An Autonomous 3-D Photogrammetric Approach to Airborne Video Geo-Registration

Steven G. Blask, John A. Van Workum
{sblask, jvanwork}@harris.com
Harris Corporation GCSD
Outline

• Overview of Harris Registration Approach

• Airborne Video Extensions - PVR System

• DARPA AVS-PVR Processing Results

• Discussion
Impact of ESD Errors

Geo-Reference Image

Video Frame

DARPA

next level solutions

13 July 2001
Photogrammetric Model Based Registration Overview

**Initial Transformation Process**
- Image -> 3-D Surface -> 2D View
- Tile Overlap Area in Scene Space
- Build Common Neighborhood Windows

**Normalized X-Correlation**
- In Enhanced Edge Space
- Build Correlation Surface
- Evaluate Correlation Peaks

**Consistent Subset Analysis**
- Compute Mean Offset Vector
- Sequentially Sort Peaks
- Resolve Ambiguities & Outliers
- Adjust Sensor Parameters
- Repeat at Next Resolution Level

**Support Data Initializes Sensor Geometry Model**

**Output Adjusted Support Data**

**Registered Images**

**Converged Solution**

**Adjusted Parameters**
Initial Transformation Process

- The images are subsampled to create reduced resolution data sets
- Software resampler creates patches at any required GSD on demand
Initial Transformation Process
Initial Transformation Process

- Use *a priori* knowledge of each sensor imaging event and a Digital Elevation Model (DEM) to project imagery to the 3D terrestrial surface.

\[
(u, v) = P_u (\phi, \lambda, h) \quad \text{and} \quad v = P_v (\phi, \lambda, h)
\]

Geometry Model for Sensor 1

\[
(\phi, \lambda, h) = F (\text{line, sample, } X_v, Y_v, Z_v, \text{ roll, pitch, heading, } \text{azimuth, elevation, twist, focal length})
\]

Geometry Model for Sensor 2

DEM
Initial Transformation Process

• Orthorectification places the images in a common orientation with minimal distortion present (unmodelled buildings & trees still layover)
Normalized X-Correlation

\[ r = \sqrt{\frac{N_3}{N_2}} \left( \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} (x_{ij} - \bar{x}) y_{ij}}{\left( \sum_{i=1}^{n} \sum_{j=1}^{n} x_{ij} \right)^2} - \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} y_{ij}^2}{N_3^2} \right) \]

\( N_3 = \) # of elements in reference patch
\( N_2 = \) # of elements in comparison patch
\( x_{ij} = \) elements in comparison patch
\( y_{ij} = \) elements in reference patch

Comparison Patch

Reference Patch

Correlation Patch

up to 4 candidates are chosen
Matchpoint Display

Video Mission Image

Geo-Reference Imagery
Estimate of Misalignment

- Multiple correlation peaks are computed for each grid point neighborhood
- A parametric hill finder is used to evaluate each peak
- The mean and standard deviation of registration error are calculated from the offset and average ellipse
- The best consistent subset of correlation peaks is chosen by sequential sorting
- Offset vectors imply global ground “correction” needed to improve registration, wild pt. editing eliminates outliers
Sensor Adjustment Process

- Sensor parameters are adjusted to minimize the error between ground projections of common match points.
- Conjugate Gradient Search, Least Squares, and Kalman Filter adjustment algorithms.

Registration measurements (correspondences)

Minimal Perturbation Adjustment Procedure

Image 1 geometry parameters
\[ x_1, y_1, z_1, \hat{v}_1, \hat{\hat{v}}_1 \]

Image 2 geometry parameters
\[ x_2, y_2, z_2, \hat{v}_2, \hat{\hat{v}}_2 \]
Output & Derivative Products

• Improved telemetry used by Geolocation & Mosaic
  – Telemetry parameters initialize sensor model to define a 3D ray through any pixel in the image, which may be intersected with the DEM to produce a geolocation or orthorectify a video frame.
  
  – By improving telemetry, we improve geodetic accuracy of pixels.
Registration Solution

- Advantage of model-based approach: can perform rigorous error propagation to characterize geopositioning solutions and provide *a posteriori* error covariances for adjusted sensor model params

\[ e = \sqrt{\left(\frac{\partial f}{\partial x_1}\right)^2 \cdot \sigma_1^2 + \left(\frac{\partial f}{\partial x_2}\right)^2 \cdot \sigma_2^2 + \ldots + \left(\frac{\partial f}{\partial x_n}\right)^2 \cdot \sigma_n^2} \]

- \( x_1, x_2, \ldots, x_n \) represents the parameters
- \( \sigma_1, \sigma_2, \ldots, \sigma_n \) represents the variances of \( x_i \)
- \( f \) represents the function of the parameters

Registered Sensor 1 & Sensor 2
Airborne Video Extensions

Precision Video Registration System
PVR Architecture

CAGS Services

- Video and Telemetry
- Video A/D and Telemetry Decoder
- Video

PVR Processing

- Reference & Frame Repository
- Video Frames
- Telemetry & Registration Processes (RTVR)
- Adjusted Telemetry
- Precision Mosaic Processes
- Precision Geolocation Processes
- Precision Broadcast

PVR Clients

- C2 User
- IA User
- Auto'd Proc.

