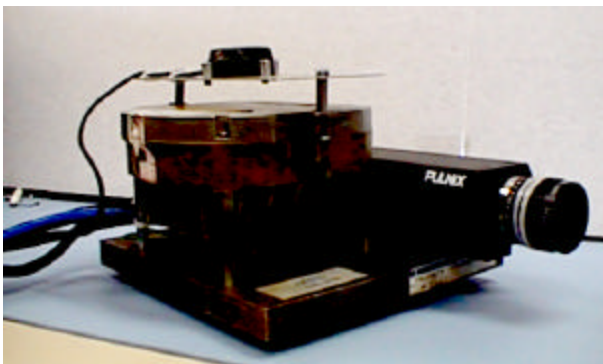


Figure 2 GI-Eye GPS/Inertial/Video Targeting System

More recently, miniaturized, man-portable systems are also being developed that integrate GPS with micro-electro-mechanical (MEM) inertial instrument technology to provide the same integrated navigation capability. Such systems are being developed by NAVSYS under contract to the Navy for use in precision targeting (see Figure 3²) and are being considered by the Army for applications such as the Land Warrior program.

Electro-Optic Sensor

The NEOSIT application can be used to process data from a variety of different sensors including optical, infra-red (IR) or hyperspectral devices. These sensors must only be capable of providing digital data in a standard image format to the NEOSIT application. The NEOSIT software integrates this information with the navigation and GIS geospatial data to precisely georegister the sensor data against the GPS reference frame. Our baseline design is integrated with a commercial video camera to provide a cost-effective COTS solution.

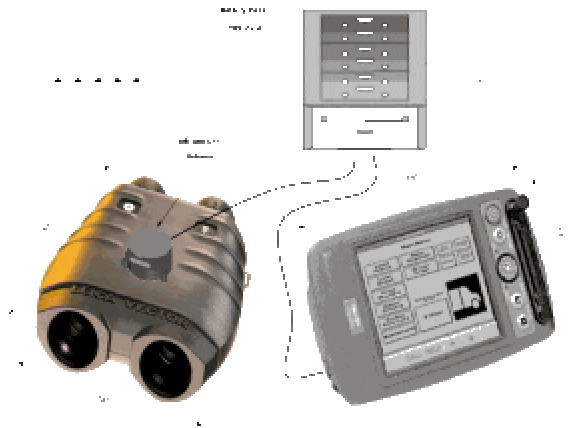


Figure 3 SPOTS Targeting Sensor Assembly

GIS Geospatial Data

The NEOSIT application can accept data from a variety of different digital data sources including government and commercial. This includes rectified imagery (such as the Controlled Image Base (CIB), Digital Precision Point Data Base (DPPDB), digital terrain elevation data (DTED) and vector maps (such as VMAP or commercial equivalents). We achieve this by leveraging a COTS Geographic Information System (GIS) application to support the manipulation of the various types of geospatial data to be fused including maps, terrain models and imagery. Our baseline design includes ESRI's ArcView³ product which supports analysis and integration of a wide variety of commercial and military geographic information sources.

3 VIDEO-UPDATE ALGORITHM

The NEOSIT application relies on the following relationship between the navigation, electro-optic and geographic navigation data to implement the video update algorithm.

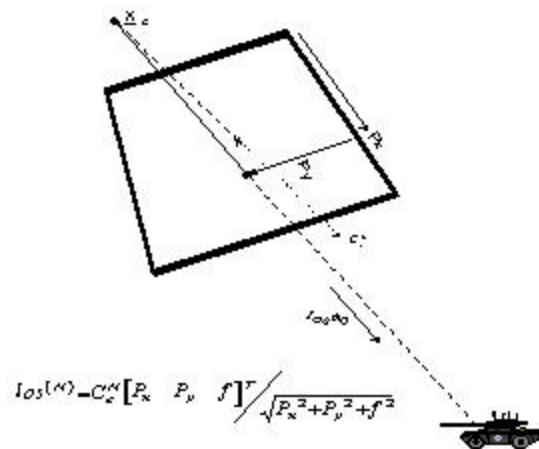


Figure 4 GPS/Inertial Georegistration

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, as illustrated in Figure 4.

