Flight Test Results of a Video-Aided GPS/Inertial Navigation 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. She was a member of the GPS-3 Independent Review Team and the Interagency GPS Executive Board Independent Advisory Team, and is an Editor of GPS World Magazine. She is an ION Fellow and an Honorary Fellow of Sidney Sussex College, Cambridge.

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Dave Wetlesen is a Program Manager for GPS/inertial/video systems and software at NAVSYS Corporation. He has a B.S. in Astronautical Engineering from the USAF Academy and a M.S. in Astronautical/Aeronautical Engineering from Purdue University.

ABSTRACT

NAVSYS Corporation has been developing a navigation system that can apply aiding to an inertial navigation solution using video-updates to provide a back-up navigation mode in the event that GPS is unavailable. Tactical UAVs carry onboard video sensors that are being used to provide situational awareness on the battlefield. By using NAVSYS' integrated GPS/inertial/video (GI-Eye) technology, we are able to use this onboard sensor data to provide navigation augmentation during periods of GPS dropouts. The video updates are performed by networking georegistered images from the UAV to the ground station where we run our Web-based GeoReferenced Image Manager (WebGRIM™) software. WebGRIM includes the capability to compare visible landmarks within the GI-Eye images to reference imagery stored in the WebGRIM database. The offset between the two provides an observation of the position error in the onboard navigation solution of this waypoint. This is then sent as a Waypoint update (WUPT) to the UAV's onboard inertial navigation system. This provides a reliable, robust back-up navigation mode during GPS dropouts that can be used with inexpensive tactical grade or MEMS Inertial Measurement Units (IMU). The video-aided system design and test results are presented in this paper.

INTRODUCTION

A key issue for small UAVs is their inability to operate during periods of GPS denial. While larger UAVs carry inertial navigation systems that can provide back-up navigation during GPS dropouts, smaller tactical UAVs generally only accommodate low-quality flight control sensors including MEMS IMUs that are unable to continue providing adequate navigation solutions in the event that GPS drops out. Current flight regulations require that UAVs land following loss of navigation. There is a strong motivation, therefore, to develop a back-up navigation solution to GPS for use on these smaller, lower cost UAV platforms.

While small UAVs do not carry inertial navigation systems (INS) that allow navigation without GPS updates, they do carry onboard video sensors (EO, IR, SAR) to provide situational awareness on the battlefield. The following steps are required to use this video data to aid the navigation solution when GPS is not available.

1. When GPS is available, GPS/Inertial outputs gathered using GI-EYE can be used to provide registration metadata to imagery.

2. This imagery, along with the camera position and attitude metadata, can be used to develop a geo-referenced mosaic of the overflight area. In addition, the geo-referenced images can be used to support targeting. In our approach, the mosaicking is produced in a ground station using NAVSYS WebGRIM architecture.
3. Video images, including camera position and attitude metadata, produced during GPS dropouts can be compared to the previously gathered geo-referenced mosaic. Ground Control Points (GCPs) can be automatically extracted from the previous georeferenced mosaic. By comparing Ground Control Points in the mosaic and image, the actual camera position and attitude can be estimated.
4. The estimated position and attitude can be used to provide a waypoint update to the INS system, providing inertial drift corrections as a back-up navigation mode.

These steps are presented in more detail below.

GI-EYE SENSOR REGISTRATION

The GI-Eye product provides the capability to precisely time mark each camera image and uses NAVSYS' proprietary InterNav kinematic alignment algorithm to measure the precise position and attitude of the camera using the GPS and inertial sensor data. The GI-Eye system auto-registration capability provides the location and pointing angle of the sensor with each image and also sensor calibration data from which the coordinates of each pixel in the image can be derived. This information can be used with a Digital Elevation Model (DEM) to extract the individual pixel coordinates of each image (Figure 1).