PVR Manager

- Controls PVR Processes
- Handles Status Messages
- Reports Metrics

DARPA

next level solutions

13 July 2001
RTVR Architecture

Observation Generators

- Process Control
  - Selected Video Frames
  - Precision MatchPoints
  - Precision MatchPoints
  - Precision MatchPoints

Observation Combiner

- LSE Worm Controller
  - Match Points
- Match Point Sequential State Estimator
  - Match Points
  - Raw Telemetry
  - Telemetry Adjustments

Telemetry Database

Selected ESD
Telemetry Queue/Database

Video Frames

<table>
<thead>
<tr>
<th>Raw Telemetry (from CAGS Metadata)</th>
<th>Telemetry Adjustment (from Match Pt. SSE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position 30 Hz</td>
<td>Position, Attitude, Gimbals, Sensor Deltas</td>
</tr>
<tr>
<td>10 Hz</td>
<td>Goal: 1 Hz</td>
</tr>
<tr>
<td>Attitude 30 Hz</td>
<td>Oct'99 FEX: 0.22 Hz</td>
</tr>
<tr>
<td>Gimbals 25 Hz</td>
<td></td>
</tr>
<tr>
<td>Sensor 6.25 Hz</td>
<td></td>
</tr>
</tbody>
</table>

Quality of Service:
- Precision
- Extrapolated
- Interpolated

Position, Attitude, Gimbals, Sensor Deltas

Goal: 1 Hz

Oct'99 FEX: 0.22 Hz

HARD REGISTRATION

SOFT REGISTRATION

HARD REGISTRATION
Affine Consistent Subset

• Required to account for scale and rotation distortion
Selected frames from (in order) 1 hour, sparse features, class1, and class2 data sets, 29Mar99.

Raw telemetry errors in ascending order.
Selected frames from (in order) 1 hour, sparse features, class1, and class2 data sets, 29Mar99.

Outliers due to fuselage obscuration and low elevation angles

Registration errors for original consistent subset criterion in ascending order.
Affine CSS Results

Selected frames from (in order) 1 hour, sparse features, class1, and class2 data sets, 29Mar99.

Outliers due to fuselage obscuration and extremely low low elevation angles (17-20 deg)

Registration errors for affine consistent subset criterion in ascending order.
KF Adjustment Algorithm

- Sparse scene content of Airborne video requires accumulation of match points over space and time
- Kalman filter adjustment vs. N-frame co-registration
  - Adds one image at a time to solution
  - Only need to estimate parameters for one image
  - Smaller set of equations
  - No waiting for additional images
- State vector $\mathbf{X}$ models *adjustments* to telemetry; slowly varying bias suggests constant state model is suitable:
KF vs. Single Frame Results

Oct'99 VA D2 Clip

63 frames, EO vs DOQ DTED1

<table>
<thead>
<tr>
<th>Type</th>
<th>Median</th>
<th>90th</th>
<th>Mean</th>
<th>Std Dev</th>
<th>&lt;10m</th>
</tr>
</thead>
<tbody>
<tr>
<td>kf</td>
<td>3.80</td>
<td>8.44</td>
<td>4.70</td>
<td>2.50</td>
<td>93.3%</td>
</tr>
<tr>
<td>autoreg</td>
<td>7.44</td>
<td>13.33</td>
<td>8.27</td>
<td>3.62</td>
<td>71.6%</td>
</tr>
<tr>
<td>before</td>
<td>23.25</td>
<td>28.43</td>
<td>23.24</td>
<td>4.08</td>
<td>0.0%</td>
</tr>
</tbody>
</table>
KF vs. Single Frame Results

Oct'99 VA D2 Order Stats

63 frames, EO vs DOQ DTED1

ground error (m)

before
autoreg
kf
Scene Content & Pre-screener

- Compute MPt normalized image space residuals:
  \[ \rho = \varepsilon^T \Sigma^{-1} \varepsilon \]

\[ \varepsilon = \begin{bmatrix} y_1 - x_1 \\ y_2 - x_2 \end{bmatrix} \]

- Apply thresholds
  - min. no. match points
    - 9 for frame-to-mono ref.
    - 5 for frame-to-stereo ref.
    - 4 for frame-to-frame
  - avg. norm. res. \( \leq 1 \) pixel
  - max. norm. res. \( \leq 2 \) pixels
Dynamic Video Worm

Significant Scene Content Changes

Low Salient Feature Density

- Successful Mission-to-Reference Single Frame Event
- Worm Anchor Mission-to-Reference Frame
- Prescreened Mission-to-Mission, Unanchored End of Worm
- Unanchored Worm Segment, Interpolated “Soft” Adjustment
Further Accuracy Improvement

Geometry effects

DTED Terrain Surface

Solution Point

Ray Covariance

Image Ray/Range Arc

DTED Accuracy

Image 1

Solution Covariance

Video 1

Geo-Ref

Video 2

Video 1

Geo-Ref

Video 2

Geometry effects
PVR Georegistration Performance
Using DOQ & DTED

Dynamic Worm
(LSE, KF, & Prescreener)
DOQ Timing

- **Reference Data**
  - USGS Digital Ortho Quarter-Quad (1m GSD)
  - NIMA Digital Terrain Elevation Data (100m posts)

