Space-time ocean wave measurement using variational stereo vision systems

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Outlines

- Some vision-based systems for wave measurement
- Two variational stereo methods: disparity, elevation.
- Extensions
  - Enforce wave height models
  - Space-time processing
  - Refinement of camera parameters
- Conclusions
What? and Why?

2. Data Analysis

Spectra

Distribution of energy in frequency domain.

- Estimated 3D power spectrum.
- Directional spectrum $F(\alpha, \theta)$

Statistics

Analysis of time series at virtual probes.

<table>
<thead>
<tr>
<th>Exp</th>
<th>CNR</th>
<th>$H_{\text{max}}$ [m]</th>
<th>$H_{1/3}$ [m]</th>
<th>$T_2$ [s]</th>
<th>$T_1$ [s]</th>
<th>Dir [°]</th>
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<tr>
<td>1</td>
<td>0.25</td>
<td>0.47</td>
<td>0.88</td>
<td>2.91</td>
<td>-</td>
<td>-</td>
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<tr>
<td>2</td>
<td>0.45</td>
<td>0.41</td>
<td>0.83</td>
<td>4.34</td>
<td>3.09</td>
<td>148.3°</td>
</tr>
<tr>
<td>3</td>
<td>1.13</td>
<td>1.09</td>
<td>2.03</td>
<td>4.59</td>
<td>3.51</td>
<td>65.0°</td>
</tr>
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<td>1.10</td>
<td>2.18</td>
<td>4.83</td>
<td>3.62</td>
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<td>2.16</td>
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<td>6.37</td>
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<td>2.17</td>
<td>2.16</td>
<td>3.95</td>
<td>6.36</td>
<td>4.85</td>
<td>70.1°</td>
</tr>
</tbody>
</table>

Wave parameters estimated from both WASS instruments operational at Aqua Alta. Dir is the mean wave direction of propagation, measured clockwise from geographic North (wave directions depend upon the platform orientation that is known with an error ~3°). During Experiment 1, $H_{\text{max}}$, $H_{1/3}$, and Dir were not available at Aqua Alta.

Spatial-Time Extremes of Oceanic Seas.

- Expected shape of largest waves.
- Ratio between the expected maximum wave height over an area and that expected at a point.

- Swell
- Wind waves

Space-time wave height $Z(x,y,t)$

Temporal processing

- Estimated wave height ($Z$), surface model
- Variational stereo, Multigrid methods

Multi-view videos

Data Analysis

- Images: 406 x 309 pixels at 10 fps
- Grid: 129 x 129 x 1025 points
- Resolution: 10 cm x 10 cm x 0.1 m
- Area: 12.8 x 12.8 m²
- Snapshots: 5125

Linear dispersion (in deep water)

$k = \frac{\omega^2}{g}$

Estimate surface currents causing Doppler shift of dispersion.

Wave height exceedance prob.

Normalized freq. Spectrum (dispersity, elevation methods)
Goal: to study and predict ocean wave patterns from image sensors

- **Image acquisition**
  (Bi/Trinocular synchronized and calibrated digital cameras)

- **Image processing**
  Reconstruct the surface of the water (epipolar stereo method)

Water surface elevation in time: from 2D image sequences to 3D map sequences

- $Z_0 \sim 1.70$ m, $b = 0.22$ m
- Matched Area: $0.94 \times 0.78$ m$^2$
- $e_{rx} = e_{ry} = 0.15$ cm, $e_{rz} = 0.69$ cm
- 90% of points matched
- 480 x 640 pixel camera
- $F = 6.3$ mm, $ss=1/200$ s

Literature review. WASS (Benetazzo, 2006)
Literature review. ATSIS

- Automatic Trinocular Stereo Imaging System (ATSIS) (Wanek and Wu, 2006).
- Virtual wave gauges for measuring surface wave characteristics (Bechle and Wu, 2011).
Literature review. Stereo systems

- Three-Dimensional Imaging of the High Sea-State Wave Field encompassing ship slamming events (Brandt et al 2010).
Remote sensing of surf zone waves using stereo imaging
(S. de Vries et al, 2011)

Fig. 12. Perspective view of the sample reconstruction of water surface elevation. Color contours denote elevation in meters.

Fig. 13. Perspective view of original camera image mapped onto the three-dimensional water surface elevation.
Literature review. Stereo systems

- Extraction of short wind wave spectra from stereo images (Kosnic and Dulov, 2011).

Problem: gaps (holes) in reconstructed surface

Sample reconstructions:

Spectrum
• Observations of Surface Waves Interacting with Ice using Stereo Imaging (Campbell, Bechle, Wu, 2014).
Classical stereo methods

Difficulties / disadvantages:

• Point correspondences are not easy to find.
• Very sensitive to image noise.
• Unmatched regions: gaps in the surface.
• Requires strongly textured surfaces.
• Each point is treated independently (does not exploit continuity of surface).
• Considerable post-processing is required.

