COSI-Corr: A Solution for 3D Change Detection using Optical Imagery

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COSI-Corr: Co-registration of Optically Sensed Images and Correlation

1. Satellite imagery acquired at different times, any resolution, possibly by different sensors

Measuring surface processes from optical imagery

2. Automatic registration with accuracy of 1/10 of the pixel size (sub-pixel)

3. Automatic comparison of images to measure motion

4. Ground deformation

Vector field

Leprince et al., IEEE TGRS, 2007

http://www.tectonics.caltech.edu/slip_history/spot_coseis/
Sub-Pixel Image Correlation: Locally Rigid Translations

- Fourier Shift Theorem
  
  \[ i_2(x, y) = i_1(x - \Delta_x, y - \Delta_y) \]
  
  \[ I_2(\omega_x, \omega_y) = I_1(\omega_x, \omega_y)e^{-j(\omega_x \Delta_x + \omega_y \Delta_y)} \]

- Normalized Cross-spectrum
  
  \[ C_{i_1i_2}(\omega_x, \omega_y) = \frac{I_1(\omega_x, \omega_y)I_2^*(\omega_x, \omega_y)}{|I_1(\omega_x, \omega_y)I_2^*(\omega_x, \omega_y)|} = e^{j(\omega_x \Delta_x + \omega_y \Delta_y)} \]

- Finding the relative displacement
  
  \[ \phi(\Delta_x, \Delta_y) = \sum_{\omega_x = -\pi}^{\pi} \sum_{\omega_y = -\pi}^{\pi} W(\omega_x, \omega_y)|C_{i_1i_2}(\omega_x, \omega_y) - e^{j(\omega_x \Delta_x + \omega_y \Delta_y)}|^2 \]

  \( W \) weighting matrix. \((\Delta_x, \Delta_y)\) such that \(\phi\) minimum.

S. Leprince et al., IEEE TGRS, 2007
COSI-Corr: a wide range of applications

- Earthquake
- Glacier
- Landslide
- Sand dunes
- Agriculture
- Urban DSM
In This Presentation:

• First COSI-Corr results on Landsat 8 images
  ➢ The Mw 7.7 Balochistan earthquake, Sept. 2013

• 3D change detection
  ➢ General principles
  ➢ Application to glacier flow monitoring in New Zealand using Worldview
  ➢ Application to urban damage mapping after the Oklahoma tornado, May 2013, using Worldview
First Large Earthquake seen by Landsat 8: The Sep. 24, 2013 Mw 7.7 Balochistan earthquake, Pakistan

Studied fault rupture using Landsat 8, Panchromatic band at 15 m GSD.

Images acquired:

- September 10, 2013 - 14 days before the event,
- September 26, 2013 - 2 days after the event.
- Fault rupture covered 2 Landsat scenes with extent of 200 km.
Balochistan Earthquake seen by Landsat 8

- Distortions from CCD misalignments,
- Biases of up to 1.5m, or 1/10 of pixel size,
- Very good registration of Landsat 8 images!

Avouac et al., EPSL, 2014
Balochistan Earthquake seen by Landsat 8

East-West component of the rupture recovered from Sub-Pixel correlation

- After destriping noise on the order of 40-60 cm on ground displacement
- Can extract reliable rupture map

Avouac et al., EPSL, 2014
Balochistan Earthquake seen by Landsat 8

- Parallel and normal slip distributions
- Noise level better than 1/20 of pixel size once corrected for CCD distortions.

Avouac et al., EPSL, 2014
3D and 4D Processing Flow

1. Optimize Viewing Parameters
Jointly optimize external parameters:

- roll, pitch, yaw angles: $r(t), p(t), y(t)$
- Spacecraft position in time $x(t), y(t), z(t)$
- $2^{nd}$ order polynomials approximation
- If no GCP, regularized solution to stay within instrument uncertainties.
3D and 4D Processing Flow

1. **Optimize Viewing Parameters**
   - Pairwise image matching between all images,
   - Only keep tie-points on stable surfaces (e.g., bedrock),
   - Optimize external viewing parameters of all images jointly using regularized bundle adjustment.

2. **Produce Disparity Maps**
Produce Disparity Maps

Project each image onto common reference surface (smooth topo surface)

Given a stereo-pair of images \((I_S, I_T)\) how to retrieve the disparity map \(d\)?

Image Matching Framework with Regularization

\[
E(d) = E_M(I_S, I_T \circ (id + d)) + E_R(d)
\]

\[
E_M(I_S, I_T \circ (id + d)) \approx \sum_{x \in I_S} S(I_S, I_T \circ (id + d(x)), x)
\]

\[
E_R(d) \approx \sum_{x \in I_S} \sum_{y \sim x} w(x, y) |d(x) - d(y)|
\]

- Similarity criteria (ZNCC)
- \(d\) constant on patch
- Piecewise constant prior
- Weighs the prior
- Neighbors of pixel \(x\)
Produce Disparity Maps

Use of multi-scale pyramidal approach to lower the complexity

Regularization: Semi-Global Matching (SGM) – current implementation

\[
d^* = \arg\min_d \left( \sum_{x \in I_S} S(I_S, I_T \circ (id + d(x)), x) + \sum_{x \in I_S} \sum_{y \sim x} w(x, y) |d(x) - d(y)| \right)
\]

Non convex problem => variational approaches won’t work

=> Restrict \(d(x)\) to a finite set of value and rewrite as first order Markov Random Field

(a) Minimum Cost Path \(L_x(p, d)\)

(b) 16 Paths from all Directions \(r\)

Only regularize along 1D directions and aggregate costs. Reduces complexity.