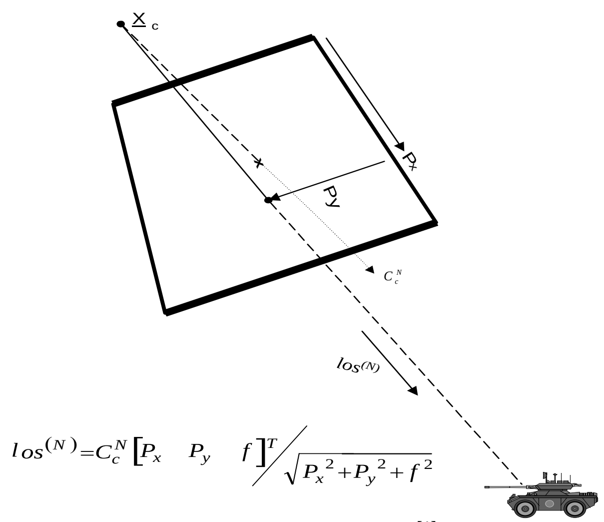

Figure 1 GI-Eye Sensor Registration[1]

GRIM ARCHITECTURE

NAVSYS' WebGRIM was configured for this program to use Oracle Express on the UAV to allow access to image thumbnails and associated geo-registration data from the UAV sensor system via NAVSYS' GI-Eye software. The full images and thumbnails, along with georegistration messages, are then downloaded as communications bandwidth allows, to an Oracle Database on the ground station. The majority of the image processing, including ortho-rectification, mosaicking, ground control point selection, etc., is done in the ground station. This architecture includes the use of iSmart[2] J2EE Server and PCI Geomatica via PPFs, as can be seen in Figure 2. An example GRIM mosaicked image is shown in Figure 3.

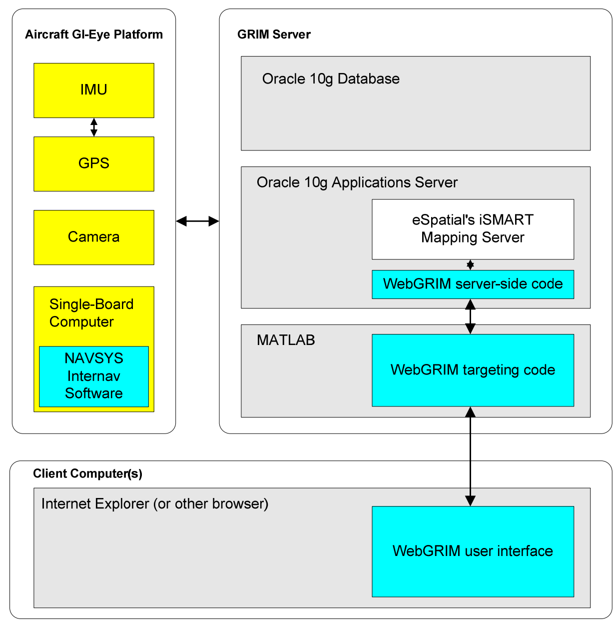

Figure 2 GRIM Architecture

The GRIM architecture consists of a compact payload package for collecting geo-registered digital imagery, a database and applications server computer, and zero or more client computers (Figure 2). Depending on the application all three of these components may be located on the same physical computer.

The payload package consists of a GPS, IMU, digital camera and a single-board computer (typically a PC/104 stack). This computer runs NAVSYS' InterNav Kalman filter and is responsible for logging camera, GPS and IMU data. Depending on the application this computer may also manage a live link to the server, enabling real-time viewing of collected data.

The GRIM server hosts an Oracle 10g database and application server, eSpatial's iSMART next generation mapping server, and the server-side components of

WebGRIM. Dedicated MATLAB code is responsible for single and multi-shot targeting.

Any number of client computers can use a web browser to access the WebGRIM application. WebGRIM provides an easy-to-use interface to perform targeting, sort and manipulate imagery, and display maps and image mosaics.

