Fusing Multi-Modality Inverse Data through Shared Boundary Structure

W. Clem Karl
Boston University
The Challenge

- Fuse heterogeneous, multi-modal inverse imaging data
- Examples:
  - CT and MRI
  - Tomosynthesis and DOT
  - PET and CT
“Vulnerable” plaques lead to heart attacks or strokes

Calcifications indicate plaque, not necessarily vulnerable

Vulnerable plaques have lipid pool and thin fibrous cap: soft tissue

- No single modality can reliably detect/localize
Typical Fusion Approach

- Perform separate reconstruction, registration, enhancement steps, followed by fusion/interpretation
  - Simple, but information reinforcement is at the “back end”
  - Reconstructions do not benefit from the presence of other modalities
Brute Force Fusion Approach

- Relate each modality to a common set of parameters
- Perform one reconstruction from the combined data
  - Requires physical models relating each observed quantity to the common parameters – usually not practical!

Raw Data
CT Projections

Single Reconstruction

MR Low Res.
Our Approach: Exploit shared structure

- Boundary structure often shared, despite different sensing mechanisms
- Idea: Exploit this shared structure for unified reconstruction, registration, and enhancement
- Modalities benefit from each other!
Shared Structure Fusion Formulation

- Minimize unified objective function based on shared boundary field
- Framework simultaneously incorporates:
  - Inversion
  - Enhancement/Regularization
  - Registration
  - Boundary fusion

\[
\arg\min_{f, s, \phi} \sum_{k=1}^{K} \left[ \mathcal{E}_{k}^{\text{fid}} (T_k f_k; g_k) + \mathcal{E}_{k}^{\text{sm}} (f_k, s, \phi_k) + \mathcal{E}_{k}^{\text{alg}} (\phi_k) \right] + \mathcal{E}^{\text{bnd}} (s)
\]

- Data Fidelity
- Edge Enhancement
- Registration Model
- Boundary Model
Component terms in objective function

\[
\arg\min_{f, s, \phi} \sum_{k=1}^{K} \left[ E_k^{\text{fid}} (T_k f_k; g_k) + E_k^{\text{sm}} (f_k, s, \phi_k) + E_k^{\text{align}} (\phi_k) \right] + E^{\text{bnd}} (s)
\]

- **Data fidelity**
  \[
  E_k^{\text{fid}} (f_k, g_k) = \gamma_k^2 \int_{U_k} \left[ g_k - T_k f_k \right]^2 \, du_k
  \]

- **Edge Enhancement**
  \[
  E_k^{\text{sm}} (f_k, s, \phi_k) = \lambda_k^2 \int_{X_0} \left\| \nabla f_k (\phi_k (x_0)) \right\|^2 \left[ (1 - \alpha) [1 - s(x_0)]^2 + \alpha \right] \, dx_0
  \]

- **Registration Model**
  \[
  E_k^{\text{align}} (\phi_k)
  \]

- **Boundary Model**
  \[
  E^{\text{bnd}} (s) = \int_{X_0} \rho \left\| \nabla s \right\|^2 + \frac{1}{\rho} s^2 \, dx_0
  \]

Ambrosio-Tortorelli boundary model
Block Coordinate Optimization

Initialize leakage, $\alpha$, large

$\rho$ fixed

Estimate Recon.'s

Estimate Common Boundary Field

Recon. Optimization

Reduce leakage, $\alpha$

Quadratic, fast

Estimate Common Boundary Field

Update Alignments

Align. Optimization

Reduce $\rho$

Quadratic, fast

Nonlinear, small

$\rho$ fixed

Increase boundary, $\rho$
Simulated Example

- True CT
- Data \( g_1 \)
- Unimodality \( f_1 \)
- Joint \( f_1 \)

- True MR
- Data \( g_2 \)
- Unimodality \( f_2 \)
- Joint \( f_2 \)

Joint Boundary
Simulated Vessel Alignment

Boundary width scale:
\[
\rho = 16 \rightarrow \rho = 8 \rightarrow \rho = 4 \rightarrow \rho = 2
\]

CT: \( f_1(x_1) \)

MR: \( f_2(\phi_2(x_1)) \)

composit
<table>
<thead>
<tr>
<th></th>
<th>True CT</th>
<th>Fused s</th>
<th>Composite</th>
<th>True MR</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Unimodality</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Fused CT</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Fused MR</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Ex Vivo Right Coronary Artery

MR, Unimodal
Calcium
Lumen
Fatty
CT FBP Recon.
Unimodal

Fused MR

Joint Boundary
CT/MR Composite

Fused CT
Conclusions

- Joint multi-modality inversion framework
  - Modular:
    - Can utilize different modalities, forward models, and constituent inversion approaches
  - Incorporates:
    - Physical observation models
    - Piecewise-homogeneous priors
    - Fused boundaries
    - Image registration
  - Provides principled framework for multi-modality fusion