Hirschmuller, CVPR, 2005
Produce Disparity Maps

Regularization: Global Matching (GM) – under implementation

\[
d^* = \arg\min_d \left( \sum_{x \in I_S} S(I_S, I_T \circ (id + d(x)), x) + \sum_{x \in I_S} \sum_{y \sim x} w(x, y) |d(x) - d(y)| \right) \]

=> Restrict d(x) to a finite set of value and rewrite as first order Markov Random Field

\[
p^* = \arg\min_{p_x} \left( \sum_{x \in I_S} c_x(p_x) + \sum_{x \in I_S} \sum_{y \sim x} w_{xy} |\delta(p_x) - \delta(p_y)| \right) \]

Complex problem (NP-Hard) but several effective techniques exist, e.g. Fast Primal-Dual from Komodakis, Tziritas and Paragios
3D and 4D Processing Flow

1. **Optimize Viewing Parameters**
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   - Optimize external viewing parameters of all images jointly using regularized bundle adjustment.

2. **Produce Disparity Maps**
   - Project all images on reference surface (e.g. low res DTM, GTOPO or smoothed GDEM),
   - Cross-correlate image pairs using multi-scale, regularized image correlation.

3. **Produce Point and Vector clouds (3D, 4D)**
Produce Point and Vector clouds (3D, 4D)

Triangulate multiple disparity maps to retrieve 3D topography and displacement fields.
3D and 4D Processing Flow

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   - Project all images on reference surface (e.g. low res DTM, GTOPO or smoothed GDEM),
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3. **Produce Point and Vector clouds (3D, 4D)**
   - Triangulate disparity maps,
     - \((x_1, y_1, z_1)\)
     - \((x_2, y_2, z_2)\)
     - \((x_1, y_1, z_1, D_x, D_y, D_z)\)
   - Output surface models at all times.
3D and 4D Processing Flow

1. Optimize Viewing Parameters
   - Pairwise image matching between all images,
   - Only keep tie-points on stable surfaces (e.g., bedrock),
   - Optimize external viewing parameters of all images jointly using regularized bundle adjustment.

2. Produce Disparity Maps
   - Project all images on reference surface (e.g. low res DTM, GTOPO or smoothed GDEM),
   - Cross-correlate image pairs using multi-scale, regularized image correlation.

3. Produce Point and Vector clouds (3D, 4D)
   - Triangulate disparity maps,
     - \( (x_1, y_1, z_1) \)
     - \( (x_2, y_2, z_2) \)
     - \( (x_1, y_1, z_1, D_x, D_y, D_z) \)
   - Output surface models at all times.

4. Grid Point Clouds and Vector Clouds
   - Use standard gridding libraries on each components (only external processing).
Monitoring Glacier Flow in New Zealand

Multi-temporal Stereo Acquisitions using Worldview GSD 50 cm:

- January 30, 2013 (x2)
- February 9, 2013 (x2)
- February 28, 2013 (x2)

- Bundle adjustment between all images,
- Multi-scale image matching due to large disparities (up to 1000 pixels),
- Regularized matching because of occlusions

Collaboration F. Herman, Univ. Lausanne, Switzerland
Monitoring Glacier Flow in New Zealand

3D motion between January 30 and February 9, 2013

Measurements with intersection errors larger than 2m (20cm/day) have been removed (white areas).
Monitoring Glacier Flow in New Zealand

3D motion between January 30 and February 9, 2013

Measurements with intersection errors larger than 2m (20cm/day) have been removed (white areas).
Monitoring Glacier Flow in New Zealand

1m GSD Shaded Elevation Model generated from stereo pair:

January 30, 2013
Monitoring Glacier Flow in New Zealand

1m GSD Shaded Elevation Model generated from stereo pair:

February 9, 2013
Monitoring Glacier Flow in New Zealand

1m GSD Shaded Elevation Model generated from stereo pair:

February 28, 2013
Monitoring Glacier Flow in New Zealand

Jan 30 – Feb 9, 2013

Velocity changes
Monitoring Glacier Flow in New Zealand

Feb 9 – Feb 28, 2013

Velocity changes
Glacial dynamics strongly affected by hydrology

B. Anderson (pers. Com.)
Univ. Wellington, NZ
Average daily velocity of up to 4 m/day at the Fox Glacier
Extracting Urban Topography

COSI-Corr DSM extraction using high resolution aerial photographs. Now to be extended to pushbrrom stereo acquisitions.
Oklahoma May 20, 2013 – Tornado damages in Moore

Facts:
• Peak winds estimated at 210 mph (340 km/h)
• 25 casualties
• 377 injured
• $2 billion damages

Idea:
• Detecting building damages by comparing high resolution DSM produced from Worldview stereo imagery.

Imagery:
• Pre-event: WV1 stereo pair acquired on May 17, 2012
• Post-event: WV1 stereo pair acquired on June 21, 2013

Imagery courtesy of DigitalGlobe.
Oklahoma May 20, 2013 – Tornado damages in Moore
Oklahoma May 20, 2013 – Tornado damages in Moore

Digital Surface Model - City of Moore, Oklahoma, before tornado 2013
Conclusions

• Well established methods to measure 2D ground deformations,

• Landsat 8 allows accurate measurement of ground deformation and flow tracking (earthquakes, glaciers, sand dunes), far exceeding the geometrical quality of other sensors at similar GSD,

• Extension to 3D monitoring,

• Generic methods to monitor a variety of surface processes (fault rupture, landslides, sand dune migration, glaciers, etc.),

• Still improving the urban DSM change detection workflow, stay tuned!