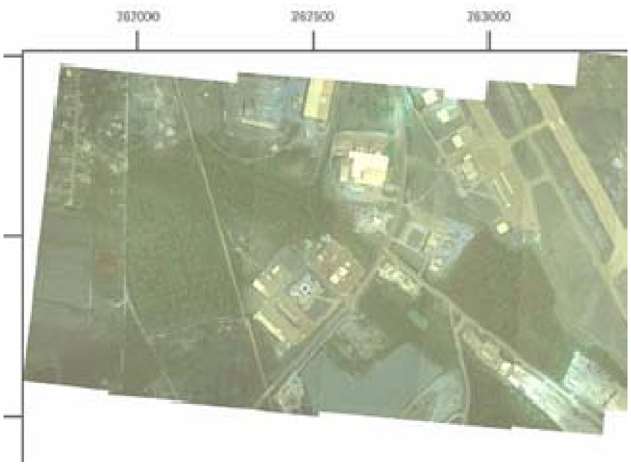

Figure 3 GRIM Mosaicked Image Products

VIDEO UPDATING

The CONOPS for this system is to use UAV generated GPS/INS data processed in a Kalman Filter to provide geo-registered data input to produce a GeoRaster database of auto-mosaicked images during flight. When GPS is denied, the UAV can return home using the images in the data base to limit drift in the INS only navigation solution onboard the UAV. This is done by a Waypoint Update calculated in the ground station and applied in the UAV's navigation system. The top level data flow for this is shown in Figure 4.

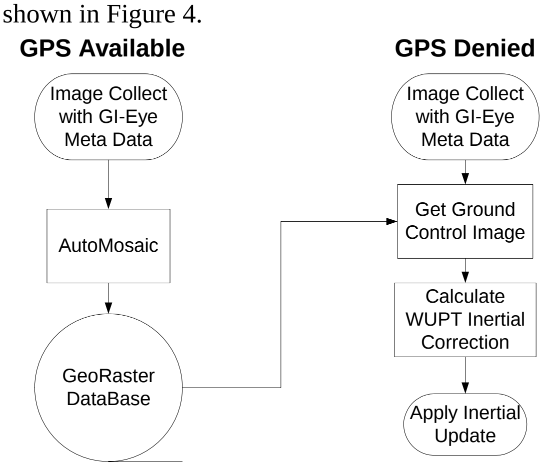

Figure 4 Video Updating Architecture

WAYPOINT UPDATES (WUPT)

The Waypoint Updates capability uses the PCI Pluggable Framework created by PCI Geomatics[3] to automatically process images by modeling their position and orientation, extracting Ground Control Points (GCPs), and comparing those points with the points on a reference image to correct any error in the position and attitude information of the sensor. The WUPT data flow is shown in Figure 5.

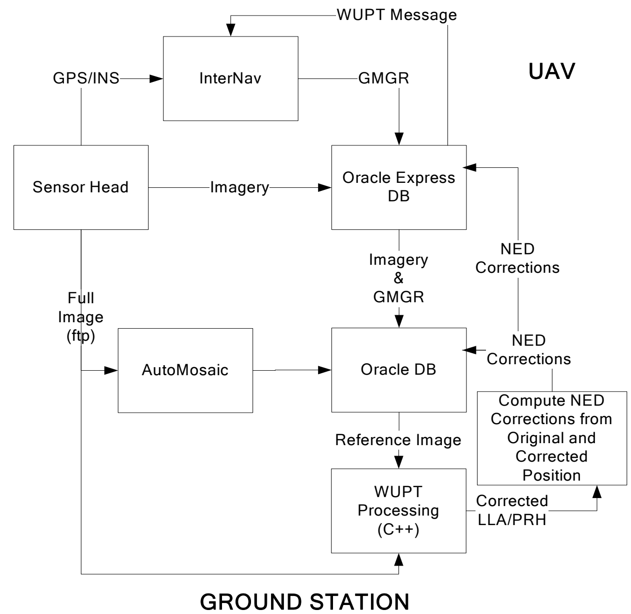

Figure 5 WUPT data flow

The PCI functions required for this are described below and shown in Figure 6.

pci.crproj
Creates Orthoengine project to guide the image processing

- pci.camimport

Imports camera calibration data from XML data extracted from database. This data includes camera focal length, CCD width and height, and optionally distortion information for the lens.