Equation 1

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

where p_x and p_y are the pixel coordinates of geographic reference features 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.

Equation 2

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

When the feature location is known a-priori (\underline{x}_R), the observed line-of-sight to the feature provides a measure of the estimated camera location error and the estimated camera attitude error through the following equation.

Equation 3

$$\begin{aligned} \underline{x}_R^{(N)} &= \underline{x}_C^{(N)} + R \underline{l}^{(N)} & R &= \underline{x}_R - \underline{x}_C \\ \underline{z} &= \underline{x}_R - \hat{\underline{x}}_R = \underline{x}_T - \hat{\underline{x}}_C^{(N)} - R \hat{\underline{l}}^{(N)} \\ &= \underline{x}_T - \hat{\underline{x}}_C^{(N)} - R \hat{C}_C^N \underline{l}^{(C)} \end{aligned}$$

This residual provides a measure of the following error sources.

- Error in the initial estimate of the feature coordinates ($\hat{\underline{x}}_T$) – this corresponds to errors in the GIS data source
- Error in the estimate of the camera location ($\hat{\underline{x}}_C$) – this corresponds to errors in the navigation solution
- Error in the estimate of the camera attitude (\hat{C}_C^N) – this corresponds to errors in the inertial alignment and misalignment angle errors between the inertial system and the video camera

When a feature update is applied to the navigation solution, the NEOSIT integration algorithm computes the residual offset between the observed pixel location for the feature and the estimated pixel location based on the current navigation solution. Since there are only two

degrees of freedom in each pixel observation, the residual vector \underline{z}_x also only includes two degrees of freedom. It is convenient therefore to map the residual equation shown in Equation 3 back to the image 2-D plan to enable the estimation algorithm to work with uncorrelated observations.

Equation 4

$$\begin{aligned} z &= C_N^C(t_k)_{23} \left(\hat{\underline{x}}_C(t_k) - \hat{\underline{x}}_T + \hat{R}(t_k, \underline{x}_T) \hat{\underline{l}}^{(N)} \right) \\ &= \hat{R}(t_k, \underline{x}_T) (-\hat{p}(t_k, \underline{x}_T)_2 + p(t_k, \underline{x}_T)_2) / \left| \hat{p}(t_k, \underline{x}_T) \right| \\ &= \hat{R}(t_k, \underline{x}_T) \tilde{p}(t_k, \underline{x}_T)_2 / \left| \hat{p}(t_k, \underline{x}_T) \right| \end{aligned}$$

This residual is applied as an update to the inertial Kalman filter to observe the position and attitude error states as shown in the following equation. In this case, the feature coordinate error ($\tilde{\underline{x}}_T$) is assumed to be zero.

Equation 5

$$z = H_x(t_k, \underline{x}_T)(\tilde{\underline{x}}_T - \tilde{\underline{x}}_C(t_k)) + H_q(t_k, \underline{x}_T)\underline{q}$$

When the feature location is unknown, or the coordinate error ($\tilde{\underline{x}}_T$) is large, the observation equation of the feature pixel offset in multiple image frames can instead be applied as an inertial velocity update. In this case, the video observations provide a measure of the relative distance traveled, which is analogous in many ways to a Zero-velocity Update (ZUPT), but in this case the vehicle can be in motion while the updates are applied. We term this class of updates, Video-velocity updates or VUPTS.

In the following sections a description is included of how these updates are generated and applied in the NEOSIT application.

4 VUPT NAVIGATION ACCURACY

To illustrate the effect of the video feature updates and VUPTS on the navigation solution, a simulation was run to model the effect of the video updates on an inertial navigation solution. This assumed the error propagation typical with the LN-200 fiber optic IMU system used in the NAVSYS' GI-Eye. This has a 10 deg/hr gyro drift rate. The simulation was run first to show the error propagation assuming no updates were available (e.g. in the event of a GPS drop-out).

The results of the simulation run (Figure 5) show that the position accuracy of the GI-Eye system without any updates grows very rapidly, exceeding 100 meters within only 5 minutes following GPS drop-outs. This is because of the random walk of the gyroscopes which cause the tilt error to build up rapidly.

