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

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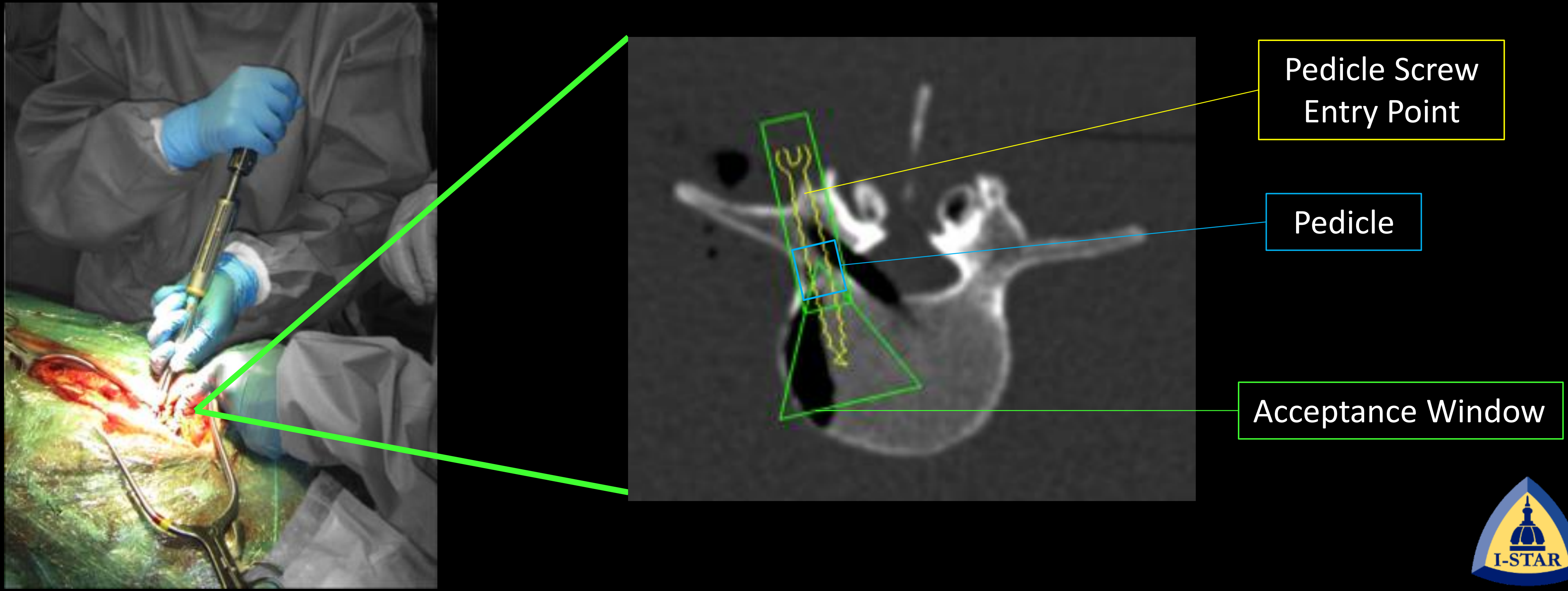
Overview

