Robust Feature-Based Registration of Remotely Sensed Data

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NASA / Goddard Space Flight Center
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King Mongkut’s University, Thailand
NEC Research Institute (Ret.)
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What is Image Registration / Alignment / Matching?

The above image over Colorado Springs is rotated and shifted with respect to the left image.
Definition and Motivation

- Task of bringing together two or more digital images into *precise alignment* for analysis and comparison

- A *crucial, fundamental* step in image analysis tasks, where final information is obtained by the combination / integration of multiple data sources.
Motivation / Applications

- **Computer Vision** (target localization, quality control, stereo matching)

- **Medical Imaging** (combining CT and MRI data, tumor growth monitoring, treatment verification)

- **Remote Sensing** (classification, environmental monitoring, change detection, image mosaicing, weather forecasting, integration into GIS)
Literature of Automatic Image Registration

• Books:
  – *Medical Image Registration*, J. Hajnal, D.J. Hawkes, and D. Hill (Eds.), CRC 2001
  – *2-D and 3-D Image Registration*, A. Goshtasby, Wiley 2005

• Surveys:
Application Examples

• Change Detection

Satellite images of Dead Sea, United Nations Environment Programme (UNEP) website
Change Detection (cont’d)

IKONOS images of Iran’s Bushehr nuclear plant, GlobalSecurity.org

Tools and Methods for Image Registration, CVPR, June 24, 2011
Change Detection (cont’d)

Satellite imagery of Sendai Airport before and after the 2011 earthquake
Automatic Image Registration for Remote Sensing

- Sensor webs, constellation, and exploration
- Selected NASA Earth science missions
- IR challenges in context of remote sensing
Sensor Webs, Constellation, and Exploration

Automatic Multiple Source Integration

Satellite/Orbiter, and In-Situ Data

Intelligent Navigation and Decision Making

Planning and Scheduling
### Selected NASA Earth Science Missions

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Number of Channels</th>
<th>Ultra Violet</th>
<th>Visible</th>
<th>Near-IR</th>
<th>Mid-IR</th>
<th>Thermal-IR</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AVHRR (D)</strong></td>
<td>5 Channels</td>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>(1.1 km)</td>
<td></td>
<td>Ultra Violet</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td><strong>TRMM/VIRS</strong></td>
<td>5 Channels</td>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>(2.1 km)</td>
<td></td>
<td>Visible</td>
<td></td>
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<tr>
<td><strong>Landsat4-MSS</strong></td>
<td>4 Channels</td>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>(80 m)</td>
<td></td>
<td>Visible</td>
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<tr>
<td><strong>Landsat5&amp;7-TM&amp;ETM</strong></td>
<td>7 Channels</td>
<td></td>
<td></td>
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<tr>
<td>(30 m)</td>
<td></td>
<td>Near-IR</td>
<td></td>
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<tr>
<td><strong>Landsat7-Panchromatic</strong></td>
<td>1 Channel</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>(15 m)</td>
<td></td>
<td>Mid-IR</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>JERS-1</strong></td>
<td>4 Channels</td>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>LISS-I (73m) - LISS-2 (36.5m)</td>
<td>8 Channels</td>
<td></td>
<td></td>
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</tr>
<tr>
<td><strong>SPOT-HRV Panchromatic</strong></td>
<td>1 Channel</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(10m)</td>
<td></td>
<td>Visible</td>
<td></td>
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</tr>
<tr>
<td><strong>SPOT-HRV Multispectral</strong></td>
<td>1 Channel</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>(20 m)</td>
<td></td>
<td>Near-IR</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>MODIS</strong></td>
<td>36 Channels</td>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>(Ch1-2:250 m;3-7:500m;8-36:1km)</td>
<td>36 Channels</td>
<td></td>
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<tr>
<td><strong>EO/1</strong></td>
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<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
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<tr>
<td><strong>ALI-MultiSpectr.</strong></td>
<td>9 Channels (30m)</td>
<td></td>
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<tr>
<td><strong>ALI-Panchrom.</strong></td>
<td>1 Channel (10m)</td>
<td></td>
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<tr>
<td><strong>Hyperion</strong></td>
<td>1 Channel (30m)</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>220 Channels</td>
<td></td>
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<tr>
<td><strong>LAC</strong></td>
<td>256 Channels (250m)</td>
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<td></td>
<td></td>
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</tr>
<tr>
<td><strong>IKONOS-Panchromatic</strong></td>
<td>1 Channel</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1m)</td>
<td></td>
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</tr>
<tr>
<td><strong>IKONOS-MS</strong></td>
<td>4 Channels (4m)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14 Channels</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td><strong>ASTER</strong></td>
<td>14 Channels</td>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>(Ch1-3:15m;4-9:30m;10-14:90m)</td>
<td>14 Channels</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>CZCS</strong></td>
<td>6 Channels</td>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>(1 km)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>SeaWiFS (D)</strong></td>
<td>8 Channels</td>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>(1.1 km)</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>TOVS-HIRS2 (D)</strong></td>
<td>20 Channels</td>
<td></td>
<td>20</td>
<td>19</td>
<td>17</td>
<td>11, 10, 9, 8, 7 to 1</td>
</tr>
<tr>
<td>(15 km)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>GOES</strong></td>
<td>5 Channels</td>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>(8 km:1, 4km:2, 2km: 5, 8km:3)</td>
<td>5 Channels</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>METEOSAT</strong></td>
<td>3 Channels</td>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>(V:2.5km, Wv&amp;IR:5km)</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
MODIS Satellite System