The green line in Figure 5 shows the navigation performance when relative position updates are applied – or VUPTs. The accuracy of these was assumed to be within 1 cm which is consistent with observations taken close-in to the video camera from fixed points. When these VUPT updates are applied every 5 minutes, the position accuracy can be maintained to within 20-30 meters. If updates are available more frequently, then the solution can be further improved.

The final simulation assumed that two known reference points could be used to provide bearing data to update the navigation location every five minutes. The accuracy of the reference points was assumed to be within 1 meter. In this case, (the red line in Figure 5), the position accuracy immediately improves to 1 meter accuracy - demonstrating the effectiveness of this video feature update method to provide a navigation capability.

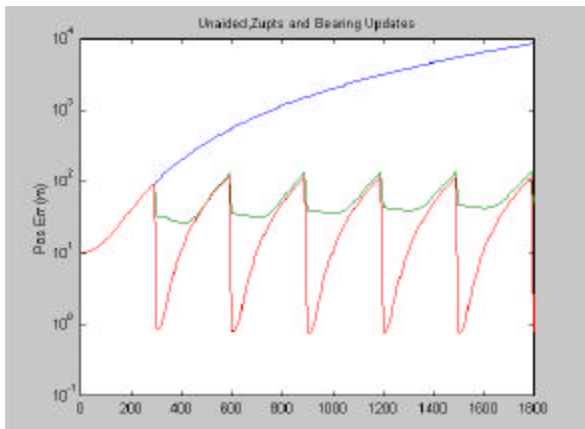


Figure 5 Video/Inertial Position Updates

NAVIGATION UPDATE METHOD

The steps to be performed in implementing the navigation update procedure are described Table 1. Currently this process requires manual intervention for selection of the video features from which the updates are applied. Under the next phase of the NEOSIT project, fully automated system operation is planned through the introduction of the automated GIS and image processing functions which are described further in following sections of this paper.

Table 1 Automated Airborne-NEOSIT Navigation Update Procedure

NEOSIT AUTOMATED PROCEDURE	
1	Operator uses a menu to identify classes of GIS features that are to be used for navigation updates
2	Video/DTM software periodically freezes and time tags the displayed video frame and, using GPS/Inertial (GI) data creates a 3-D View of the selected classes of GIS features from the GIS data-base (if any are in view) and the stored digital elevation model
3	Image processing is used to cross-correlate the

	GIS 3-D view with the image from the displayed video frame
4	Pixel coordinates from video image are extracted corresponding with each GIS feature location from which they are generated
5	Pixel offsets between the predicted and observed feature location in the video image are generated
6	NEOSIT algorithm verifies that accuracy of GIS feature updates is better than accuracy of the navigation solution
7	Maximum likelihood estimation algorithm is used to estimate position, velocity and alignment errors for the navigation reference solution

The functions required to implement these steps are illustrated in Figure 6. These are described in the following subsections.

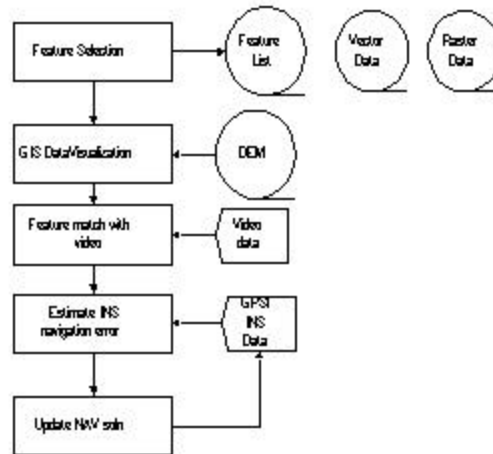


Figure 6 Navigation Update Software Functions

Feature Selection

From the features that are visible within the estimated camera view, a selected set of these features must be extracted that can be used as reference points from which to determine the NEOSIT navigation data errors. This extraction is performed using a search algorithm on the GIS database using the GIS data management tools.

GIS Data Visualization

From the GPS/inertial reference data, it is possible to estimate the position viewing angle of the electro-optic sensor as illustrated in Figure 4. The position of the camera and view angle can be used to create a model of the 3D perspective view of this data from the camera source. We have selected this approach to perform the correspondence matching between the video and GIS data sources rather than orthorectifying the video data to a planar 2-D view. The inertial aiding enables us to efficiently map the GIS data to the camera frame of reference which significantly simplifies the subsequent image processing functions to be performed.