- Project Summary
- Progress
- Timeline
- Next Milestones
- Conclusions

Project Summary

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



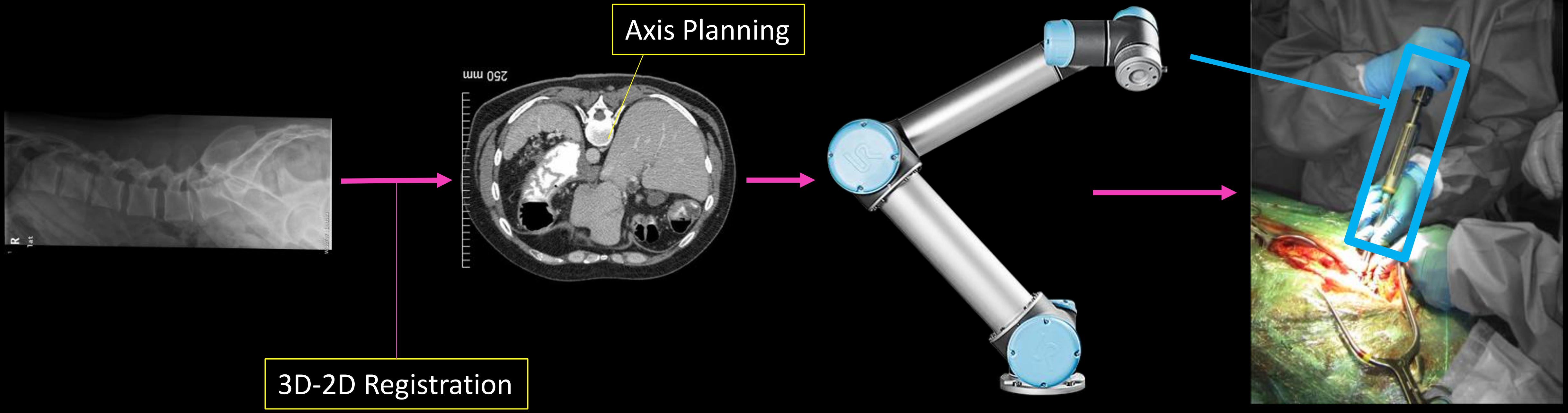
Project Summary

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

Intraoperative Radiographs

Preoperative CT

UR5 Robotic Arm



Project Summary

Validate → Refine

Collect time-synchronized measurements from UR5 and optical tracker

Validate → Refine

Perform AX=XB calibration to register UR5 to optical tracker

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

Validate → Refine

Apply calibration methods to register UR5/tool to CT data

“Pre-operative” CT

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

“Intraoperative” Radiographs

Validate → Refine

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

Validate → Refine

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

Validate → Refine

I-STAR

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

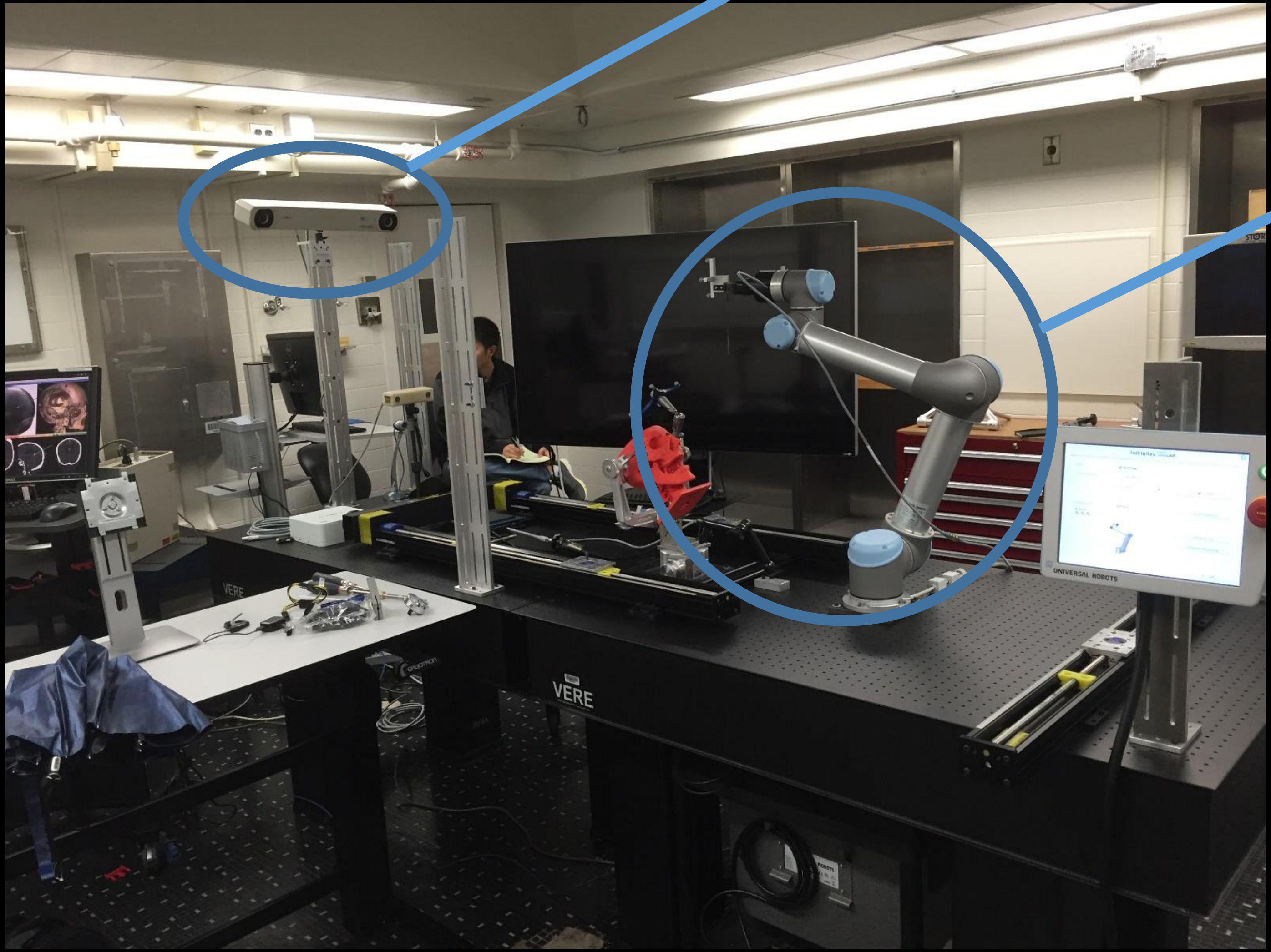
- Registration of UR5 to optical tracker
  - Collection of data
    - Initial grid collection
    - Improved grid collection
  - Validation of AX=XB solvers
  - Demonstration
- Calibration error analysis
- Resolution of prior dependencies