From the NASA MODIS website
## MODIS Satellite Specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Orbit:</strong></td>
<td>705 km, 10:30 a.m. descending node (Terra) or 1:30 p.m. ascending node (Aqua), sun-synchronous, near-polar, circular</td>
</tr>
<tr>
<td><strong>Scan Rate:</strong></td>
<td>20.3 rpm, cross track</td>
</tr>
<tr>
<td><strong>Swath Dimensions:</strong></td>
<td>2330 km (cross track) by 10 km (along track at nadir)</td>
</tr>
<tr>
<td><strong>Telescope:</strong></td>
<td>17.78 cm diam. off-axis, afocal (collimated), with intermediate field stop</td>
</tr>
<tr>
<td><strong>Size:</strong></td>
<td>1.0 x 1.6 x 1.0 m</td>
</tr>
<tr>
<td><strong>Weight:</strong></td>
<td>228.7 kg</td>
</tr>
<tr>
<td><strong>Power:</strong></td>
<td>162.5 W (single orbit average)</td>
</tr>
<tr>
<td><strong>Data Rate:</strong></td>
<td>10.6 Mbps (peak daytime); 6.1 Mbps (orbital average)</td>
</tr>
<tr>
<td><strong>Quantization:</strong></td>
<td>12 bits</td>
</tr>
</tbody>
</table>
| **Spatial Resolution:** | 250 m (bands 1-2)  
                        | 500 m (bands 3-7)  
                        | 1000 m (bands 8-36) |
| **Design Life:**      | 6 years                                                               |
Landsat-7 Satellite System

New Orleans, before and after Katrina 2005 (from the USGS Landsat website)
## Landsat-7 Satellite Specifications

