Synthetic Tracked Aperture Ultrasound Imaging: Virtual Fixtures and Force Control
Group 2: Checkpoint Presentation

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Motivation

- Aperture size of the ultrasound transducer limits image quality
- Synthetic tracked aperture imaging shows improvement
  - Current system is autonomous by robot
    - Difficulty in clinical translation
    - Force control required for anatomy specific imaging and patient safety
- Goal is to bring system from autopilot to co-robotic freehand
Deliverables

Minimum
• Code implementing virtual fixtures ✓
• Code implementing compliance force control ✓
• Comparison of actual trajectory of robot with planned trajectory ✓ - (minor issue)
• Demonstration of translational path in water tank using co-robotic control ✓

Expected
• Demonstration of translational path on general US phantom, without contact force control ✓
• Demonstration of translational path on general US phantom, with contact force control – Next step

Maximum
• Demonstration of rotational path in water tank using co-robotic control – Planned
• Demonstrate control on more anatomically accurate path using rotation and force control on abdominal phantom – Possible
Robot Control: Constrained Optimization Approach

\[ \dot{x}_{des} = Kf \]

\[ q_{des} = \min_{\dot{q}} \| x_{des} - Jq_{des} \| \]
Robot Control: Constrained Optimization Approach

\[ \dot{x}_{des} = Kf \]

\[ \dot{q}_{des} = \min_{\dot{q}} \| x_{des} - J\dot{q}_{des} \| \]

Subject to:

\[
\begin{bmatrix}
H_{\text{line}} & 0 \\
0 & H_{\text{jointvel}}
\end{bmatrix}
\begin{bmatrix}
J \\
I_{6\times 6}
\end{bmatrix}
\begin{bmatrix}
\dot{q}
\end{bmatrix}
\leq
\begin{bmatrix}
H_{\text{line}} \\
H_{\text{jointvel}}
\end{bmatrix}
\]

\[
H_{\text{line}} = \begin{bmatrix}
[R[\cos \frac{2\pi}{n}, \sin \frac{2\pi}{n}, 0]'] & 0 & 0 & 0 \\
[R[\cos \frac{2\pi}{n}, \sin \frac{4\pi}{n}, 0]'] & 0 & 0 & 0 \\
\vdots & & & \\
[R[\cos \frac{2n\pi}{n}, \sin \frac{2n\pi}{n}, 0]'] & 0 & 0 & 0
\end{bmatrix},
\]

\[
h_{\text{line}} = \begin{bmatrix}
\epsilon \\
\epsilon
\end{bmatrix} - H \begin{bmatrix}
[x_p - P_{cl}]_{3 \times 3} \\
\bar{0}
\end{bmatrix}
\]

\[
H_{\text{jointvel}} = \begin{bmatrix}
-I_{6\times 6} \\
I_{6\times 6}
\end{bmatrix},
\]

\[
\dot{h}_{\text{jointvel}} = \begin{bmatrix}
\dot{q}_{\text{lower}, 6\times 1} \\
\dot{q}_{\text{upper}, 6\times 1}
\end{bmatrix}
\]

where \( n = 8, \epsilon = 0.5 \text{ mm} \),
\(-\dot{q}_{\text{lower}} = \dot{q}_{\text{upper}} = 0.5 \text{ rad/sec} \)
Stay On Line Virtual Fixture

\[ \dot{q}_{\text{des}} = \min_{\dot{q}} \|\dot{x}_{\text{des}} - J\dot{q}_{\text{des}}\| \]

Subject to:

\[ H\dot{q} \leq \dot{h} \]

\[ H_{\text{line}} = \begin{bmatrix}
[R[\cos\frac{2\pi}{n}, \sin\frac{2\pi}{n}, 0]' & 0 & 0 & 0 \\
[R[\cos\frac{4\pi}{n}, \sin\frac{4\pi}{n}, 0]' & 0 & 0 & 0 \\
... & & & \\
[R[\cos\frac{2n\pi}{n}, \sin\frac{2n\pi}{n}, 0]' & 0 & 0 & 0
\end{bmatrix},
\]

\[ h_{\text{line}} = \begin{bmatrix}
\varepsilon \\
\epsilon \\
\ldots
\end{bmatrix} - H \begin{bmatrix}
x_p - P_{cl}
0
0
\end{bmatrix}_{3x3} \]