Workstation

Optical Tracker: NDI Polaris Spectra

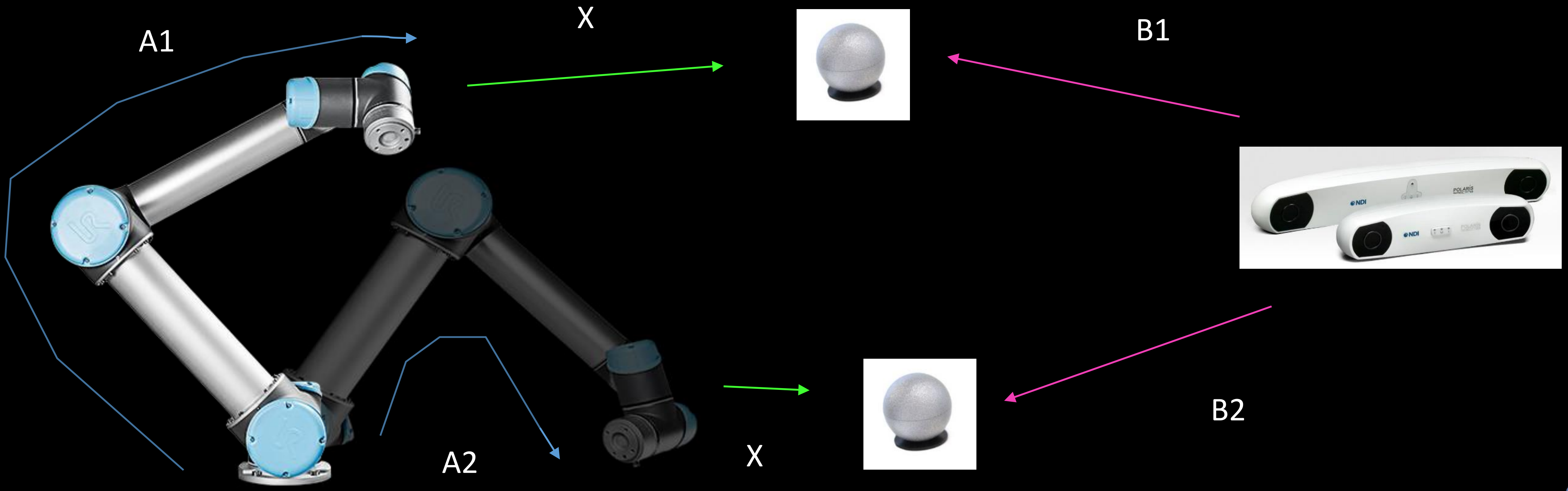
UR5 Robot Arm

Pivot calibrated tool tip with OT markers



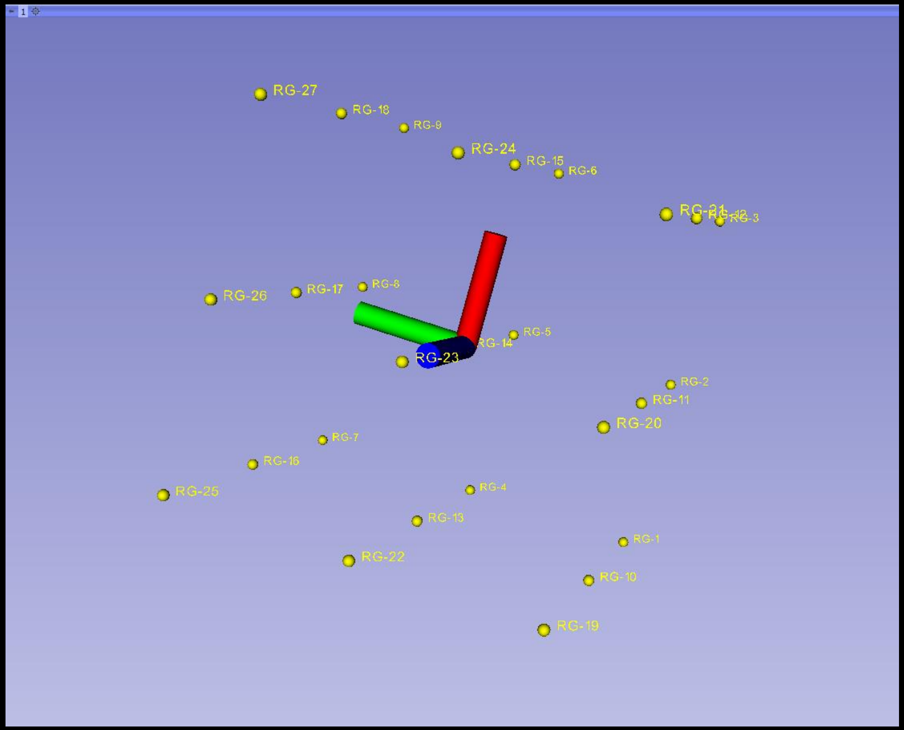