Feature Match with Video

The selected feature from the GIS data visualization image must be matched with the same feature within the actual video image. This matching is performed using a model matching technique described in the following section.

Estimated INS Navigation Error

The offset between the predicted feature pixel location (based on the NEOSIT navigation solution) and the actual location (observed from within the video frame) is a function of the error in NEOSIT navigation solution. This residual is applied as an update to the inertial Kalman Filter to estimate the position, velocity and attitude errors in the navigation solution, as illustrated in Figure 7.

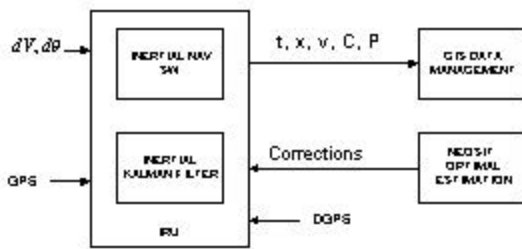


Figure 7 Navigation Data Interfaces

5 GIS DATA MANAGEMENT

The GIS data management function in the NEOSIT application is performed using the ArcView® software product provided by ESRI. This allows both raster and vector GIS data sources to be read in a variety of different formats including those listed in Table 2.

Table 2 NEOSIT GIS Data Sources

Military Products	Commercial Products
Controlled Image Base™ (CIB™)	Digital Orthophoto Quadrangles (DOQ)
Digital Terrain Elevation Data (DTED)	Digital Elevation Model (DEM)
Vector Smart Map Product (VMAP)	Digital Raster Graphics TIGER® 95

The following GIS functions are performed by the NEOSIT application.

GIS Data Management

This function manages the storage and retrieval of the GIS data relevant to the particular mission. This is coordinated with the current region of interest using the navigation coordinates provided from the NEOSIT navigation sensor. Retrieval and management of the different data sources is accomplished using the Avenue™ programming language.

GIS Feature Selection

The GIS feature selection algorithm operates using a GIS query to select the identified types of features from the GIS database that fall within the field of view of each image. This information is used by the image processing function to narrow the search focus and analysis to be performed and to optimize the algorithm applied for the type of feature being identified. These features can include easily identifiable objects such as signage, road intersections, bridges, or background features such as mountains or buildings. Using the DLL interface, the GIS feature selection software can direct ArcView® to load and display selected features or regions of interest from the image and terrain database files. In Figure 8, data is shown loaded from multiple Digital Ortho Quadrant files.

GIS Data Visualization

To facilitate correspondence matching between the sensor data and the digital mapping data, the NEOSIT application uses the navigation sensor position and attitude information to map the 2D display into a 3D perspective view image. The corresponding 3D view for a typical sensor location is shown in

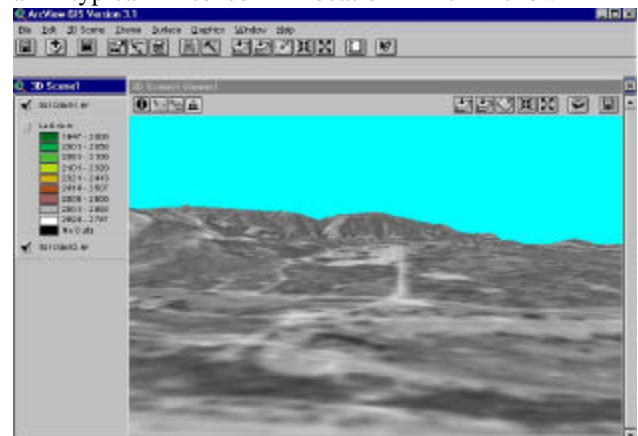


Figure 9 mapped from the 2D data shown in Figure 8.

