Joint transform optical correlation applied to sub-pixel image registration

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Overview

Program Goals
Background Theory—the JTC
Simulation Results
Experimental Verification
Conclusions
Program Goals

Establish an optical signal processing lab
Demonstrate a high-resolution image registration system based on the optical joint transform correlator
Demonstrate near-real-time operation
Demonstrate an all-optical processor
Assess applicability to future systems
Image Co-Addition

Basic Premise

• Shoot a movie
• Line up the frames and add them together

Benefits

• Suppress motion blur
• Increase resolution
• Suppress transient noise, hot, and dead pixels
• Relax requirements on focal plane
Background: Joint Transform Correlators

Illustration courtesy U.S. Air Force
JTC Operation

Input

Power Spectrum

Joint Power Spectrum

Output

Illustration courtesy U.S. Air Force
The BJTC

Binarization in the transform plane

Output peaks approach delta functions

Illustration courtesy U.S. Air Force
Input plane preprocessing

Two methods used:

Linear display of bitmap

Laplacian based binarization:

Convolve with

\[
\begin{bmatrix}
0 & -1 & 0 \\
-1 & 4 & -1 \\
0 & -1 & 0
\end{bmatrix}
\]

Threshold at zero

1 shift, 3 adds, 1 compare per pixel
Fourier plane processing

Two methods used:

**High pass filter:**
- Convolve with: \([-1 2 -1]\)
- Threshold at zero
- 1 add, 1 shift, 1 compare per pixel

**Frame subtraction:**
- Capture Fourier images for R+S and R-S
  - In the second input the scene image is inverted
- Subtract the Fourier plane images
- Threshold at zero
- Two optical operations, 1 compare per pixel
JTC Image Registration: Simulation Results

Position error vs. sub-image size (in pixels)

| Root mean position error (pixels) vs. image size and processing for NYC Landsat data |
|----------------------------------|----------------------------------|----------------------------------|----------------------------------|----------------------------------|----------------------------------|
| Input Processing     | Fourier plan | 16x16 | 20x20 | 32x32 | 64x64 | 128x128 |
| 3x3 Laplacian, Bina  | linear       | 0.1102 | 0.0999 | 0.1076 | 0.1005 | 0.1124 |
| 3x3 Laplacian        | linear       | 0.0810 | 0.0854 | 0.1039 | 0.1114 | 0.1104 |
| none                 | linear       | fail   | fail   | fail   | fail   | fail   |
| 3x3 Laplacian        | binary       | 0.1145 | 0.1190 | 0.1201 | 0.1244 | 0.1215 |
| 3x3 Laplacian, Bina  | binary       | 0.1158 | 0.143  | 0.1357 | 0.125  | 0.1265 |
| none                 | binary       | 0.3340 | 0.2662 | 0.1563 | 0.1311 | 0.1166 |

Localization based on centroid of 5x5 region in output plane
Study area is centered in downtown Manhattan
Test images have 1/2 resolution of original Landsat images

Similar to Experimental Case Modeled

Photo courtesy NASA
Transform Input Image to System Resolution using PICASSO and Sample on 750µ Grid

Size: 153x146    f = 16 mm
GSD: 750µ    F# = 5.9
R = 81 cm    Q = 0.22
D = 2.7 mm    Res ~ 0,2

Single Frame
Input set is 32 frames with sub-pixel jitter
After registration, these are the same

Sub-pixel jitter
\( \sigma^2_x = 0.083 \) pixels
Size: 153x146
Res ~ 0,3

± 1 pixel jitter
\( \sigma^2_x = 0.75 \) pixels
Size: 153x146
Res ~ -1,2

± 2 pixel jitter
\( \sigma^2_x = 2.1 \) pixels
Size: 153x146
Res ~ -2,3
Sum of five frames with registration