- pci.eoimport

Imports Exterior Orientation Data from GI-Eye Inertial Sensor's position/attitude metadata. The data is then used to model the location and orientation of the image.

- pci.autogcp

Collects GCPs for an input image from a reference image. The GCPs are visible features in the image automatically chosen for their uniqueness, to allow them to be matched with the same features in the reference image.

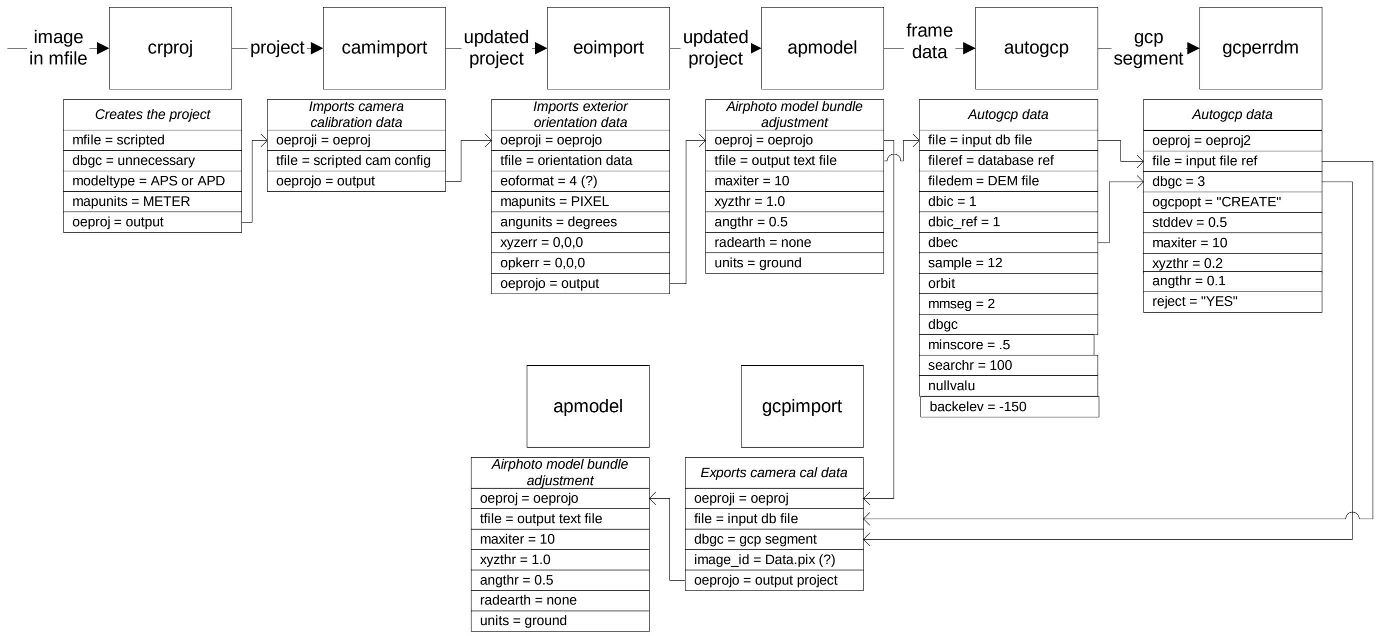

Figure 6 Image bundle adjustment data flow

- pci.gcperrdm

Detects and removes outlier GCPs for an aerial image. Outliers are GCPs that seem to be in error when compared with the results of the rest of the GCPs available. These GCPs are then excluded from use in determining the image bundle adjustment.