Integration of UR5 with Tracking System

$$A_1 * X * B_1^{-1} = A_2 * X * B_2^{-1}$$
$$A_2^{-1} * A_1 * X = X * B_2^{-1} * B_1$$
$$AX = XB$$



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



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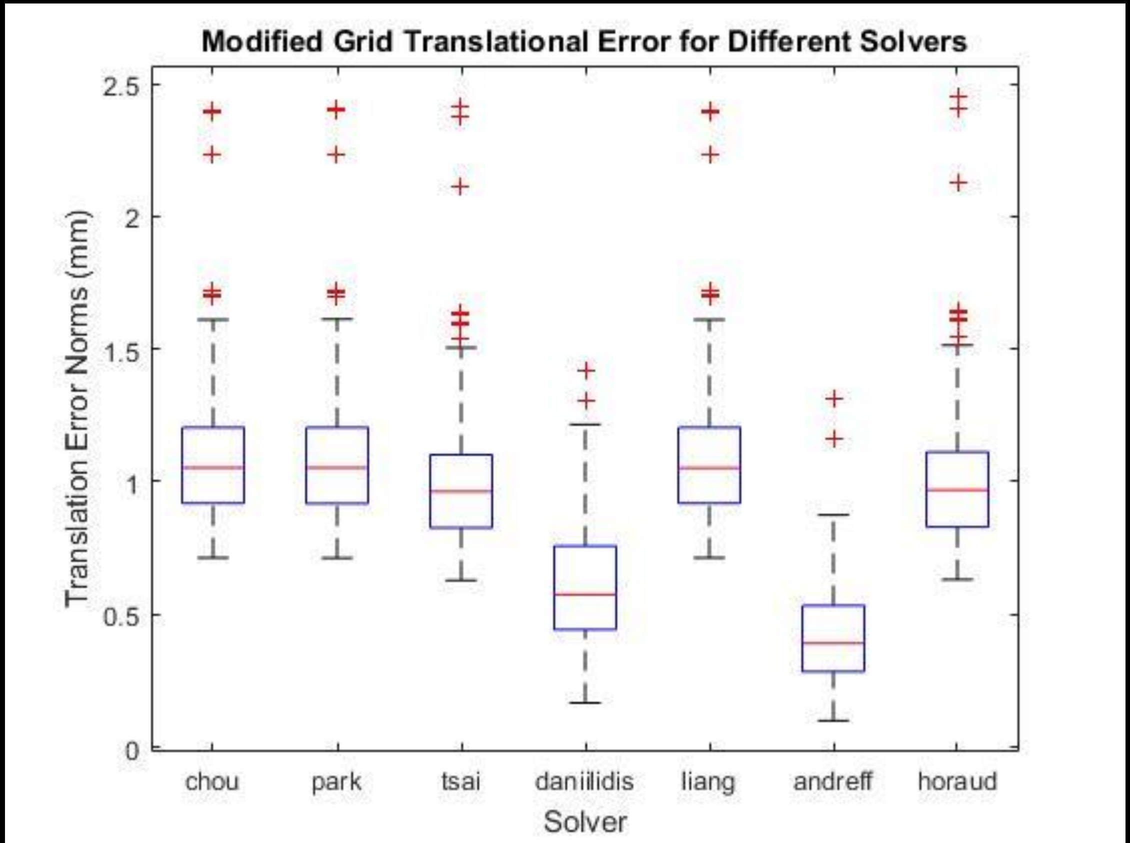
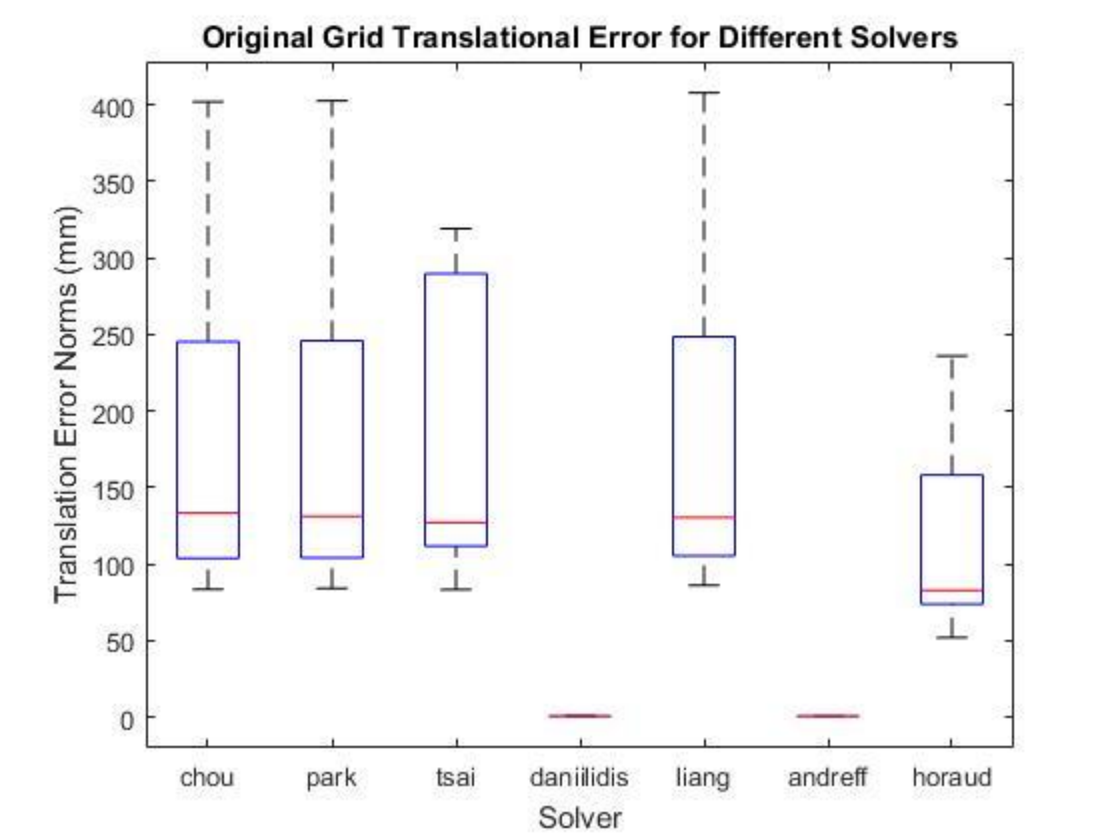
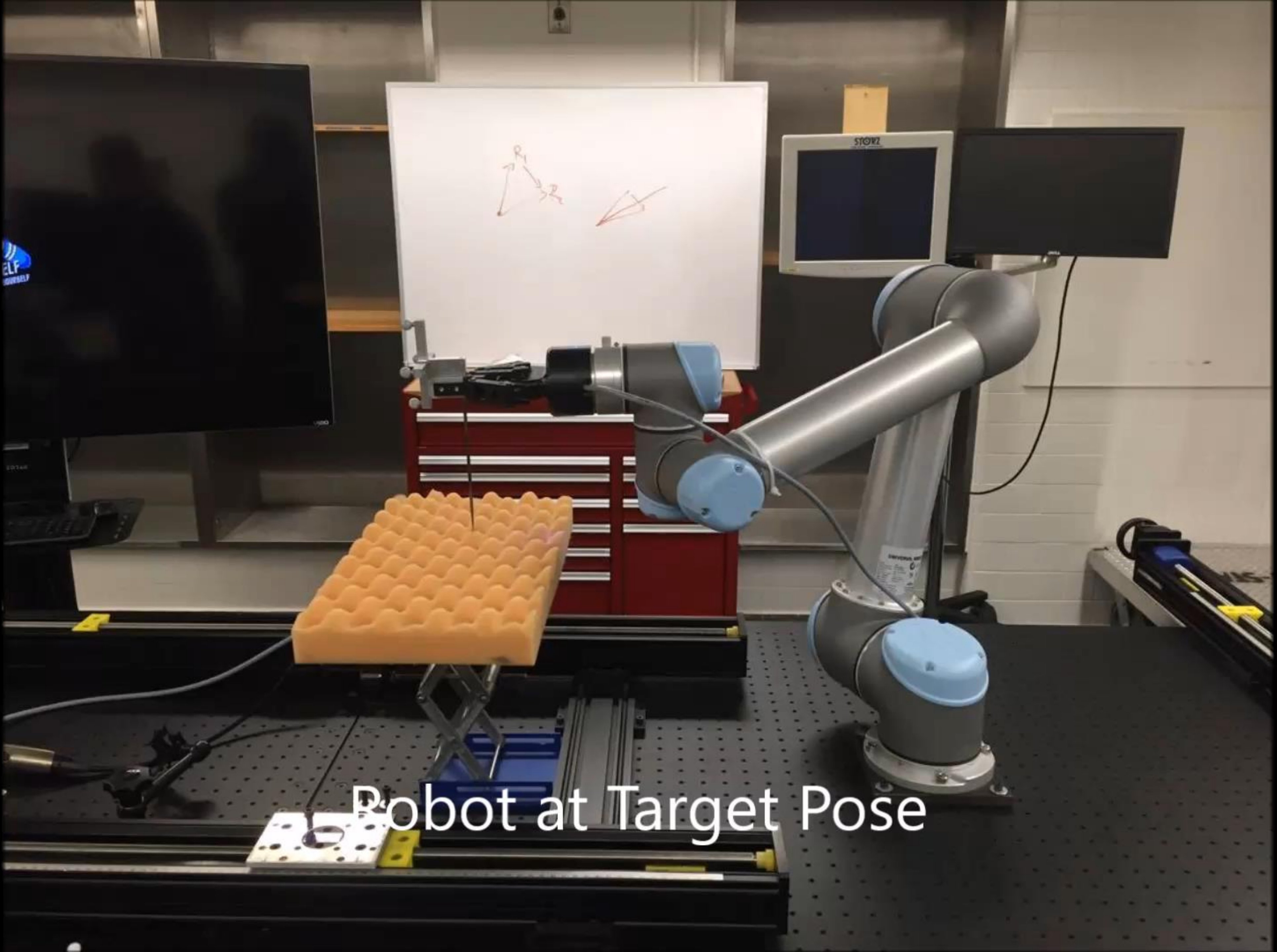
Validation of AX=XB Solvers