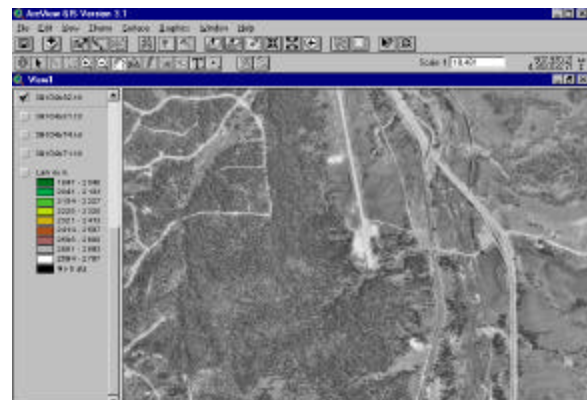


Figure 8 ArcView 2D view window with 5 themes loaded

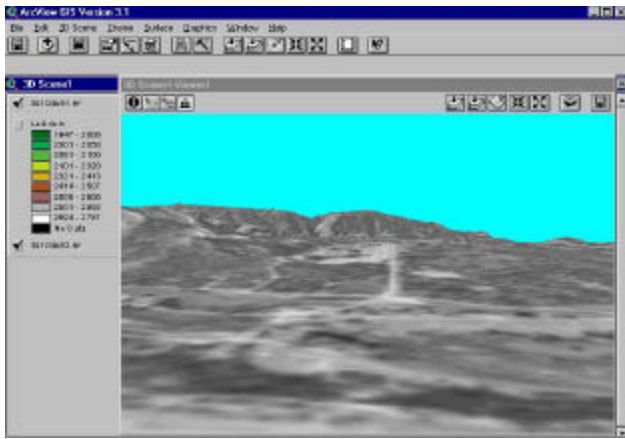


Figure 9 ArcView 3D view window looking west from Larkspur I-25 interchange

6 IMAGE PROCESSING

The core function to be performed by the image processing software is to observe the pixel coordinate offsets between the predicted location of a feature in the image and the actual location of the same feature. This observation enables either the navigation errors to be identified from known feature locations or, in the reverse application, to use the pixel offset to identify errors in the recorded location for that feature.

The basic steps to be followed for generating this observation are illustrated in Figure 10. First a Model is generated of the feature to be matched. Using the a-priori information on the sensor field of view the correct aspect angle and pose of this model is created. The predicted locations of the feature to be matched are also used to Extract the region of interest from the sensor imagery to aid the processing function. Finally the extracted data is matched to the model to observe the offset between the two data sources.



Figure 10 Symbolic Processing Methodology

The symbolic processing methodology applies equally well to processing and aligning digital mapping data from both vector and raster imagery sources, as illustrated in the following examples.

6.1 Feature Matching using Vector Data

The first example illustrates how actual sensor imagery can be automatically aligned with a vector data model. The first step in the process is to generate the model data. The ArcView program was used to generate a view of the road data over the same area covered by the DOQ view. This reference model is shown in Figure 11 generated

from TIGER 96 data files. A region of interest (ROI) is selected to identify the road segment to be used for the matching process. The ROI is shown as the blue area in Figure 11 and is converted by the NEOSIT application to a template for cross correlation with the sensor image. For this example overhead sensor imagery was used to demonstrate the alignment process between the two data sources.

In Figure 12 the DOQ input image is shown with a ROI selected that includes the template segment. This ROI is a larger area to account for possible data errors between the reference model data source and the sensor imagery. The image data is digitally enhanced to highlight the road segments which will be used for cross-correlation. The filtered image data is shown in Figure 13.

The NEOSIT matching function is used to search for the template ROI over the image ROI. In Figure 14 the location of the template match with the image data is shown. In this case, the image processing showed that there was a 4 pixel or roughly 12 meter offset between the two data sets at these coordinates.