<table>
<thead>
<tr>
<th>Launch</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>April 15, 1999</td>
</tr>
<tr>
<td>Vehicle</td>
<td>Delta II</td>
</tr>
<tr>
<td>Site</td>
<td>Vandenberg AFB</td>
</tr>
<tr>
<td>Orbit</td>
<td></td>
</tr>
<tr>
<td>Characteristics</td>
<td></td>
</tr>
<tr>
<td>Reference system</td>
<td>WRS-2</td>
</tr>
<tr>
<td>Type</td>
<td>Sun-synchronous, near-polar</td>
</tr>
<tr>
<td>Altitude</td>
<td>705 km (438 mi)</td>
</tr>
<tr>
<td>Inclination</td>
<td>98.2°</td>
</tr>
<tr>
<td>Repeat cycle</td>
<td>16 days</td>
</tr>
<tr>
<td>Swath width</td>
<td>185 km (115 mi)</td>
</tr>
<tr>
<td>Equatorial crossing time</td>
<td>10:00 AM±15 minutes</td>
</tr>
</tbody>
</table>
IKONOS Satellite System
# IKONOS Satellite Specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
</table>
| **Launch Date**                                    | 24 September 1999  
Vandenberg Air Force Base, California, USA |
| **Operational Life**                               | Over 7 years                                 |
| **Orbit**                                          | 98.1 degree, sun synchronous                 |
| **Speed on Orbit**                                 | 7.5 kilometers per second                    |
| **Speed Over the Ground**                          | 6.8 kilometers per second                    |
| **Number of Revolutions Around the Earth**         | 14.7 every 24 hours                          |
| **Orbit Time Around the Earth**                    | 98 minutes                                   |
| **Altitude**                                       | 681 kilometers                               |
| **Resolution**                                     | Nadir:                                       |
|                                                    | 0.82 meters panchromatic                     |
|                                                    | 3.2 meters multispectral                     |
|                                                    | 26° Off-Nadir                                |
|                                                    | 1.0 meter panchromatic                       |
|                                                    | 4.0 meters multispectral                     |
| **Image Swath**                                    | 11.3 kilometers at nadir                     |
|                                                    | 13.8 kilometers at 26° off-nadir             |
| **Equator Crossing Time**                          | Nominally 10:30 a.m. solar time              |
| **Revisit Time**                                   | Approximately 3 days at 40° latitude         |
| **Dynamic Range**                                  | 11-bits per pixel                            |
| **Image Bands**                                    | Panchromatic, blue, green, red, near IR      |
Image Registration in the Context of Remote Sensing

- **Navigation** or model-based *systematic correction*
  - Orbital, attitude, platform/sensor geometric relationship, sensor characteristics, Earth model, etc.

- **Image Registration** or feature-based *precision correction*
  - Navigation within a few pixels accuracy
  - Image registration using selected features (or control points) to refine geolocation accuracy

- **Two common approaches:**
  1. Image registration as post processing *(taken here)*
  2. Navigation and image registration in closed loop
Challenges in Registration of Remotely Sensed Imagery

- **Multisource data**
  - Multitemporal data
  - Various spatial resolutions
  - Various spectral resolutions

- **Subpixel accuracy**
  - 1 pixel misregistration $\geq 50\%$ error in NDVI classification

- **Computational efficiency**
  - Fast procedures for very large datasets

- **Accuracy assessment**
  - Synthetic data
  - *Ground truth* (manual registration?)
  - Consistency (*circular* registrations) studies
Fusion of Multitemporal Images

Improvement of NDVI classification accuracy due to fusion of multitemporal SAR and Landsat TM over farmland in The Netherlands (source: The Remote Sensing Tutorial by N.M. Short, Sr.)
Integration of Multiresolution Sensors

Registration of Landsat ETM+ and IKONOS images over coastal VA and agricultural Konza site
(source: J. LeMoigne et al., IGARSS 2003)
What is the “Big Deal” about IR?

How do humans solve this?

By matching control points, e.g., corners, high-curvature points.

Zitova and Flusser, IVC 2003
Automatic Image Registration Components

0. Preprocessing
   - Image enhancement, cloud detection, region of interest masking

1. Feature extraction (*control points*)
   - Corners, edges, wavelet coefficients, segments, regions, contours

2. Feature matching
   - Spatial transformation (a priori knowledge)
   - Similarity metric (correlation, mutual information, Hausdorff distance, discrete Gaussian mismatch)
   - Search strategy (global vs. local, multiresolution, optimization)

3. Resampling

\[ (x, y) \quad \rightarrow \quad T_p \quad \rightarrow \quad (i, j) \quad \rightarrow \quad (i + \Delta_i, j + \Delta_j) \]

\[ I_1 \quad \rightarrow \quad I_2 \]
Example of Image Registration Steps

- Feature extraction
- Feature matching
- Resampling

Registered images after transformation

Zitová and Flusser, IVC 2003
Step 1: Feature Extraction

Top 10% of wavelet coefficients (due to Simoncelli) of Landsat image over Washington, D.C. 
Step 1: Feature Extraction (cont’d)