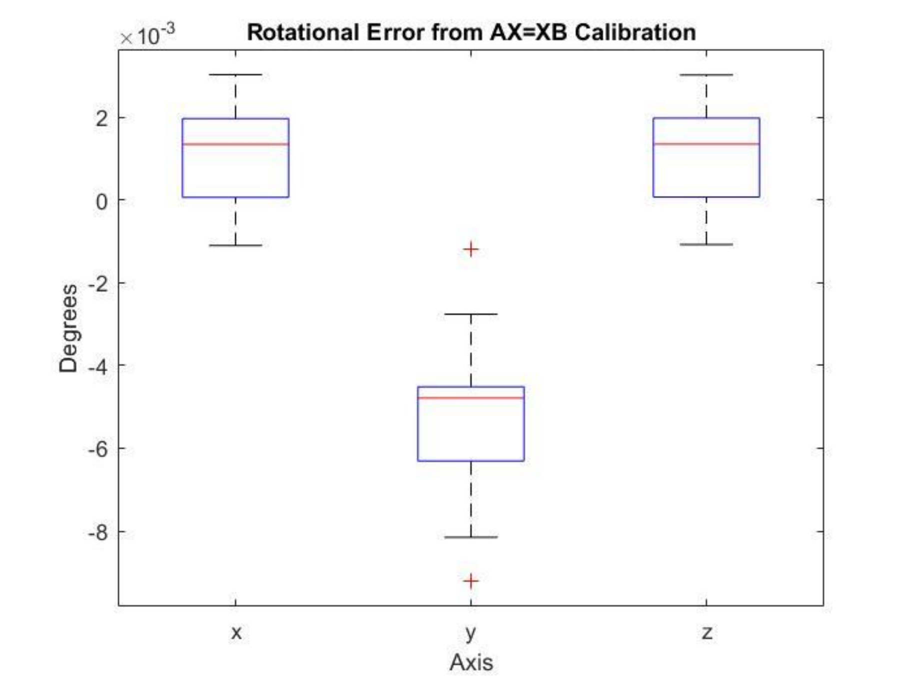


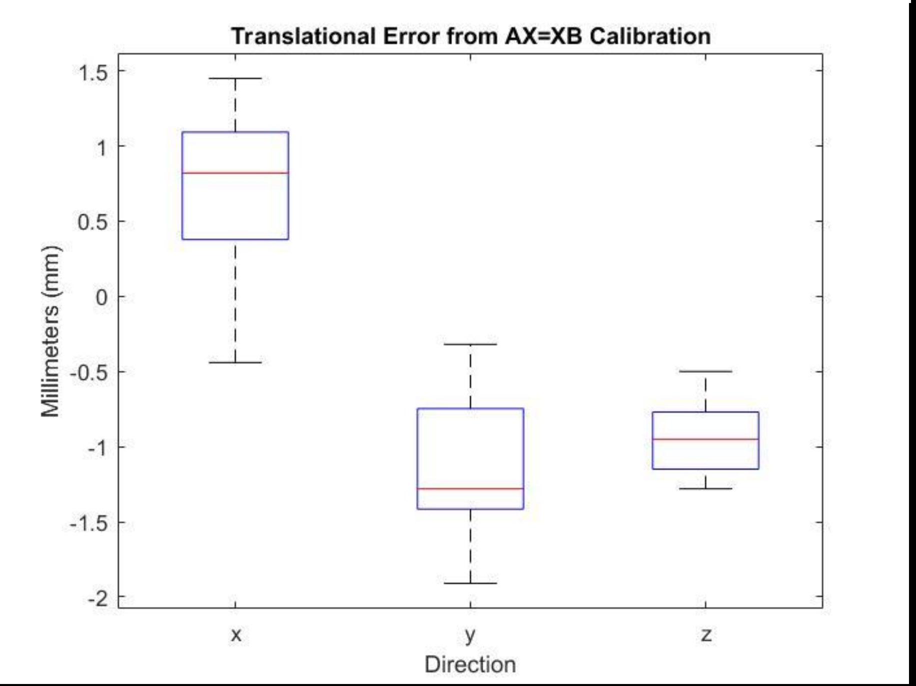
Shah, Mili, Roger D. Eastman, and Tsai Hong. "An Overview Of Robot-Sensor Calibration Methods For Evaluation Of Perception Systems". Proceedings of the Workshop on Performance Metrics for Intelligent Systems - PerMIS '12 (2012): n. pag. Web. 4 Feb. 2016.