How do we work around it?
Advantages of variational methods

- Enforce continuity of the wave surface in space & time: recovered points are not treated independently.
- Improve robustness: less sensitive to matching problems.
- Provide dense surface reconstructions.
- Allow controllability/priors on the unknowns.
- Can incorporate global properties of wave heights.
- Imply less post-processing than classical methods.
Steps:
1. Compute matching between images (dense disparity)
2. Back-project matched points to 3-D world
3. Fit a surface through the points

Dense disparity map method (1 snapshot)

3D point cloud
Matched image regions.
Back-projection
Underlying surface

Left image
Right image

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Underlying surface

Left image
Right image
Dense disparity map method

Variational optimization approach to point matching:

– Cost functional: \( E = E'_\text{data} + \alpha'E_{\text{smooth}} \), with

\[
E'_\text{data}(\lambda) = \int_{\Omega} \frac{1}{2} \left( I_1(x_1) - I_2(x_2) \right)^2 dx_1
\]

\[
E_{\text{smooth}}(\lambda) = \int_{\Omega} \frac{1}{2} ||\nabla \lambda||^2 dx_1
\]

– Unknown: 2-D coherent disparity map.

Euler-Lagrange equations

\[
\alpha' \Delta \lambda + \left( I_1(x_1) - I_2(x_2) \right) \frac{\partial I_2(x_2)}{\partial \lambda} = 0
\]
Strategy: adjust a 3D model to the 3D world represented by the data (images) so that an energy functional is minimized.

Deform surface until "best match" is achieved by energy minimization.

Explicit & deformable 3D model of surfaces

Forward projection

Left image

Right image
Graph representation: \( S(u, v) = (u, v, Z(u, v)) \)

Design a **cost functional** to be minimized:
- Joint estimation of height \( Z(u, v) \) or the waves and its radiance \( f(u, v) \)

**Cost:**
\[
E(S, f) = E_{\text{data}}(S, f) + \alpha E_{\text{geom}}(S) + \beta E_{\text{rad}}(f), \quad \alpha, \beta > 0.
\]

**Data fidelity term:**
\[
E_{\text{data}} = \sum_{i=1}^{N_c} E_i \quad \text{where} \quad E_i = \int_{\Omega_i} \phi_i \, dx_i, \quad \phi_i = \frac{1}{2}(I_i(x_i) - f(x_i))^2.
\]

**Regularizers:** penalize the norm of the gradients of the height and the radiance

Cost as a function of height and radiance
\[
E(Z, f) = \int_U L(Z, Z_u, Z_v, f, f_u, f_v, u, v) \, du.
\]

→ **Euler-Lagrange equations**
Elevation method (1 snapshot)

Necessary optimality conditions:
System of coupled PDEs in height $Z$ and radiance $f$ of the surface.

\[
\begin{align*}
g(Z, f) - \alpha \Delta Z &= 0 \quad \text{in } U, \\
b(Z, f) + \alpha \frac{\partial Z}{\partial \nu} &= 0 \quad \text{on } \partial U, \\
- \sum_{i=1}^{N_c} (I_i - f)J_i(Z) - \beta \Delta f &= 0 \quad \text{in } U, \\
\beta \frac{\partial f}{\partial \nu} &= 0 \quad \text{on } \partial U,
\end{align*}
\]

Non-linear term (due to data-fidelity cost):

Focal length
Depth of point
Optical ray and Unit Normal

\[
g(Z, f) = \nabla f \cdot \sum_{i=1}^{N_c} |M_i| Z_i^{-3} (I_i - f)(u - C_i^1, v - C_i^2),
\]

Radiance deriv
Photometric error

Multigrid solver: standard method for non-linear elliptic boundary value problems like this one.
Steepest descent method for the system of non-linear PDEs.
Elevation method (1 snapshot)

Reconstructed surface & texture (height $Z$ and radiance $f$)
Comparison of estimated wave heights

Disparity method

Elevation method
**Differences:**
- Bottom-up approach: from pixels to surface
- Handle >2 images by pairs
- Requires triangulation + surface fitting.
- Does not take into account scene depth
- Does not take into account surface normal
- No radiance model: sensitive to noise
- Single PDE in the unknown

**Differences:**
- Top-bottom approach: from surface to pixels
- Easily handle more than 2 images
- No need to fit a surface through 3-D points
- Takes into account scene depth.
- Takes into account surface normal.
- Radiance model: less sensitive to noise
- Can incorporate physics of the waves.
- More mathematically involved: system of coupled PDEs.
Things we can do & things we are working on

• Enforce wave statistics during estimation.