Image features (extracted from two overlapping scenes over D.C.) to be matched
Step 2: Feature Matching / Transformations

- Given a *reference* image, $I_1(x, y)$, and a *sensed* image $I_2(x, y)$, find the mapping $(T_p, g)$ which “best” transforms $I_1$ into $I_2$, i.e.,

$$I_2(x, y) = g(I_1(T_p(x, y), T_p(x, y)))$$

where $T_p$ denotes spatial mapping and $g$ denotes radiometric mapping.

- Spatial transformations:
  - Translation, rigid, affine, projective, perspective, polynomial

- Radiometric transformations (resampling):
  - Nearest neighbor, bilinear, cubic convolution, spline
**Step 2: Transformations (cont’d)**

**Objective:** Find parameters of a transformation $T_p$ (consisting of a translation, a rotation, and an isometric scale) that maximize similarity measure.

$$x' = s \cos \theta \cdot x - s \sin \theta \cdot y + t_x$$
$$y' = s \sin \theta \cdot x + s \cos \theta \cdot y + t_y$$

$$T_p = \begin{pmatrix}
  s \cos \theta & -s \sin \theta & t_x \\
  s \sin \theta & s \cos \theta & t_y \\
  0 & 0 & 1
\end{pmatrix}$$
Step 2: Similarity Measures (cont’d)

- **$L_2$-norm:**
  Minimize sum of squared errors over overlapping subimage
  
  $$
  \sum [I_2 - T_p(I_1)]^2
  $$

- **Normalized cross correlation (NCC):**
  Maximize normalized correlation between the images

  $$
  NCC(I_1, I_2) = \frac{\sum \sum [I_1(x, y) - \bar{I}_1][I_2(x, y) - \bar{I}_2]}{\sqrt{\sum \sum [I_1(x, y) - \bar{I}_1]^2 \cdot \sum \sum [I_2(x, y) - \bar{I}_2]^2}}
  $$
Step 2: Similarity Measures (cont’d)

- **Mutual information (MI):**
  Maximize the degree of dependence between the images

\[
MI(I_1, I_2) = \sum_{g_1} \sum_{g_2} p_{I_1, I_2}(g_1, g_2) \cdot \log \left( \frac{p_{I_1, I_2}(g_1, g_2)}{p_{I_1}(g_1) \cdot p_{I_2}(g_2)} \right),
\]

or using histograms, maximize

\[
MI(I_1, I_2) = \frac{1}{M} \sum_{g_1} \sum_{g_2} h_{I_1, I_2}(g_1, g_2) \cdot \log \left( \frac{Mh_{I_1, I_2}(g_1, g_2)}{h_{I_1}(g_1) \cdot h_{I_2}(g_2)} \right)
\]
Step 2: Similarity Measures (cont’d), An Example

MI vs. $L_2$-norm and NCC applied to Landsat-5 images

Step 2: Similarity Measures (cont’d): An MI Example

Source: A.A. Cole-Rhodes et al., IEEE-TIP, 2003
Step 2: Similarity Measures (cont’d)

• (Partial) Hausdorff distance (PHD):

\[ H_K(I_1, I_2) = K^{th}_{p_1 \in I_1} \min_{p_2 \in I_2} \text{dist}(p_1, p_2), \]

where \( 1 \leq K \leq |I_1| \)
Step 2: Similarity Measures (cont’d): A PHD Example

Step 2: Similarity Measure (cont’d)

• Discrete Gaussian mismatch (DGM) distance:

\[ w_\sigma(a) = \exp \left( - \frac{\text{dist}(a, I_2)^2}{2\sigma^2} \right) \]

where \( w_\sigma(a) \) denotes the weight of point \( a \), and

\[ \text{DGM}_\sigma(I_1, I_2) = 1 - \frac{\sum_{a \in I_1} w_\sigma(a)}{|I_1|} \]

is the similarity measure ranging between 0 and 1
Step 2: Feature Matching / Search Strategy

