Deformable Registration of Pre-Op MRI with iMRI for Brain Tumor Resection: Progress Report

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In memory of Dr. Ferenc Jolesz

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Contributions

1. Improved NRR accuracy by relying on adaptive change of the model [1].

2. Performed within time constrains of the surgery by relying on many-core and GPU accelerators [3].

3. Open Source Software and available through ITK and Slicer3D a cross-platform library and IGS tool.

4. Used Cloud computing to perform computational intensive task of a parameter search to potential reduce error within 2mm [2] within the time constrains of the surgery.

5. Trained three graduate students/experts:
   1. Dr. A. Fedorov
   2. Dr. Y. Liu
   3. Mr. F. Drakopoulos

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Upper bound of alignment error (HD in mm)

<table>
<thead>
<tr>
<th></th>
<th>HD&lt;sub&gt;RR&lt;/sub&gt;</th>
<th>HD&lt;sub&gt;PBNRR&lt;/sub&gt;</th>
<th>HD&lt;sub&gt;PAPBNRR&lt;/sub&gt;</th>
<th>HD&lt;sub&gt;RR/HD_PBNRR&lt;/sub&gt;</th>
<th>HD&lt;sub&gt;PBNRR/HD_PAPBNRR&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 case</td>
<td>29.93</td>
<td>27.76</td>
<td>2.83</td>
<td>10.57 times</td>
<td>9.81 times</td>
</tr>
<tr>
<td>30 cases</td>
<td>19.03</td>
<td>17.59</td>
<td>3.63</td>
<td>5.47 times</td>
<td>5.06 times</td>
</tr>
</tbody>
</table>

Average alignment error (mm) on 6 anatomical easily recognizable and points away from the tumor.

<table>
<thead>
<tr>
<th></th>
<th>Err&lt;sub&gt;RR&lt;/sub&gt;</th>
<th>Err&lt;sub&gt;PBNRR&lt;/sub&gt;</th>
<th>Err&lt;sub&gt;PAPBNRR&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 case</td>
<td>8.83</td>
<td>7.39</td>
<td>4.47</td>
</tr>
<tr>
<td>30 cases</td>
<td>5.60</td>
<td>3.47</td>
<td>3.22</td>
</tr>
</tbody>
</table>

Execution time (seconds) and speed-up
(12 Intel Xeon X5690@3.47 GHz CPU cores and 96 GB of RAM)

<table>
<thead>
<tr>
<th></th>
<th>RR</th>
<th>PBNRR</th>
<th>PAPNRR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time (12 cores)</td>
<td>8.38</td>
<td>81.46</td>
<td>149.49</td>
</tr>
</tbody>
</table>


Overview of the PBNRR Method (2005)

Physics-Based Non-Rigid Registration Formulation

\[
W = U^T K U + (H U - D)^T S (H U - D)
\]

U: Mesh displacement vector (3n)
K: Mesh mechanical stiffness matrix (3n*3n)
H: Piece-wise polynomial approximation to compute displacement on mesh vertices from the block-matching “measured” displacements (3p*3n)
S: Matching stiffness matrix, including the correlation coefficient (3p*3p)
D: “Measured” displacements (3p)

First ever clinical study using Volume tracking at BWH (2006-7)


Open Source Software: ITK & 3D Slicer Extension (2010-14)

- Physics-Based Non-Rigid Registration (PBNRR) in ITK [7,8]. Improved accuracy compared to rigid registration, and faster execution using GPU and multi-core accelerators.

<table>
<thead>
<tr>
<th>Case</th>
<th>Intel (R) Xeon</th>
<th>Quadro 6000 GPU</th>
<th>AMD 6276</th>
<th>Tesla K20X GPU</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 thread</td>
<td>12 threads</td>
<td>1 thread</td>
<td>16 threads</td>
</tr>
<tr>
<td>1</td>
<td>19.06</td>
<td>1.83</td>
<td>0.49</td>
<td>312.9</td>
</tr>
<tr>
<td>2</td>
<td>21.08</td>
<td>1.96</td>
<td>0.54</td>
<td>34.67</td>
</tr>
<tr>
<td>3</td>
<td>18.68</td>
<td>0.50</td>
<td>0.30</td>
<td>30.96</td>
</tr>
<tr>
<td>4</td>
<td>23.43</td>
<td>2.65</td>
<td>0.60</td>
<td>39.18</td>
</tr>
<tr>
<td>5</td>
<td>18.97</td>
<td>1.77</td>
<td>0.48</td>
<td>39.18</td>
</tr>
</tbody>
</table>

Average speedup: 10.07, 36.65, 9.35, 82.70

- PBNRR in 3D Slicer.


Improved Mathematical Model & Add Adaptivity

➢ Nested Expectation-Maximization (NEMNRR) [9]. Formulation of the problem as a three-variable (point correspondence \(D\), deformation field \(U\), and resection region \(M\)) functional minimization.

\[
W(U, C) = \sum_{E \in (M - M')} U^T K E U + \lambda \| (HU - D(C)) \|^2
\]

➢ Parallel Adaptive PBNRR Framework [10]:

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Recent Results on Accuracy of Deformable Registration

Quantitative evaluation results with 6 anatomical landmarks (see Appendix). The values are the average minimum, maximum and mean errors computed on the 6 anatomical locations, from 30 patients.

<table>
<thead>
<tr>
<th>Method</th>
<th>Average min Error (mm)</th>
<th>Average max Error (mm)</th>
<th>Average mean Error (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RR</td>
<td>3.19</td>
<td>8.90</td>
<td>5.60</td>
</tr>
<tr>
<td>PBNRR</td>
<td>1.11</td>
<td>6.81</td>
<td>3.47</td>
</tr>
<tr>
<td>PAPBNRR</td>
<td>1.03</td>
<td>6.59</td>
<td>3.22</td>
</tr>
</tbody>
</table>


[12] Fotis Drakopoulos, Chengjun Yao, Yixun Liu, and Nikos Chrisochoides, "Biomechanical Non-Rigid Registration of Pre-Operative Multi-Modal Imaging (MRI, fMRI, DT-MRI) with iMRI for Brain Glioma Surgery", to be submitted in Neuroimage.
Future Work

- We will evaluate the feasibility of implementing and using in clinical setting the speculative execution of the PABNRR method on a private and a public cloud to further improve the accuracy of PAPBNRR.

- Use Machine Learning for reducing the search space algorithm to find a subset of input parameters that has a higher probability of producing the lowest errors and run the speculative execution only for those potential candidates.

- Address Challenges due to topologic changes in the brain tissue in case with deep brain tumors.
Appendix: Anatomical Points used for evaluation

Locations of the anatomical landmarks (A - F) used for the quantitative evaluation of the registration accuracy by a neurosurgeon.
- A, B: cortex near tumor.
- C: anterior horn of later ventricle.
- D: triangular part of later ventricle.
- E: junction between pons and mid-brain.
- F: roof of fourth ventricle.