Robot at Target Pose

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

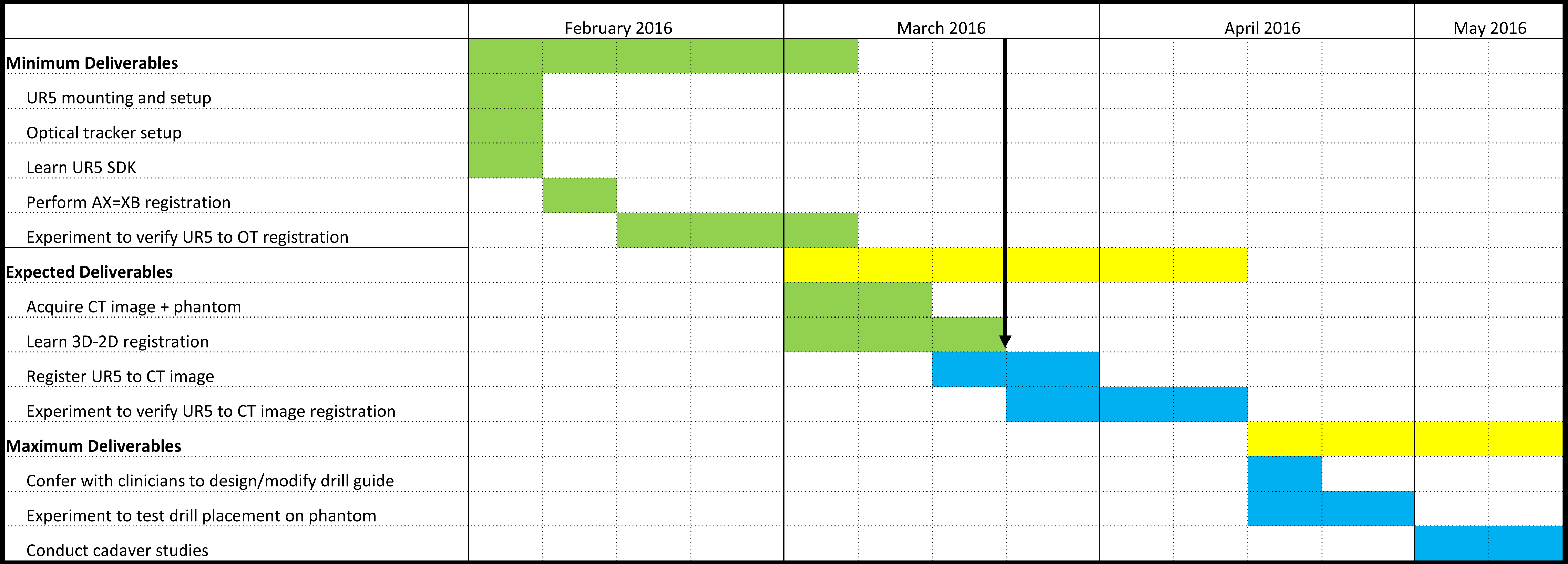




Dependencies

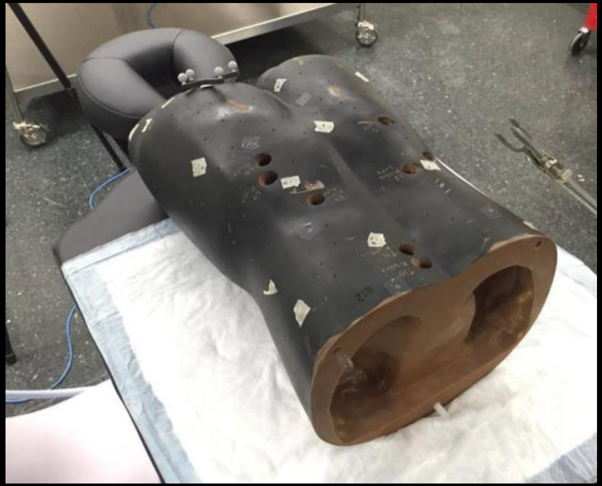
1. Transportation from/to medical campus (JHMI Shuttle) ✓
2. Fully operational UR5 that can be modified by program ✓