- Exhaustive search
- Fast Fourier transform (FFT)
- Optimization (e.g., gradient descent; Thévenaz, Ruttimann, and Unser (TRU), 1998; Spall, 1992)
- Robust feature matching (e.g., efficient subdivision and pruning of transformation space; Huttenlocher et al., 1993, Mount et al., 1999, 2011)
Search Strategy: Geometric Branch and Bound

- **Space of affine transformations**: 6-D space
- **Subdivide**: Quadtree or kd-tree. Each cell $T$ represents a set of transformations; $T$ is *active* if it may contain $t_{opt}$; o/w, it is *killed*
- **Uncertainty regions (UR’s)**: Rectangular approximation to the possible images $\tau(a)$ for all $\tau \in T, a \in I_1$
- **Bounds**: Compute *upper bound* (on optimum similarity) by sampling a transformation and *lower bound* by computing *nearest neighbors* to each UR
- **Prune**: If lower bound exceeds best upper bound, then kill the cell; o/w, split it
Branch and Bound (cont’d)

Illustration of uncertainty regions
**Algorithmic Outline of B & B (Sketch)**

- For all active cells $T$ do
  1) Compute upper bound $dist^*$ on similarity metric
  2) For each active $T$ compute a lower bound on the similarity measure (can be done using a variant of efficient NN-searching)
  3) Prune search space, i.e., discard $T$ if lower bound exceeds best (upper bound) seen thus far
  4) O/w, split $T$ (e.g., along “longest dimension”) and enqueue $T_1, T_2$ in queue of active cells $Q$
  5) If termination condition met, e.g., $Q$ empty or $dist^* \leq \varepsilon_a$, then report transformation and exit; o/w, goto 1)
Extended B & B Framework

- **Approximate algorithm** applies to both PHD and DGM

- **Upper bound** variants:
  - Pure
  - Bounded alignment (BA)
  - Bounded least squares alignment (BLSA)

- **Priority strategies** for picking next cell
  - Maximum uncertainty (MaxUN)
  - Minimum upper bound (MinUB)
  - Minimum lower bound (MinLB)
Upper Bound Variants

- **Pure:**
  - Cell midpoint is candidate transformation

- **Bounded alignment (BA):**
  - Apply *Monte Carlo sampling*, i.e., sample a small number of point pairs, provided that UR of a point contains only one point from the other set
  - For each point pair compute a transformation
  - Return transformation whose distance is smallest

- **Bounded least squares alignment (BLSA):**
  - Apply *iterative closest pair*; first compute transformation that aligns centroids, then compute scale (that aligns spatial variances), and then compute rotation which minimizes sum of squared distances
Search Priorities

• **Maximum uncertainty** (MaxUN):
  – Next active cell with *largest average diameter* of its URs

• **Minimum upper bound** (MinUB):
  – Next active cell with *smallest upper bound*

• **Minimum lower bound** (MinLB):
  – Next active cell with *smallest lower bound*
Dataset Features Superimposed

VA

Cascades

Konza
Experimental Results for VA, Cascades, and Konza Sites (Exp. 1)
Experimental Results (cont’d) for VA, Cascades, and Konza Sites (Exp. 2)
Performance Results on Tested Sites

- Tested running time and transformation distance

- MinLB demonstrated best performance

- DGM (with certain $\sigma$, e.g., $\sigma = 0.5$) outperforms PHD; see in particular VA dataset (IR-IN)

- Comparable performance across same image pairings (e.g., Cascades and Konza)

- BA was almost always fastest but had highest degree of variation in accuracy

- In general, demonstrated the algorithm’s efficacy for many additional datasets, including multisensor images covering various spectral bands
Computational Efficiency

• Efficient search strategy (e.g., B & B variants)