One pixel jitter

Registered to nearest ½ pixel

Size: 153x146
Res ~ 0.1

Size: 306x292
Res ~ 0.6
Sum of 32 frames with registration

One pixel jitter

Registered to nearest $\frac{1}{2}$ pixel

Size: 153x146
Res $\sim 0.3$

Size: 360x292
Res $\sim 1.2$
Experimental JTC Setup

Input SLM
BNS 256x256
HWP
BS (POL)
FTL 175mm
Spatial Filter
Output Camera
HeNe Laser
Input Plane

Positive

Negative
Input Plane

Laplacian filtered input

\[
\begin{bmatrix}
0 & -1 & 0 \\
-1 & 4 & -1 \\
0 & -1 & 0 \\
\end{bmatrix}
\]
Fourier Plane

Positive

Negative

Laplacian
Fourier Plane Binarization

Positive

Negative

Laplacian

Convolution Filtering

Frame Subtraction

Laplacian, Conv. Filter.
Output Plane: Single SLM

Convolution Filtering

Frame Subtraction

Laplacian, Conv. Filter.
Experimental JTC Registration

RMS error

Simulation : 0.192 pixels
Experimental : 0.246 pixels
### All Optical JTC

**HeNe Laser**

**Spatial Filter**

**BS 1 90/10**

<table>
<thead>
<tr>
<th>Input SLM</th>
<th>HWP</th>
<th>BS 2 (POL)</th>
<th>FTL 1 200mm</th>
<th>FP SLM Hamamatsu OASLM</th>
<th>HWP</th>
<th>BS 3 (POL)</th>
<th>FTL 2 175mm</th>
<th>Output Camera</th>
</tr>
</thead>
</table>

#### Lab Setup
Laser illumination
First JTC stage
All Optical JTC

Second JTC stage
Output Plane: All Optical

- All Optical: Linear Input
- All Optical: Laplacian Filtered Input
All Optical JTC Registration Results

X Displacement

Y Displacement

RMS error

Linear input : 0.150 pixels

Laplacian filter : 0.121 pixels
Experimental Data—32 Frame Co-Adds

Simulated JTC Registration

Experimental JTC Registration

Both Simulated and Experimental Registration Yield Resolution 1,2
Conclusions

Sub-pixel registration has been demonstrated using an all-optical JTC

Registration error with standard deviation less than 1/8 pixel has been demonstrated

Applying experimental registration to image coaddition has been demonstrated to nearly double resolution

All this in the first month that our lab has been open

Work to automate the system is under way—the goal of tracking registration on a live moving image should be met by summer’s end
Backup
Applications of Sub-Pixel Registration

Image co-addition
Image splicing
Scene-based adaptive optics
Moving object detection
Goals for First Year

Establish an optical correlation lab 😊

Model high-resolution image registration and co-addition 😊

Develop efficient algorithms for use with an optical co-processor – *Working on it*

Demonstrate an all-optical correlator 😊

Demonstrate correlation with sub-pixel (1/8 pixel or better) resolution 😊
# JTC Image Registration: Simulation Results

<table>
<thead>
<tr>
<th>Input Processing</th>
<th>Fourier pla.</th>
<th>8x8</th>
<th>12x12</th>
<th>16x16</th>
<th>20x20</th>
<th>25x25</th>
<th>32x32</th>
</tr>
</thead>
<tbody>
<tr>
<td>3x3 Laplacian, Bin</td>
<td>linear</td>
<td>0.3328</td>
<td>0.1659</td>
<td>0.1426</td>
<td>0.1362</td>
<td>0.1042</td>
<td>0.0577</td>
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<tr>
<td>3x3 Laplacian</td>
<td>linear</td>
<td>0.1472</td>
<td>0.1319</td>
<td>0.1216</td>
<td>0.1333</td>
<td>0.1113</td>
<td>0.0644</td>
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<tr>
<td>none</td>
<td>linear</td>
<td>fail</td>
<td>fail</td>
<td>fail</td>
<td>fail</td>
<td>fail</td>
<td>fail</td>
</tr>
<tr>
<td>3x3 Laplacian</td>
<td>binary</td>
<td>0.1522</td>
<td>0.1510</td>
<td>0.1280</td>
<td>0.1341</td>
<td>0.1405</td>
<td>0.1272</td>
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<tr>
<td>3x3 Laplacian, Bin</td>
<td>binary</td>
<td>fail</td>
<td>0.1414</td>
<td>0.0991</td>
<td>0.0992</td>
<td>0.0861</td>
<td>0.0901</td>
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<tr>
<td>none</td>
<td>binary</td>
<td>fail</td>
<td>0.3441</td>
<td>0.2822</td>
<td>0.3807</td>
<td>0.2709</td>
<td>0.2726</td>
</tr>
</tbody>
</table>