This example has shown how the NEOSIT matching function can automatically match road segments from a digital vector data source to a digital sensor image of the same area. A similar process can be employed using raster data mapped to a 3D perspective as shown in

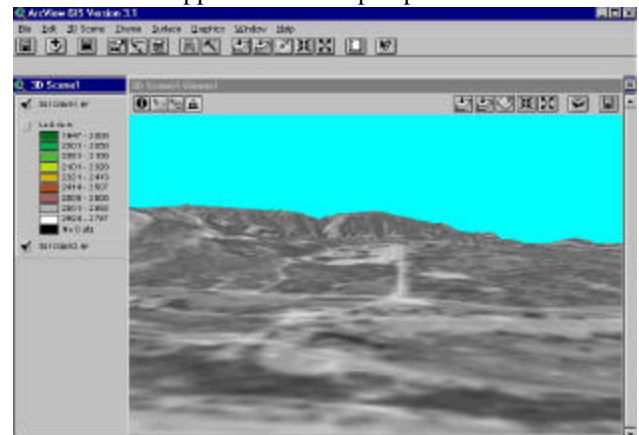


Figure 9 to extract the model used for template matching in place of the vector data model generated in Figure 11.

6.2 Feature Matching Using DEM Data

In this example, digital elevation model (DEM) data provided by the USGS for the Palmer Lake area was used to generate a 3-D perspective view from the location of an image provided by NAVSYS' GI-Eye GPS/inertial/video system

The first step in this process is to extract a skyline profile from the DEM data to be used as the reference model for template matching on the GI-Eye image. This is mapped to the same perspective as the image using the GI-Eye

position and attitude data. The reference model generated from this data is shown in Figure 15 overlaid on the GI-Eye image data. The next step in this process is to extract a symbolic representation of the image to be used in the NEOSIT matching process. The results of this step are plotted in Figure 15 in yellow. As can be seen, there is a significant offset in the horizontal direction between the model and the image.

The NEOSIT matching algorithm was used to observe the pixel offset between the model data and the image. This algorithm observed an offset of (48,0) pixels between the two data sources. In Figure 16 the Model data corrected for this offset is shown overlaid on the segmented image data. This shows the corrected view once the video update has been applied to the navigation solution to correct the observed navigation errors.