• Hierarchical, pyramid-like approach

• Extraction of corresponding regions of interest (ROI)
Computational Efficiency (cont’d): An Example of a Pyramid-Like Approach

\[ \theta \leftarrow \theta \]
\[ s \leftarrow s \]
\[ t_x \leftarrow 2t_x \]
\[ t_y \leftarrow 2t_y \]
Hierarchical IR Example
Using Partial Hausdorff Distance

64 x 64

128 x 128

256 x 256
Image Registration Subsystem Based on a Chip Database

(1) Find chips that correspond to the incoming scene
(2) For each chip, extract window from scene, using UTM of:
   - 4 approx. scene corners
   - 4 correct chip corners
(3) Register each (chip-window) pair and record pairs of registered chip corners
(4) Compute global transformation from multiple local registrations
(5) Compute correct UTM of 4 scene corners of input scene
Chip-Window Refined Registration Using Robust Feature Matching

- Overcomplete wavelet-type decomposition: Simoncelli steerable pyramid
- Maxima extraction of top 10% of histogram
Compute Global Transformation from All Local Chip-Window Registrations

• From each local chip-window registration:
  • Compute *corrected locations* of 4 corners of each window, i.e., for each chip-window pair, establish correspondence of 4 points
  • If $n$ chips, then correspondence for set of $4n$ points is obtained

• Use *least median of squares* (LMS) procedure to compute global image transformation (in pixels)

• Use global transformation to compute new UTM coordinates for each of the 4 corners of the incoming scene
**Results of IR Subsystem for Landsat Imagery**

<table>
<thead>
<tr>
<th>Scene</th>
<th>( \theta )</th>
<th>( t_x )</th>
<th>( t_y )</th>
<th>PHD</th>
<th>[Sec]</th>
</tr>
</thead>
<tbody>
<tr>
<td>chip-wind1</td>
<td>-0.25</td>
<td>5.00</td>
<td>-45.00</td>
<td>0.37</td>
<td>151.0</td>
</tr>
<tr>
<td>chip-wind2</td>
<td>-0.50</td>
<td>5.00</td>
<td>-48.00</td>
<td>0.65</td>
<td>42.0</td>
</tr>
<tr>
<td>chip-wind3</td>
<td>0.45</td>
<td>4.73</td>
<td>-45.23</td>
<td>1.69</td>
<td>32.0</td>
</tr>
<tr>
<td>chip-wind4</td>
<td>0.12</td>
<td>6.29</td>
<td>-46.16</td>
<td>0.71</td>
<td>20.0</td>
</tr>
<tr>
<td>chip-wind5</td>
<td>0.00</td>
<td>4.00</td>
<td>-48.00</td>
<td>1.00</td>
<td>29.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scene</th>
<th>( \Delta \theta )</th>
<th>( \Delta t_x )</th>
<th>( \Delta t_y )</th>
</tr>
</thead>
<tbody>
<tr>
<td>chip-wind3</td>
<td>0.005</td>
<td>0.43</td>
<td>0.62</td>
</tr>
<tr>
<td>chip-wind4</td>
<td>0.017</td>
<td>0.09</td>
<td>0.37</td>
</tr>
<tr>
<td>chip-wind5</td>
<td>0.010</td>
<td>0.11</td>
<td>0.15</td>
</tr>
</tbody>
</table>

**Source:** N.S. Netanyahu, J. Lemoigne, and J.G. Masek. IEEE TGRS, 2004
**Computational Efficiency (cont’d), ROI Extraction**

**UTM of 4 scene corners known from systematic correction**

1. **Extract** reference chips and corresponding input windows using *mathematical morphology*

2. **Register** each (chip-window) pair and record pairs of registered chip corners (refinement step)

3. **Compute** global registration from multiple local ones

4. **Compute correct UTM** of 4 scene corners of input scene

**Advantages:**
- Eliminates need for chip database
- Cloud detection can easily be included in process
- Process any size images
- Initial registration closer to optimal registration => reduces computation time and increases accuracy

**Source:** A. Plaza, J. LeMoigne, and N.S. Netanyahu, *MultiTemp ‘05*
**Step 1: Chip-Window Extraction Using Mathematical Morphology**