Source:
Frame Transformation

- Used in STRATUS image reconstruction according to: $M = X^{-1} B_i^{-1} B_j X$ for each pose
- Used in “stay on line” to define desired trajectory relative to long axis of probe

\[
X = \begin{bmatrix}
0 & 0 & -1 & 0 \\
-0.9998 & 0.0175 & 0 & 0 \\
0.0175 & 0.9998 & 0 & 177 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]
Demonstration of VF
Actual vs. Expected Robot Trajectory

**Motivation**

**Deliverables**

**Completed Work**

**Dependencies**

**Timelines**
**Image Improvement**

**Left:** Single pose B-mode ultrasound image of general US phantom.

**Right:** STRATUS images synthesized in the range of 60 mm motion data; field-of-view expanded by 65.5 mm.

<table>
<thead>
<tr>
<th></th>
<th>Single</th>
<th>STRATUS: 60 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>FWHM (mm)</td>
<td>3.87</td>
<td>2.37</td>
</tr>
<tr>
<td>Contrast (dB)</td>
<td>-7.14</td>
<td>-10.67</td>
</tr>
<tr>
<td>SNR (dB)</td>
<td>25.01</td>
<td>29.35</td>
</tr>
</tbody>
</table>
Additional Accomplishments

• Paper submitted to 2016 MICCAI Conference
  ▫ “Co-Robotic Synthetic Tracked Aperture Ultrasound Imaging with Virtual Fixture Control”
Dependencies & Problems

Original

- Access to mentors ✓
- Access to water tank & phantoms ✓
- Access to STrAtUS real-time visualization system ✓
- Deeper understanding of virtual fixtures and implementation ✓
- Access to UR5 robot and force sensors- **minor issue, addressed**
- Access to Sonix Touch ultrasound system- **minor issue, addressed**
Management Updates

- Weekly meetings with Kai ✔
- Bi-weekly team meetings ✔
  - Design documentation
  - Working code
    - Updated after every meeting via shared folder
  - Experimental data
Complete minimum deliverables
3/14/16

Complete expected deliverables
3/31/16

Complete maximum deliverables
4/29/16

2016

Feb | Mar | Apr | 2016

- Literature review 2/15/16 - 2/29/16
- Review CISST VF examples 2/15/16 - 2/29/16
- Implement compliance force control code 2/22/16 - 3/7/16
- Implement virtual fixtures code 2/22/16 - 3/7/16
- Demonstrate accurate trajectory 2/29/16 - 3/14/16
- Demonstrate translational path in water tank 2/29/16 - 3/14/16
- Demonstrate translational path on general US phantom 3/14/16 - 3/31/16
- Demonstrate rotational path in water tank 3/14/16 - 3/31/16
- Demonstrate translational and rotational path on abdominal phantom 4/1/16 - 4/29/16
Updated Timeline

2016

Feb | Mar | Apr

Literature review
- 2/15/16 - 2/29/16

Review CISST VF examples
- 2/15/16 - 2/29/16

Implement compliance force control code
- 2/22/16 - 3/7/16

Implement virtual fixtures code
- 2/22/16 - 3/7/16

Demonstrate accurate trajectory
- 2/29/16 - 3/14/16

Demonstrate translational path in water tank
- 2/29/16 - 3/14/16

Demonstrate translational path on general US phantom (without contact force control)
- 3/14/16 - 3/31/16

Demonstrate translational path on general US phantom (with contact force control)
- 3/14/16 - 4/8/16

Demonstrate rotational path in water tank
- 3/31/16 - 4/29/16

Demonstrate translational and rotational path on abdominal phantom
- 3/31/16 - 4/29/16

Complete minimum deliverables
- 3/14/16

Complete expected deliverables
- 3/31/16

Complete maximum deliverables
- 4/29/16

Motivation | Deliverables | Completed Work | Dependencies | Timelines