- pci.gcpimport

Import GCPs into an OE Project File.

- pci.apmodel

Performs a bundle adjustment for a set of aerial images Returns position and attitude offset of initial inertial meta-data. This is used to determine the position and attitude errors of the sensor and correct those errors.

The result of this processing provides an image based estimate of the UAV camera position and orientation when the GPS is denied.

FLIGHT TESTING

A flight test was conducted on 10 May 2007 using the dual GI-Eye systems shown in Figure 7. The dual GI-Eye systems were operated by Bruce Bockius of NAVSYS on the Cessna 206 flown by Dick Stefanski of the US Forest Service Region 2. The US Forest Service is interested in applications of the GI-Eye and WebGRIM technologies to provide real-time situational awareness and the employment of UAVs for persistent surveillance of hostile and dynamic environments (fire fighting).

Figure 7 Dual GI-Eye System Flown at USAFA

Figure 8 shows the NGA Tactical Surveying and Targeting System (TS2), which contained high-performance GPS, IMU and camera components. This system was flown as a reference system to compare results with the Landmark GI-Eye system. Figure 9 shows the components of the Landmark GI-Eye system, which had a low performance Crista IMU. Figure 7 shows the two systems as they were co-mounted to fly on the US Forest Service Cessna 206.

Figure 8 NGA Tactical Surveying and Targeting System (TS2)[4]

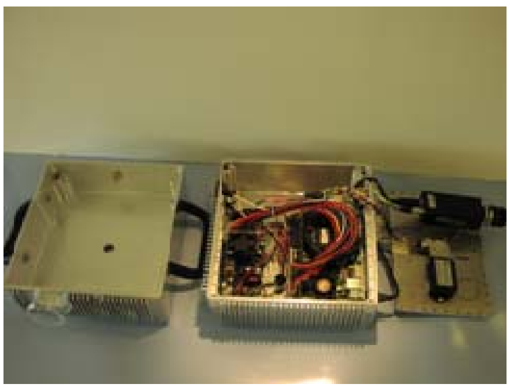

Figure 9 Landmark GI-Eye System Flown at USAFA

The collection area was the northeast section of the USAF Academy, Colorado, around the Aardvark Airfield and Jacks Valley (Figure 12and Figure 15). The area has a variety of buildings and ground features to include a runway with large white numbers, dirt and asphalt roads, a river bed, railroad tracks, bridges, concrete pads, static display aircraft, and small and large buildings. Daniel Steineman and Glenn Noll of the National Geospatial-Intelligence Agency (NGA) precisely surveyed 25 ground control points (GCPs) in June 2006 (less than 1 decimeter of error in latitude, longitude and ellipsoid height (WGS 84). These 25 GCPs represent a wide variety, size and contrast of features that can be identified from overhead imagery and were referenced in the single-shot and multi-shot targeting.

The Cessna 206 was specially modified to allow sensor payload to be mounted to look nadir through the bottom of the fuselage (Figure 10). The Cessna 206 was flown at 5000 feet above ground level (AGL) with northerly tracks into the wind (see Figure 11 and Figure 12). The Cessna was flown as slowly and safely as possible (100 knots IAS) to reduce pixel blur from translation over the ground. Since it was an afternoon flight with 10-15 knots of northerly wind at altitude and light turbulence, the Cessna 206 experienced roll excursions of a few degrees. This induced lateral blur in most images. Since the operation system for the two payloads did not include shutter and aperture control, this blur could not be reduce or eliminated real-time. However, approximately 25% of the images were sharp enough for processing. The data collected was evaluated and processed to determine system performance, to produce single-shot, multi-shot and mosaicking results and to demonstrate the WUPT navigation performance.