- **Timing Data**
  - SGI Octane
  - Dual 225MHz R10,000 cpu’s
  - 512Mb RAM total
  - Controller, Generator, Worm Combiner thread
NY Intersection Circle Stare

Feb'00 NY Site, Clip A4

61 frames, EO vs DOQ & DTED1

Ground Error (m)

<table>
<thead>
<tr>
<th>Type</th>
<th>Median</th>
<th>90th</th>
<th>Mean</th>
<th>Std Dev</th>
<th>&lt;10m</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>before</td>
<td>33.1</td>
<td>42.4</td>
<td>32.5</td>
<td>8.6</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>kf</td>
<td>2.7</td>
<td>4.4</td>
<td>3.0</td>
<td>1.3</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>
NY Intersection Circle Stare

Feb'00 NY Site, Clip A4 Timing Stats

61 frames, EO vs DOQ & DTED 1

<table>
<thead>
<tr>
<th>mean</th>
<th>9.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>stdev</td>
<td>2.6</td>
</tr>
</tbody>
</table>
VA 15-Oct Fast Straight Line

Oct'99 VA Site, Clip D2

63 frames, EO vs DOQ & DTED3

<table>
<thead>
<tr>
<th></th>
<th>before:</th>
<th>median: 23.2</th>
<th>90th: 28.4</th>
<th>mean: 23.2</th>
<th>std dev: 4.1</th>
<th>&lt;10m: 0%</th>
</tr>
</thead>
<tbody>
<tr>
<td>kf</td>
<td>median: 3.8</td>
<td>90th: 8.4</td>
<td>mean: 4.7</td>
<td>std dev: 2.5</td>
<td>&lt;10m: 93%</td>
<td></td>
</tr>
</tbody>
</table>
VA 15-Oct Fast Straight Line

Oct'99 VA Site, Clip D2 Timing Stats

63 frames, EO vs DOQ & DTED3
NC Suburban Run
NC Suburban Run

Mar'00 NC Site, Clip B4

55 frames, EO vs DOQ & DTED1

<table>
<thead>
<tr>
<th></th>
<th>before</th>
<th>median</th>
<th>90th</th>
<th>mean</th>
<th>std dev</th>
<th>&lt;10m</th>
<th>96%</th>
</tr>
</thead>
<tbody>
<tr>
<td>kf</td>
<td>median</td>
<td>4.5</td>
<td>9.1</td>
<td>4.9</td>
<td>2.3</td>
<td>96%</td>
<td></td>
</tr>
</tbody>
</table>

before: median: 24.4 90th: 27.6 mean: 24.3 std dev: 3.1 <10m: 0%

13 July 2001
NC Suburban Run

Mar’00 NC Site, Clip B4 Timing Stats

55 frames, EO vs DOQ & DTED 1

Latency (sec)
DOQ Validation Summary

Rollup - DOQ - Before Registration

Rollup - DOQ - After Registration

Note 2X scale change
Before vs. After

LEGEND:
- maximum
- 90th percentile
- 3rd quartile
- median
- 1st quartile
- 10th percentile
- minimum

0 5 10 15 20 25 30 35
1 2 3 4 5 6 7 8 9
A1 A2 A3 A4 B3 B4 D2 D3 D4

Ground Error (m)

Ground Error (m)
11 June 2001 Rollup - DOQ

### Ground Error (m)

- 0.0%
- 20.0%
- 40.0%
- 60.0%
- 80.0%
- 100.0%
- 120.0%

### Success (% <10m)

#### Mean Before

<table>
<thead>
<tr>
<th>Look Angle</th>
<th>GSD</th>
<th># Frames</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>Fine</td>
<td>0</td>
</tr>
<tr>
<td>High</td>
<td>Medium</td>
<td>273</td>
</tr>
<tr>
<td>High</td>
<td>Coarse</td>
<td>6</td>
</tr>
<tr>
<td>Moderate</td>
<td>Fine</td>
<td>0</td>
</tr>
<tr>
<td>Moderate</td>
<td>Medium</td>
<td>134</td>
</tr>
<tr>
<td>Moderate</td>
<td>Coarse</td>
<td>165</td>
</tr>
<tr>
<td>Low</td>
<td>Fine</td>
<td>0</td>
</tr>
<tr>
<td>Low</td>
<td>Medium</td>
<td>12</td>
</tr>
<tr>
<td>Low</td>
<td>Coarse</td>
<td>60</td>
</tr>
<tr>
<td><strong>DOQ Total:</strong></td>
<td></td>
<td><strong>650</strong></td>
</tr>
</tbody>
</table>

#### Mean After

#### Std Dev Before

#### Std Dev After

#### Success Rate

- High > 55
- Mod 35-55
- Low < 35

- Fine .15-.3
- Med .3 - 1
- Coarse > 1

### Next Level Solutions

13 July 2001
References