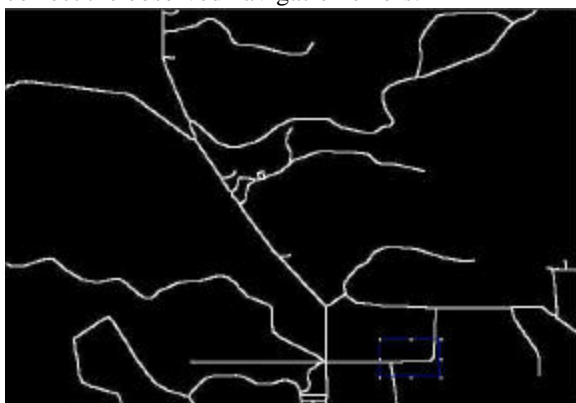


Figure 11 Reference Model with feature selected

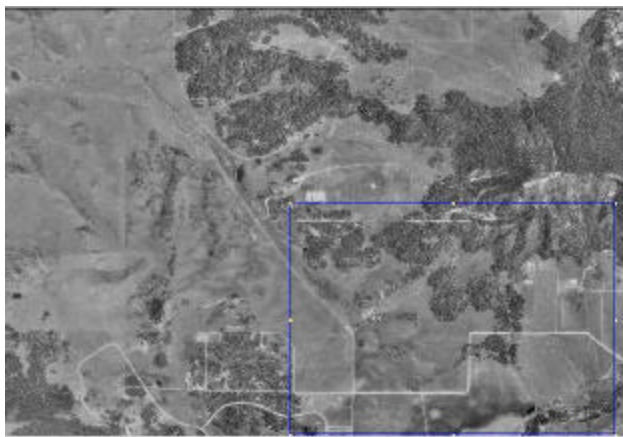


Figure 12 Input Image with area to search selected

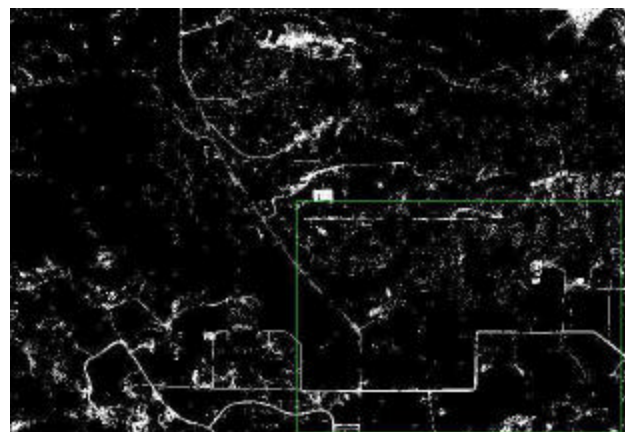


Figure 13 Input image after filtering to bring out roads

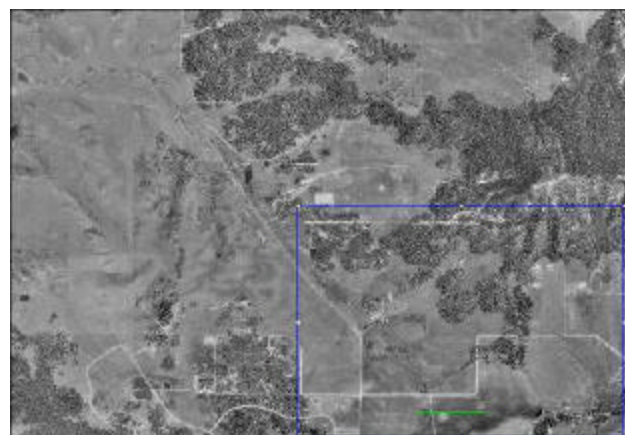


Figure 14 Input image with feature found within the search region

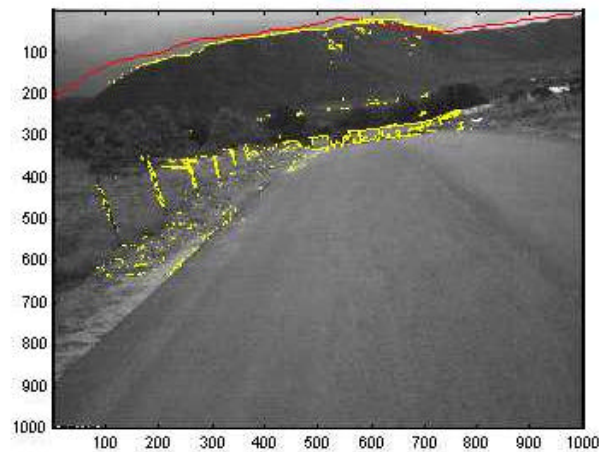


Figure 15 GI-Eye data with DEM model superimposed

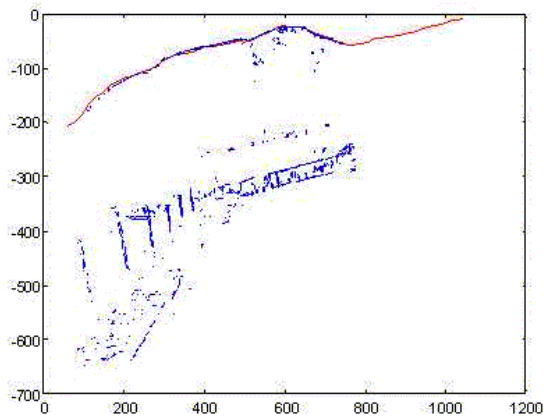


Figure 16 Symbolic image representation and Matched model

7 CONCLUSION

The NEOSIT application being developed by NAVSYS uses a video update technique to apply feature updates and motion updates from video data to bound the inertial error growth. In this paper, the video observation equations have been explained and results presented to demonstrate the performance of this approach under two different scenarios.

Work is continuing on integrating the feature update capability into our system architecture to enable automated navigation capability. Currently the system requires manual intervention to select appropriate features from the video images from which updates can be applied. Trials of the NEOSIT application are planned in early 2000 for airborne navigation (e.g. in the presence of GPS jamming) and also to provide an underground navigation capability for mining operations.

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REFERENCES

- ¹ A. Brown, G. Zhang, D. Reynolds, "Precision Targeting Using GPS/Inertial Aided Sensors," ION 55th Annual Meeting, Cambridge, MA, June 99
- ² A. Brown, R. Wilkison, "Direct Sensor to weapon Network (DSTWN) Architecture", AIAA, Huntsville, AL, October 98
- ³ Arc View GIS Version 3.2,
<http://www.esri.com/software/arcview/index.html>