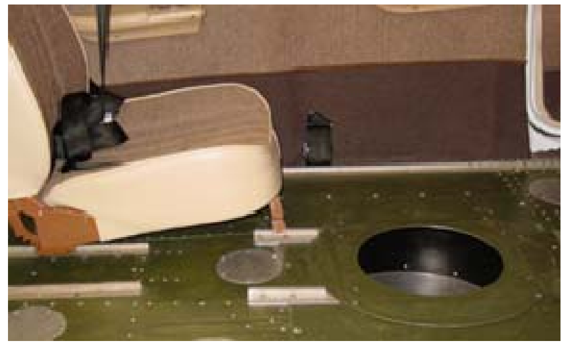

Figure 10 Nadir Opening on Cessna 206

FLIGHT TEST RESULTS

NAVSYS' web-based image processing software WebGRIM was used for the data analysis. Figure 11 shows the flight path of the aircraft during just one collection run. The average ground speed on the northerly legs was calculated from the metadata to be 41 meters per second.

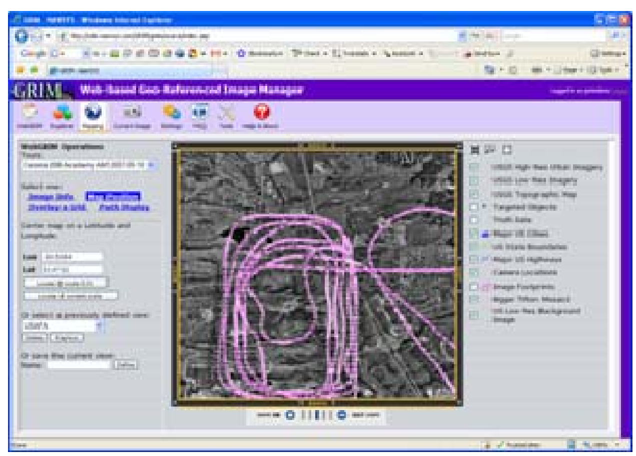

Figure 11 WebGRIM

WebGRIM can display the "footprints" of the aerial imagery as it is collected. Figure 12 shows the footprints displayed over a USGS WMS (Web Map Service) layer. This greatly aids in locating targets-of-interest.

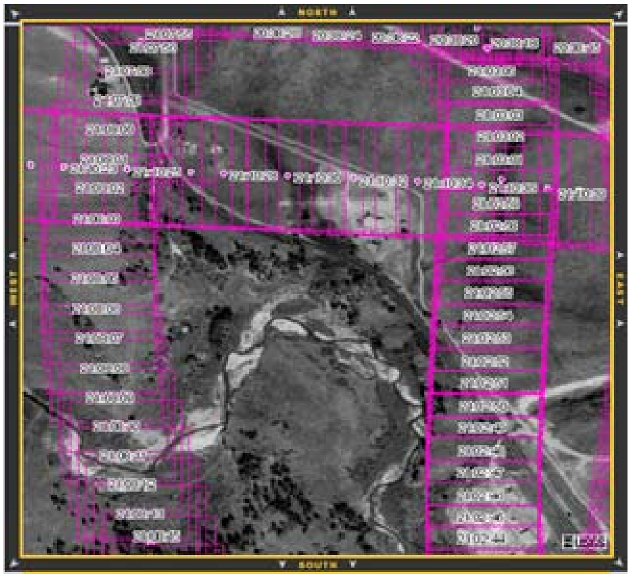

Figure 12 Imagery Footprints

Another function of WebGRIM is to mosaic collected imagery. Figure 13 shows an imagery layer mosaicked from collected data. The mosaic in the figure hasn't been color balanced so the boundaries of the source images can still be seen. Once mosaicked, the data behaves like any other map layer, and can be zoomed and panned as desired. Figure 14 shows a mosaic layer over a much older USGS WMS layer. Image footprints and times are also shown.