**Mathematical morphology (MM) concept:**
- Nonlinear *spatial-based* technique that provides a framework
- Relies on a *partial* ordering relation between image pixels
- In grayscale imagery, such relation is given by the digital value of image pixels

**Grayscale MM Basic Operations:**

- **Dilation:**
  - 3x3 structuring element defines neighborhood around pixel P
  - (4-pixel radius disk SE)

- **Erosion:**
  - Max
  - Min

- **Original image**

- **Structuring element**

- **Dilation**
Step 1 (cont’d): Binary Erosion

Structuring element

Structuring element

Structuring element
Step 1 (cont’d): Binary Dilation
Step 1 (cont’d): Grayscale Morphology, e.g., Opening = Erosion + Dilation
Step 1 (cont’d): Chip-Window Extraction
Using Mathematical Morphology

• **Scale-Orientation Morphological Profiles (SOMPs):**
  From *openings* and *closings* with SEs = line segments of different orientations
  – SOMP = Feature vector \( D(x,y) \) at each pixel (various scales + orientations)
  – Entropy of \( D(x,y) = H(D(x, y)) \)

• **Algorithm:**
  1) Compute \( D(x,y) \) for each \((x,y)\) in reference scene
  2) Extract 256×256 reference chip centered around \((x',y')\) with \( \text{Max}\{H(D(x',y'))\} \)
  3) Compute \( D(x,y) \) for each \((x,y)\) in 1000×1000 search window in input scene centered around location \((x',y')\)
  4) Compute \( \text{RMSE}(D(x',y'), D(x,y)) \) for all \((x,y)\) in search area
  5) Extract input window centered around \((x,y)\) with \( \text{Min}(\text{RMSE}) \)
  6) Return to Step 2) until predefined number of chips is extracted
Step 1 (cont’d): Extracted Chip-Window Pairs Using Mathematical Morphology

10 chips extracted from Landsat-7 reference scene (Oct. 7, 1999)

10 windows extracted from Landsat-7 input scene (Nov. 8, 1999)
Results of Global Registration on Landsat-7/ETM+ Dataset over VA

<table>
<thead>
<tr>
<th>Chip-window</th>
<th>Rotation (deg)</th>
<th>Initial Shift $x$</th>
<th>Initial Shift $y$</th>
<th>Adjusted Shift $x$</th>
<th>Adjusted Shift $y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>0.0</td>
<td>12.0</td>
<td>4.0</td>
<td>14.0</td>
<td>1.0</td>
</tr>
<tr>
<td>(b)</td>
<td>0.0</td>
<td>-1.0</td>
<td>0.0</td>
<td>13.0</td>
<td>1.0</td>
</tr>
<tr>
<td>(c)</td>
<td>0.0</td>
<td>2.0</td>
<td>-2.0</td>
<td>13.0</td>
<td>1.0</td>
</tr>
<tr>
<td>(d)</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>13.0</td>
<td>1.0</td>
</tr>
<tr>
<td>(e)</td>
<td>0.0</td>
<td>-1.0</td>
<td>3.0</td>
<td>13.0</td>
<td>1.0</td>
</tr>
<tr>
<td>(f)</td>
<td>0.0</td>
<td>59.0</td>
<td>1.0</td>
<td>14.0</td>
<td>1.0</td>
</tr>
<tr>
<td>(g)</td>
<td>0.0</td>
<td>-3.0</td>
<td>-3.0</td>
<td>13.0</td>
<td>1.0</td>
</tr>
<tr>
<td>(h)</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>13.0</td>
<td>2.0</td>
</tr>
<tr>
<td>(i)</td>
<td>0.0</td>
<td>36.0</td>
<td>4.0</td>
<td>14.0</td>
<td>2.0</td>
</tr>
<tr>
<td>(j)</td>
<td>0.0</td>
<td>2.0</td>
<td>-2.0</td>
<td>13.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>
Extension to Multispectral Images

