Spatio-temporally Regularized 4-D Cardiovascular C-arm CT Reconstruction Using a Proximal Algorithm

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Coronary Rotational Angiography

**Fig.**: Artis zeego multi-axis C-arm system, Siemens Healthcare GmbH, Forchheim, Germany.
Coronary Rotational Angiography

- 3-D anatomy of vascular trees considered beneficial [1]
  - Diagnostic assessment
  - Interventional guidance

- Requires cardiac motion management
  - Slow gantry rotation
  - ECG gating yields very few views

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Coronary Rotational Angiography

- Volumetric (tomographic) reconstruction
  - Usually requires more (consistent) data
- Compressed sensing exploits image properties
  - Total variation: Ideal images are sparse in gradient domain [1]
  - Temporal regularization addresses insufficient data more effectively [2]


Temporal Regularization vs. Undersampling

Reconstructed Phases

Measured Projections

Cardiac Phase 1  Cardiac Phase 2  Cardiac Phase 3
Vessel Extraction [1]

- Thorax is truncated, arteries are not
- Truncation can cause artifacts in tomographic reconstruction
- Perform single-frame background subtraction [1]

Electrocardiogram Gating

- Vessel images grouped into subsets (gates) based on ECG

- Trade-off:
  - Wider windows → More data per gate, higher inconsistency
  - Narrower windows → Less inconsistency, strongly undersampled
Electrocardiogram Gating

● **Our approach:**
  ● Minimize residual motion (select only best fit from each cycle)
  ● Choose the total number of gates such that all data is used
  ● Compensate for undersampling by temporal regularization
Tomographic 4-D Reconstruction

\[ \arg\min_i \ r(i) + \lambda_s \cdot \|i\|_{sTV} + \lambda_t \cdot \|i\|_{tTV} + \nu_{\mathbb{R}^+}(i) \]

Global convex objective function comprised of…

- Data fidelity
- Sparsity in spatial gradient domain
- Sparsity in temporal gradient domain
Objective Function – Data Fidelity

\[
\arg \min_i r(i) + \lambda_s \cdot \| i \|_{STV} + \lambda_t \cdot \| i \|_{TV} + \lambda_{\mathbb{R}^+}(i)
\]

\[
r(i) = \frac{1}{2} \| A i - p \|_2^2
\]

Squared residual norm

\[
i \in \mathbb{R}^{N_{ph} \cdot N_{vox}}
\]

Voxels to reconstruct (vectorized 4-D image)

\[
p \in \mathbb{R}^{N_{proj} \cdot N_{pix}}
\]

Measured line integrals after gating

\[
A \in \mathbb{R}^{(N_{proj} \cdot N_{pix}) \times (N_{ph} \cdot N_{vox})}
\]

X-ray projection operator

\[
\lambda_{\mathbb{R}^+}
\]

Characteristic function for non-negativity
Objective Function – TV Regularization

$$\arg\min_i r(i) + \lambda_s \cdot \|i\|_{sTV} + \lambda_t \cdot \|i\|_{tTV} + \mathcal{L}_{\mathbb{R}^+}(i)$$

$$\|i\|_{sTV} = \|D_s i\|_{1,2} \quad \text{Spatial TV norm (sum of spatial gradient magnitudes)}$$

$$\|i\|_{tTV} = \|D_t i\|_1 \quad \text{Temporal TV norm (sum of temporal gradients)}$$

$$D_s \quad \text{Spatial forward-difference operator (zero boundary)}$$

$$D_t \quad \text{Temporal forward-difference operator (periodic)}$$

$$\lambda_s, \lambda_t \quad \text{Regularizer weights}$$
Optimization – Proximal Algorithm by Condat [1]

\[ i_{\text{prev}} \leftarrow i \]
\[ i \leftarrow (i - \tau(\nabla r(i) + D_s^T g_s + D_t^T g_t))_+ \]
\[ g_s \leftarrow \text{prox}_{(\lambda_s \cdot \cdot_1^2)}(g_s + \sigma D_s(2i - i_{\text{prev}})) \]
\[ g_t \leftarrow \text{prox}_{(\lambda_t \cdot \cdot_1)}(g_t + \sigma D_t(2i - i_{\text{prev}})) \]

Updates given by full primal-dual splitting

- TV proximal operator (no closed-form solution) replaced by linear transforms and L^1 / L^{1,2} proximal operators (analytic solution)
- Therefore: “simple” operations only, no nested loops

Experiments

- **CAVAREV [1]**
  - Overview
    - Platform for evaluating cardiac vasculature reconstruction
    - Dynamic numerical phantom derived from patient data
    - Projections simulated using acquisition geometry of a real C-arm
  - Specifics
    - **7 heart cycles**, 133 projection images
    - Variant without respiratory motion (breathhold assumption)
    - 19 (= 133/7) gates, 256³ voxels of isotropic size 0.5 mm

Experiments

- Exemplary clinical patient data set
  - Device: Artis one (Siemens Healthcare GmbH, Forchheim, Germany)
  - 5 heart cycles, 133 projections (4s rotation)
  - 27 (≈133/5) gates, 256³ voxels of isotropic size 0.5 mm
  - Qualitative evaluation (visual inspection)
### Results: CAVAREV

<table>
<thead>
<tr>
<th>Method</th>
<th>Dice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard FDK</td>
<td>0.431</td>
</tr>
<tr>
<td>ECG-Gated FDK</td>
<td>0.595</td>
</tr>
<tr>
<td>Dynamic Level Sets [Keil 2009]</td>
<td>0.692</td>
</tr>
<tr>
<td>PICCS [Wu 2011, Chen 2012]</td>
<td>0.726</td>
</tr>
<tr>
<td>L1 minimization [Wu 2011, Li 2004]</td>
<td>0.730</td>
</tr>
<tr>
<td>Streak-Red. Gated FDK [Rohkohl 2008]</td>
<td>0.744</td>
</tr>
<tr>
<td>Resid. Motion Comp. [Schwemmer 2013a]</td>
<td>0.776</td>
</tr>
<tr>
<td>Spatial Total Variation [Wu 2011]</td>
<td>0.785</td>
</tr>
<tr>
<td>Motion Compensation [Schwemmer 2013b]</td>
<td>0.823</td>
</tr>
<tr>
<td><strong>Spatio-temporal TV (proposed)</strong></td>
<td><strong>0.876</strong></td>
</tr>
</tbody>
</table>
Results: CAVAREV

![Graphs showing Dice score over iteration and relative heart phase.](image-url)
Results: CAVAREV

MIP
Results: Clinical Data

Temporal + Spatial TV
Summary and Outlook

● Key idea:
  ● Minimize residual motion within each gate
  ● Exploit all data by spatio-temporal regularization

Potential extensions:

● Temporal regularization for background subtraction
  ● Reduce inconsistency due to segmentation errors

● Respiratory motion compensation
  ● E.g. based on Fourier-domain or epipolar consistency conditions
  ● Applicable since extracted vessel images are not truncated
Thanks for your attention!

Questions?