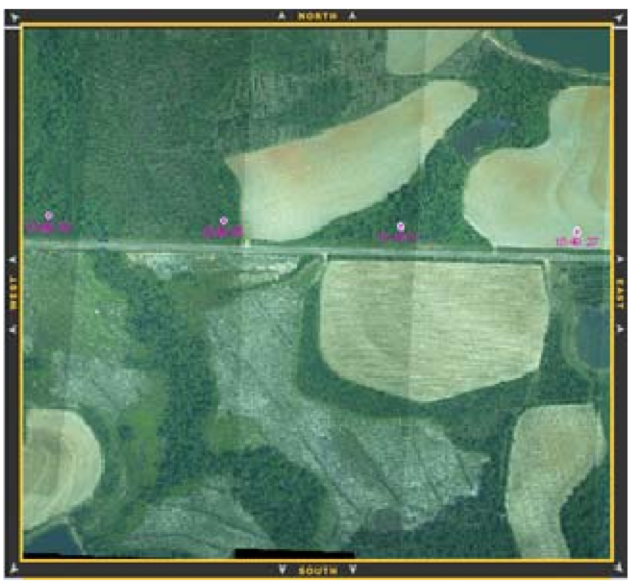

Figure 13 Auto Mosaicking

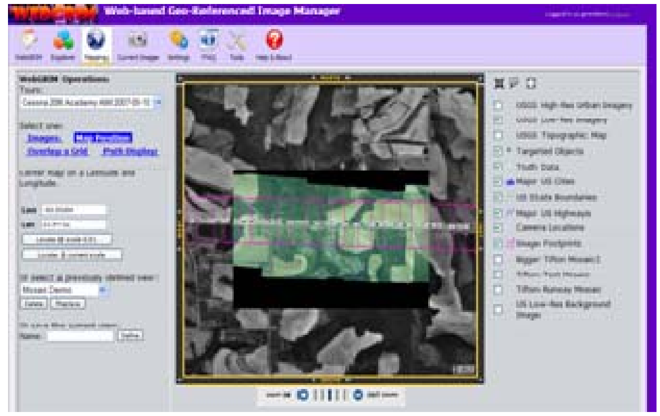

Figure 14 Mosaic Layer over WMS

Figure 15 shows the summary of the targeting results. NGA-surveyed truth points are shown as small circles superimposed over the larger green targeting results. The average accuracy of single-shot targeting was 2.7m 2DRMS.

Figure 15 Targeting Results

WUPT TEST RESULTS

Figure 16 displays actual GCPs located automatically in the image. The red numbers indicate "good" GCPs, the yellow numbers indicate outliers, in this case due to features that are not as unique as the algorithm initially expected them to be. The outliers will be rejected when creating the apmodel used in correction of the sensor attitude and location.

Figure 16 Actual GCPs located automatically

CONCLUSION

NAVSYS has developed an image aiding system for UAV flight navigation. The approach allows autonomous gathering of the required "background" georaster data base by the UAV when GPS availability provides accurate navigation position and attitude metadata. No preloaded data bases are required. This allows temporally accurate image data to be used. After gathering the geo-registered images the key issue is to develop a georaster data base and the analytical tools to provide image matching via ground control points. NAVSYS WebGRIM software has been configured to provide these tools.

Using these tools, when GPS is denied the UAV navigation system can use waypoint updates (WUPT) based on image matching to bound the inertial errors of its solution. During flight tests of this system mosaic registration and single shot target accuracy of 2.7 m (2DRMS) were demonstrated. This approach to video aiding provides a cost effective back-up navigation solution for small UAVs using their onboard avionics and sensor payloads

ACKNOWLEDGMENTS

The authors would like to acknowledge the support of the Mr. Keith Krapels, Office of Naval Research. The software development, flight tests and data analysis were funded by under contract # N00014-04-C-0017.

In addition, we'd like to acknowledge Mr. Robin Parrish, Enda McKenna and Tony Lopez at eSpatial[2]; and Mr. Johnny Lim, Dr. Richard Pollack, Trevor Taylor, Mr. Louis Burry, and Hubin Xin of PCI Geomatics[3].

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