Enhancement of US-CT registration accuracy for spinal surgery

Eduardo A. Gonzalez

Mentor: Muyinatu Bell

Background presentation – Advanced Computer-Integrated Surgery (601.656)
Spring 2018

Summary of the project

**Goal:** Explore methods to improve accuracy of US-CT image registration through improved US image resolution

Still needs to be tuned
Registration: maximizing intensity

- Successfully implemented in MATLAB

- Since it is a mapping function to an unknown image, \( U(V(A(\alpha, \beta, \gamma) \cdot \tilde{p} + \tilde{q})) \) cannot be decomposed analytically in gradient operations for conventional optimizers

- Solution: brute force but is computationally expensive

- We will keep using the mattes mutual information optimizer and LMS for registration
Input images: varying reconstruction parameters

Delay And Sum (DAS)

CT

Short Lag Spatial Coherence (SLSC)

Input images: varying reconstruction parameters

Regularized SLSC (Reg-SLSC)

CT

High regularization parameter
Metric: Partial Intensity Uniformity

\[ \text{PIU}_B = \sum_a \frac{n_a \sigma_B(a)}{N \mu_B(a)} \]

\[ \text{PIU}_A = \sum_b \frac{n_b \sigma_A(b)}{N \mu_A(b)} \]

Metric: Partial Intensity Uniformity

\[ \text{PIU}_B = \sum_a \frac{n_a \sigma_B(a)}{N \mu_B(a)} \]

\[ \text{PIU}_A = \sum_b \frac{n_b \sigma_A(b)}{N \mu_A(b)} \]
Metric: Mutual Information

\[H(A) = -\sum_a p_A^T(a) \log p_A^T(a)\]
\[H(B) = -\sum_b p_B^T(b) \log p_B^T(b)\]
\[H(A) + H(B) - H(A, B)\]
\[H(A) + H(B)\]

Metric: Normalized Cross / Gradient correlation

\[\text{NCC} = \frac{\sum_{(i,j)\in\Omega} [A(i,j) - \bar{A}] [B(i,j) - \bar{B}]}{\sqrt{\sum_{(i,j)\in\Omega} [A(i,j) - \bar{A}]^2 \sum_{(i,j)\in\Omega} [B(i,j) - \bar{B}]^2}}\]

\[0.5[\text{NCC}(\frac{\partial A(i,j)}{\partial i}, \frac{\partial B(i,j)}{\partial i}) + \text{NCC}(\frac{\partial A(i,j)}{\partial j}, \frac{\partial B(i,j)}{\partial j})]\]
Metric: Gradient difference

\[ GD(k) = \frac{1}{2N} \left( \sum_{i,j} A_v + (I_{d,j}V(i,j))^2 \right) + \sum_{i,j} A_h + (I_{d,f}U(i,j))^2 \]  

\[ I_{\text{diff}} \theta(i,j) = \frac{\partial A(i,j)}{\partial i} - k \frac{\partial B(i,j)}{\partial i} \]

\[ I_{\text{diff}} \varphi(i,j) = \frac{\partial A(i,j)}{\partial j} - k \frac{\partial B(i,j)}{\partial j} \]
LW-SLSC results of selected metric

<table>
<thead>
<tr>
<th>Kx</th>
<th>alpha</th>
<th>OL</th>
<th>GC</th>
<th>GD_CT (1)</th>
<th>GC_US (1)</th>
<th>GC_CT (30)</th>
<th>GC_CT (30)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>5</td>
<td>0.6</td>
<td>0.2355</td>
<td>0.8416</td>
<td>0.8941</td>
<td>0.7729</td>
<td>0.9288</td>
</tr>
<tr>
<td>10</td>
<td>5</td>
<td>0.7</td>
<td>0.2377</td>
<td>0.8417</td>
<td>0.8945</td>
<td>0.7737</td>
<td>0.9291</td>
</tr>
<tr>
<td>12</td>
<td>2</td>
<td>0.5</td>
<td>0.2348</td>
<td>0.8392</td>
<td>0.8893</td>
<td>0.7659</td>
<td>0.9237</td>
</tr>
<tr>
<td>12</td>
<td>5</td>
<td>0.5</td>
<td>0.2331</td>
<td>0.8401</td>
<td>0.8906</td>
<td>0.7702</td>
<td>0.9257</td>
</tr>
<tr>
<td>12</td>
<td>100</td>
<td>0.5</td>
<td>0.1979</td>
<td>0.8458</td>
<td>0.8938</td>
<td>0.7842</td>
<td>0.9341</td>
</tr>
<tr>
<td>12</td>
<td>200</td>
<td>0.5</td>
<td>0.1762</td>
<td>0.8471</td>
<td>0.8942</td>
<td>0.7856</td>
<td>0.9359</td>
</tr>
<tr>
<td>12</td>
<td>50</td>
<td>0.5</td>
<td>0.2049</td>
<td>0.8452</td>
<td>0.8939</td>
<td>0.7825</td>
<td>0.9327</td>
</tr>
</tbody>
</table>
Pre-segmenting the CT vertebra

