Enhancement of US-CT registration accuracy for spinal surgery

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Background / Challenge

1. Preoperative plan → Intraoperative situation

2. Ultrasound Imaging (US)
   - Good intraoperative imaging technique: low cost and simplicity of use
   - Poor signal-to-noise ratio (SNR)
   - Reflection from tissues with high acoustic impedance
   - Deformed image due to physician pressure

3. US/CT registration
   - Intensity-based registration (MRI applied in brain/CT applied in kidney)
   - Feature extraction (Sobel gradient)
   - Multi-component similarity measurement

Brendel et al., 2002
Objective

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

**Specific Aims:**
1. Enhance bony features in US images to improve resolution for automatic registration
2. Develop a robust beamformer to improve the appearance of bone in US images
3. Explore registration improvement when considering additional information from Photoacoustic (PA) images
Technical Approach

Conventional beamforming: Delay and Sum (DAS)

\[ \tau(x_1, z) = \frac{z + \sqrt{z^2 + (x - x_1)^2}}{c} \]

\[ s(x, z) = \int RF(x_1, \tau(x_1, x, z)) \, dx_1 \]

Advanced beamforming: Short lag spatial coherence (SLSC)

\[ \tilde{R}(m) = \frac{1}{N - m} \sum_{i=1}^{N-m} \frac{\sum_{n=0}^{n_2} s_i(n)s_{i+m}(n)}{\sqrt{\sum_{n=0}^{n_2} s_i^2(n)s_{i+m}^2(n)}} \]

\[ R_{sl} = \int \tilde{R}(m) \, dm \approx \sum_{m=1}^{M} \tilde{R}(m) \]

Feature extraction → Fuzzy C-means segmentation

Bone (desired region) + Water (and undesired reflections) + Regions outside imaging boundaries (for phased arrays)

US image = Bone (desired region) + Water + Regions outside

Technical Approach

Control the quality of US image

Dynamic range of log compression for DAS

Cumulative summed lag value for SLSC

Regularization parameter for robust SLSC

Registration → Mattes Mutual Information

Evaluation → Mean Square Error (MSE)
Deliverables

<table>
<thead>
<tr>
<th>Minimum (March 8th)</th>
<th>Expected (April 5th)</th>
<th>Maximum (April 19th)</th>
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</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>
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<td><strong>Equation</strong>: Propose algorithm for a robust SLSC technique</td>
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<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>
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Dependencies

- **Acquisition of CT images of human spine**
  - Scheduling use of CT machine options:
    - Medical campus (Professor Siewerdsen and his postdoc)
    - Homewood campus (Michelle Graham, CAMP Lab Members)
  - Cannot acquire CT myself because did not take the CT training course
- **Calibration phantom to validate registration methods (ground truth)**
- **Availability of the spine sample**
  - Coordinate with Blackberrie Eddins
**Work plan**

![Work plan diagram]

**Bibliography**

- Roche et al. “Rigid Registration of 3-D Ultrasound With MR Images: A New Approach Combining Intensity and Gradient Information”, 2001
- Wein et al. “Simulation and Fully Automatic Multimodal Registration of Medical Ultrasound”, 2007
- Bell et al. “Short-Lag Spatial Coherence of Backscattered Echoes: Imaging Characteristics”, 2011
- Shubert et al. “A novel drill design for photoacoustic guided surgeries”, 2017