• Simultaneous snapshot reconstruction.

• Refinement of (varying) camera parameters.

• Better wave analysis.

• Scalable and efficient estimation of wave heights: multiresolution + hardware parallelization.
Enforce wave statistics during estimation

Add a cost penalty to measure statistical wave height distribution error:

\[ E_{\text{stat}} := \int_{-\infty}^{\infty} w(z) \frac{1}{2} \left( G(z) - \text{cdf}^Z(z) \right)^2 \, dz \]

- PDFs
- Omnidir spectrum
- Cost evolution
Simultaneous snapshot reconstr. Time coherence

Data fidelity: measure photo-consistency throughout the video for a candidate surface.

Regularizers: enforce spatial and temporal smoothness of the solution (disparity or height & radiance).

**Disparity method**

\[
E'_{\text{data}}(\lambda) = \int_T \int_{\Omega} \frac{1}{2} (I_1(x_1) - I_2(x_2))^2 d\mathbf{x}_1 dt,
\]

\[
E_{\text{smooth}}(\lambda) = \int_T \int_{\Omega} \frac{1}{2} \|\nabla \lambda\|^2 d\mathbf{x}_1 dt,
\]

**Elevation method**

\[
E_i(Z, f) = \int_T \int_{\Omega_i} \phi_i d\mathbf{x}_i dt,
\]

\[
E_{\text{geom}}(Z) = \int_T \int_{\mathbf{U}} \frac{1}{2} \|\nabla Z\|^2 d\mathbf{u} dt,
\]

\[
E_{\text{rad}}(f) = \int_T \int_{\mathbf{U}} \frac{1}{2} \|\nabla f\|^2 d\mathbf{u} dt,
\]

**Minimization approach:**

- Obtain modified Euler-Lagrange eqs \(\rightarrow\) set gradient descent eqs.
- Discretize and solve using 3-D multigrid methods.
Elevation method. Estimated wave height volume

Input stereo video (2 cameras) at Crimean Platform:
• Input (subsampled) images: 406 x 309 pixels at 10 Hz frame rate.

Reconstruction:
• Computational grid: 129 x 129 x 1025 points
• Resolution: 10 cm x 10 cm x 0.1 s
• Reconstructed area: 12.8 x 12.8 m²
• #snapshots processed: 5125 (~8.5 min)
Elevation method. Estimated wave height volume.
Estimated 3-D (power) spectrum

Wave height volume $Z(x,y,t)$

Crimea sequence. Input: 129x129x4100.

Output: 512x512x512
3-D spectrum. Estimation of wave currents

Taking into account the effect of surface currents:

**Linear dispersion (in deep water)**

\[ k = \frac{\omega^2}{g} \]

Velocity vector: \( u = (-0.17, -0.45) \text{ m/s} \)
Slice of the 3-D spectrum

Disparity method

Slice at $f_x = 0$

Elevation method

Slice at $f_x = 0$
3-D spectrum. Omni-directional spectrum
Directional Spectrum $F(\omega, \theta)$

Disparity method

Elevation method
Wave height exceedance probability. (disparity method)

Normalized frequency spectrum. disparity method & elevation method
More Applications

- Comparison of theoretical models with real data using wave measurements: $H_s$, $T_p$, $T_m$, etc.
- Statistical analysis: space-time extremes of oceanic states (for the design of offshore structures), etc.

![Expected shape of largest waves.](image1)

![Ratio between the expected maximum wave height over an area and that expected at a point.](image2)
Camera calibration refinement

- Camera parameters:
  - Intrinsic: optical components
  - Extrinsic: relative camera pose

- Sources of noise in camera parameters:
  - Manufacturing deviations
  - Manual operation errors
  - Natural factors such as breeze or vibrations
  - Numerical errors during the camera pre-calibration

- Goal: improve robustness of wave measurements with respect to camera perturbations.
Camera calibration refinement

With camera refinement

Without camera refinement

Difference
Conclusions

- Stereo reconstruction methods...
  - have more advantages than classical wave measurements (area vs. point measurements).
  - provide reliable statistics and accurate predictions of ocean waves due to the rich information content of video data.

- Advantages of variational methods for wave measurements:
  - Provide dense wave height field estimations.
  - Allow the enforcement of continuity in space & time.
  - Require less post-processing (few assumptions on data).
  - Allow the incorporation of physics of waves.
  - Allow refinement of camera parameters.

- Disadvantages: computational cost (but feasible).
- There are still many related topics to be investigated.
References


Crimea Data from Dr. Ardhuin.

THANK YOU FOR YOUR ATTENTION.
ANY QUESTIONS?

More information:
http://www.gti.ssr.upm.es/~ggb/
http://savannah.gatech.edu/people/ffedele/Research/