Project Checkpoint: High Precision Drill/Needle Placement with the UR5 using 3D-2D Image Registration

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Overview

• Project Summary
• Progress
• Timeline
• Next Milestones
• Conclusions
Project Summary

- Procedure is generally performed manually
- Precision could be increased with some assistance
Project Summary

- Noninvasive integration of the UR5 robotic arm into the pedicle screw placement procedure
Project Summary

Collect time-synchronized measurements from UR5 and optical tracker

Perform AX=XB calibration to register UR5 to optical tracker

Register optical tracker to CT volume via point cloud to point cloud registration

Perform axis planning in CT volume to define UR5 movement/alignment for placing drill guide

Define UR5 to drive a drill-guide to a prescribed pose along CT axis and phantom (patient body) surface

Apply calibration methods to register UR5/tool to CT data

Apply 3D-2D registration to CT data and radiographs to register volume data to phantom (patient)

Register optical tracker to CT volume via point cloud to point cloud registration

“Pre-operative” CT

“Intraoperative” Radiographs
Deliverables

• Minimum Deliverable – Complete
  • Enable tracker based guidance for UR5 robot (i.e. register robot to tracking system)
  • Experimental minimization of calibration error

• Expected Deliverable – In Progress
  • Perform 2D-3D registration between radiographs and CT Volume
  • Integrate image-based guidance for UR5
  • Experimental optimization of axis planning and error reduction

• Maximum Deliverable – To Be Done
  • Devise path planning for desirable robot motion in needle placement
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Progress

• Registration of UR5 to optical tracker
  • Collection of data
    • Initial grid collection
    • Improved grid collection
  • Validation of AX=XB solvers
  • Demonstration
• Calibration error analysis
• Resolution of prior dependencies
Workstation

Optical Tracker: NDI Polaris Spectra

UR5 Robot Arm

Pivot calibrated tool tip with OT markers
Integration of UR5 with Tracking System

\[ A_1 \times X \times B_1^{-1} = A_2 \times X \times B_2^{-1} \]
\[ A_2^{-1} \times A_1 \times X = X \times B_2^{-1} \times B_1 \]
\[ AX = XB \]
Grid-Motion Data Collection

• 27 grid points centered upon tracker sweet spot, maximally spaced out to encapsulate largest possible volume of operation
• Vary 3 most distal joints at each grid point to encapsulate additional poses
Grid-Motion Data Collection

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Validation of AX=XB Solvers

Calibration Error

- Average Rotational Error:
  - 0.059 degrees along the x axis
  - -0.301 degrees along the y axis
  - 0.060 degrees along the z axis
- Rotational Std. Dev:
  - x = .001
  - y = .002
  - z = .001
- Average Translation Error:
  - 0.667 mm in the x direction
  - -1.045 mm in the y direction
  - -0.894 mm in the z direction
  - Norm: 1.528 mm
- Translational Std. Dev:
  - x = .541
  - y = .459
  - z = .228
Dependencies

1. Transportation from/to medical campus (JHMI Shuttle) ✓
2. Fully operational UR5 that can be modified by program ✓
3. Fully operational optical tracker along with OT markers ✓
4. Optical tracking tools (calibrated) ✓
5. Work bench for UR5 mounting ✓
6. Computer for UR5 programmatic control and loaded with visualization software for optical tracking ✓
7. 3D-2D registration software (in TREK) ✓
8. ***CT data accompanied by corresponding phantom*** ✓
9. Imaging Device to acquire intraoperative radiographs ✓
10. Machine shop access to modify drill guide design ✓
11. Mentors ✓
# Updated Project Timeline

<table>
<thead>
<tr>
<th>Minimum Deliverables</th>
<th>February 2016</th>
<th>March 2016</th>
<th>April 2016</th>
<th>May 2016</th>
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<tbody>
<tr>
<td>URS mounting and setup</td>
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<tr>
<td>Optical tracker setup</td>
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<tr>
<td>Learn URS SDK</td>
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<tr>
<td>Perform AX&lt;&lt;XB registration</td>
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<td>Experiment to verify URS to OT registration</td>
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<table>
<thead>
<tr>
<th>Expected Deliverables</th>
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<tbody>
<tr>
<td>Acquire CT image + phantom</td>
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<tr>
<td>Learn 3D-2D registration</td>
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<tr>
<td>Register URS to CT image</td>
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<tr>
<td>Confer with clinicians to design/modify drill guide</td>
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<tr>
<td>Experiment to test drill placement on phantom</td>
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<td>Conduct cadaver studies</td>
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Next Milestones

- Register tracker to CT data
- Complete assembly of drill guide
- Test ability of UR5 to align drill guide along pre-planned axis relative to phantom (with system including optical tracking system)
- Ultimate goal is still a system without an optical tracker
Questions?
Validation of AX=XB Solvers (Initial Grid)

Tsai-Lenz Method

\[ \text{Sk} \left( k_{RA_i} + k_{RB_i} \right) k'_{RX} = k_{RA_i} - k_{RB_i} \]

\[ k'_{RX} = \frac{2k'_{RX}}{\sqrt{1 + |k'_{RX}|^2}} \]

where the skew-symmetric matrix

\[ \text{Sk}(x) = \begin{pmatrix} 0 & -x(3) & x(2) \\ x(3) & 0 & -x(1) \\ -x(2) & x(1) & 0 \end{pmatrix}, \]

and the angle of rotation \( \theta \) for \( R_X \) by setting

\[ \theta = 2\text{atan} \left| k'_{RX} \right|. \]
Tsai-Lenz Method

\[
R = \begin{bmatrix}
\cos \theta + u_x^2 (1 - \cos \theta) & u_x u_y (1 - \cos \theta) - u_z \sin \theta & u_x u_z (1 - \cos \theta) + u_y \sin \theta \\
u_y u_x (1 - \cos \theta) + u_z \sin \theta & \cos \theta + u_y^2 (1 - \cos \theta) & u_y u_z (1 - \cos \theta) - u_x \sin \theta \\
u_z u_x (1 - \cos \theta) - u_y \sin \theta & u_z u_y (1 - \cos \theta) + u_x \sin \theta & \cos \theta + u_z^2 (1 - \cos \theta)
\end{bmatrix}
\]

\[
\begin{pmatrix}
R_{A1} - I \\
\vdots \\
R_{An} - I
\end{pmatrix} t_x = \begin{pmatrix}
R_x t_{B1} - t_{A1} \\
\vdots \\
R_x t_{Bn} - t_{An}
\end{pmatrix}
\]