Improved results in the GC

No segmentation

Pre-segmentation
Without segmenting the vertebra at 0 degrees misalignment

Noisy CT background

Pre-segmenting the vertebra at 0 degrees misalignment

No CT background
Pre-segmenting the vertebra at 0 degrees misalignment

Evaluate what happens if the initial images are not correctly aligned
Current optimizer and metric setup for registration:

<table>
<thead>
<tr>
<th>Optimizer: One plus One Evolutionary</th>
<th>Metric: Mattes Mutual Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Iterations</td>
<td>Number of Bins 8</td>
</tr>
<tr>
<td>Grow Factor</td>
<td>Number spatial samples 500</td>
</tr>
<tr>
<td>Initial Radius</td>
<td>Use All Pixels true</td>
</tr>
<tr>
<td>Epsilon</td>
<td></td>
</tr>
</tbody>
</table>

Fixed registration!

Misalignment results
Results

No misalignment (0 grad difference between initial images)
Results

Around $M>12$ starts to fail for angle < -10

Misalignment results

But is ok for positive angles
Misalignment results

Mostly fine with DAS

Some cases don’t
Deliverables

<table>
<thead>
<tr>
<th>Minimum (March 8\textsuperscript{th})</th>
<th>Expected (April 5\textsuperscript{th})</th>
<th>Maximum (April 19\textsuperscript{th})</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Images</strong>: Automatic registration of SLSC/DAS US images to CT images of spine specimen (hard tissue)</td>
<td><strong>Images</strong>: add robust SLSC to registration framework</td>
<td><strong>Images</strong>: add PA to registration framework</td>
</tr>
<tr>
<td><strong>Equation</strong>: Propose algorithm for a robust SLSC technique</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Graph</strong>: Show registration performance when varying quality parameters for SLSC and DAS</td>
<td><strong>Graph</strong>: add quality parameters for robust SLSC (e.g., kernel size and regularization parameters)</td>
<td><strong>Graph</strong>: compare CT-PA and CT-US registration performance using PA images</td>
</tr>
</tbody>
</table>

Discussion

- Changing the parameters of the optimizer/metric could potentially improve the registration robustness
- Applying morphological closing could improve the bone structure for SLSC/DAS
- The structure is well defined for Reg-SLSC, therefore should be more robust at high angle deviation
Conclusion

- More experiments with different metrics and optimizer parameters are needed to verify the robustness of the algorithm with SLSC, Reg-SLSC and DAS images.
- Segmentation of the vertebra is well performed for initial lags of SLSC and all Reg-SLSC, but is poor for DAS images
- Addition of CT markers could be another feature to further test the registration performance

Weekly work plan

<table>
<thead>
<tr>
<th>Week</th>
<th>Days</th>
<th>Task Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>April 2nd-April 6th</td>
<td>Generate L-curve testing for optimal regularization parameter</td>
</tr>
<tr>
<td>2</td>
<td>April 9th-April 13th</td>
<td>Implement registration of background article 1 / Compare</td>
</tr>
<tr>
<td>3</td>
<td>April 16th-April 20th</td>
<td>Compare registration results with misalignment start</td>
</tr>
<tr>
<td>4</td>
<td>April 23rd-April 27th</td>
<td>Test registration performance with CT - markers</td>
</tr>
<tr>
<td>5</td>
<td>May 1st-May 5th</td>
<td>Add photoacoustic imaging to the registration framework</td>
</tr>
<tr>
<td>6</td>
<td>May 8th-May 12th</td>
<td>Additional processing if needed</td>
</tr>
</tbody>
</table>