Registered dataset: ALI band 7 and Hyperion band 106
**ALI vs. Hyperion Results (cont’d)**

<table>
<thead>
<tr>
<th>Chip-window pair</th>
<th>Size (pixels)</th>
<th>Rotation (degrees)</th>
<th>Initial shift $t_x$</th>
<th>Initial shift $t_y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>128 x 128</td>
<td>11.28</td>
<td>-1.442</td>
<td>0.153</td>
</tr>
<tr>
<td>2</td>
<td>96 x 96</td>
<td>10.92</td>
<td>1.390</td>
<td>0.380</td>
</tr>
<tr>
<td>3</td>
<td>128 x 128</td>
<td>10.84</td>
<td>-0.020</td>
<td>-0.70</td>
</tr>
<tr>
<td>4</td>
<td>128 x 128</td>
<td>10.92</td>
<td>0.370</td>
<td>-1.11</td>
</tr>
<tr>
<td>5</td>
<td>128 x 128</td>
<td>10.69</td>
<td>-0.720</td>
<td>0.44</td>
</tr>
</tbody>
</table>

**Global registration** rotation = $11.48^\circ$ $t_x = -160.57$ $t_y = 152.41$

**vs. “ground truth”** rotation = $11.34^\circ$ $t_x = -160.28$ $t_y = 149.8$

**Source:** A. Plaza, J. LeMoigne, and N.S. Netanyahu, IGARSS ’07

*Tools and Methods for Image Registration, CVPR, June 24, 2011*
Image Registration for Remote Sensing
Cambridge University Press 2011
Book on IRRS (cont’d)

- Definition and survey of image registration for remote sensing (Chs. 1—3)
- Choice of similarity metrics (Chs. 4—6)
- Efficient search strategies (Chs. 7—13)
- Operational remote sensing systems (e.g., IKONOS, Landsat, AVHRR, SPOT, etc.), Chs. 14—22
IR Components (Revisited)

Features
- Gray levels
- Edges
- Wavelets or wavelet-like

Similarity measure
- Correlation
- $L_2$-norm
- Mutual information
- Hausdorff distance

Strategy
- Fast Fourier transform
- Gradient descent
- Thévenaz, Ruttimann, Unser optimization
- Spall’s optimization
- Robust feature matching
IR Components (Revisited)

Features

- Gray levels
- Spline or Simoncelli LPF
- Simoncelli BPF

Similarity measure

- Correlation
- $L_2$-norm
- MI
- $L_2$-norm
- MI
- Hausdorff distance

Strategy

- FFT
- Gradient descent
- Thevenaz, Ruttimann, Unser optimization
- Spall’s optimization
- Gradient descent
- Thévenaz, Ruttimann, Unser optimization
- Spall’s optimization

Robust feature matching
Goals of a Modular Image Registration Framework

• **Testing framework to:**
  – Assess various combinations of components
  – Assess a new registration component

• **Web-based registration tool would allow user to “schedule” combination of components, as a function of:**
  – Application
  – Available computational resources
  – Required registration accuracy

• **Prototype of web-based registration toolbox:**
  – Several modules based on wavelet decomposition
  – Java implementation; JNI-wrapped functions
Web-Based Image Registration Toolbox

TARA ("Toolbox for Automated Registration & Analysis")

1. Open Image files
   - Input Image: [Browse]
   - Reference Image: [Browse]

2. Select Registration Algorithm
   - UREG
   - TRUMI
   - SPSA
   - Use All Algorithms

3. Customize Algorithm
   - [Select Parameters]

4. Perform Registration
   - [Register Images] [Reset]
Web-Based Image Registration Toolbox
TARA ("Toolbox for Automated Registration & Analysis")
Current and Future Work

• Conclude component evaluation
  – Sensitivity to noise, radiometric transformations, initial conditions, and computational requirements
  – Integration of digital elevation map (DEM) information

• Build operational registration framework/toolbox
  – Web-based
  – Applications:
    • EOS validation core sites
    • Other EOS satellites (e.g., Hyperion vs. ALI registration) and beyond
    • Image fusion, change detection