Localization based on centroid of 5x5 region in output plane

- rms error (pixels) < 0.125

Study area is a terminal at Reagan National Airport

- < 0.25

Test images have 1/2 resolution of original images

- > 0.25
## JTC Image Registration: Simulation Results

### Root mean position error (pixels) vs. image size and processing for Bethesda 1937

<table>
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<tr>
<th>Input Processing</th>
<th>8x8</th>
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<th>20x20</th>
<th>25x25</th>
<th>32x32</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fourier plan</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3x3 Laplacian, Linear</td>
<td>0.2632</td>
<td>0.0655</td>
<td>0.0359</td>
<td>0.0374</td>
<td>0.0400</td>
<td>0.0378</td>
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<tr>
<td>3x3 Laplacian, Binary</td>
<td>0.1643</td>
<td>0.0838</td>
<td>0.0579</td>
<td>0.0466</td>
<td>0.0586</td>
<td>0.0582</td>
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<tr>
<td>3x3 Laplacian</td>
<td>0.2783</td>
<td>0.1138</td>
<td>0.1087</td>
<td>0.1189</td>
<td>0.1092</td>
<td>0.1140</td>
</tr>
<tr>
<td>3x3 Laplacian, Binary</td>
<td>0.2693</td>
<td>0.1304</td>
<td>0.1175</td>
<td>0.1213</td>
<td>0.1058</td>
<td>0.1063</td>
</tr>
</tbody>
</table>

Localization based on centroid of 5x5 region in output plane

- rms error (pixels) < 0.125

Study area is a 1937 aerial photo of Bethesda, MD

- < 0.25

Test images have 1/2 resolution of original images

- > 0.25
Co-Addition Results

12 underexposed input images
Taken with digital camera
Several pixels frame-to-frame jitter
Rotation ± 1 degree

Photo courtesy U.S. Park Service
Goals for Second Year

Demonstrate real-time (>50 Hz) image registration with a live input
Refine co-addition algorithms
Demonstrate near-real-time (seconds) image co-addition
Model and demonstrate application to scene-based adaptive optics
Model and demonstrate application to moving target detection
Establish a parallel capability in a classified lab space
Scene-Based Adaptive Optics

Developed by Lisa Poyneer at LLNL

Does not require guide star or beacon

Digital computation for 16x16 adaptive mirror

requires ~150 256 point FFTs per input image
Moving Target Detection

When a target moves relative to a moving background, two peaks will be seen in the JTC output.

The distance between the peaks shows target motion.

If the target is large enough, and the motion is far enough, the peaks will be resolvable.

The first goal in this area is to evaluate practicality.

If the effect shows promise, a demo will be developed.
Experimental Setup

WILL BE REPLACED WITH PHOTO SERIES SIMILAR TO ALL OPTICAL JTC
Output Plane

Frame Subtraction
Fourier Plane
Fourier Plane

Negative
Fourier Plane

Laplacian
Output Plane

Convolution Filtering
Output Plane

Laplacian
Output Plane

One Pass: Hamamatsu + BNS
One Pass: Hamamatsu + BNS, Laplacian input