3. Fully operational optical tracker along with OT markers ✓
4. Optical tracking tools (calibrated) ✓
5. Work bench for UR5 mounting ✓
6. Computer for UR5 programmatic control and loaded 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



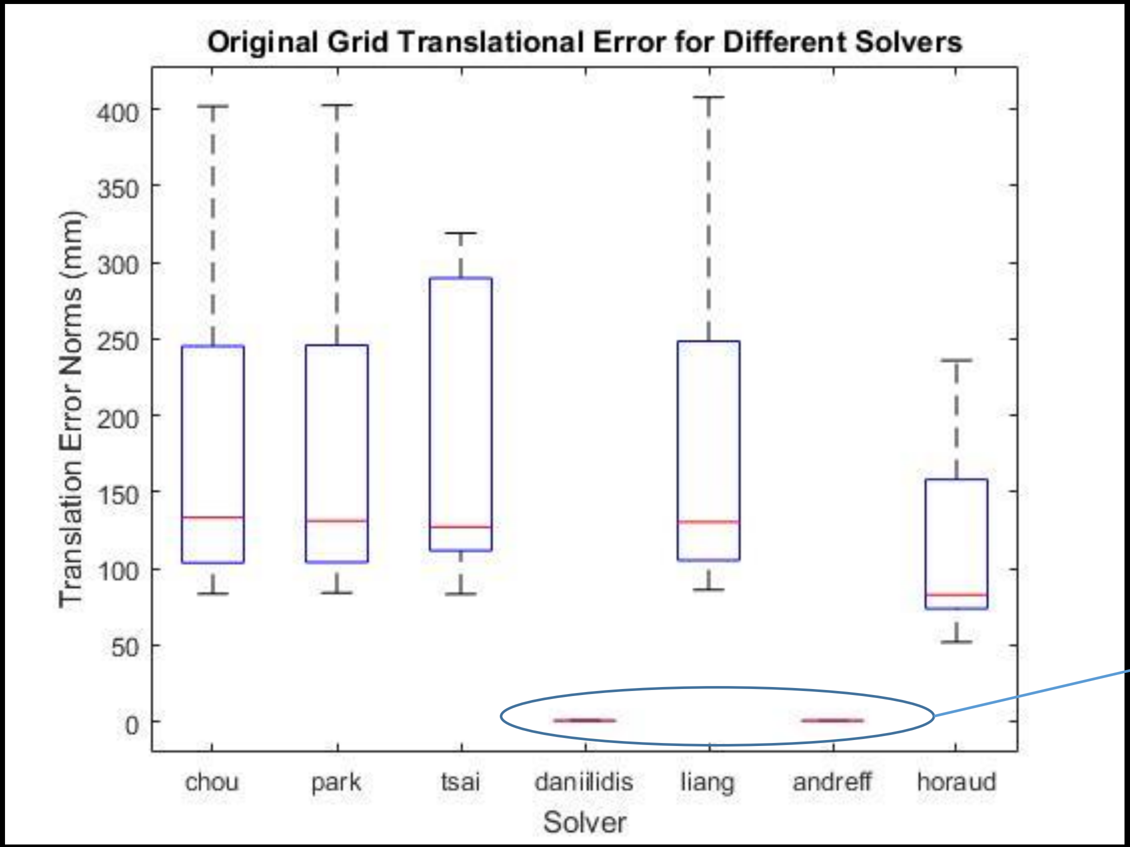
Next Milestones

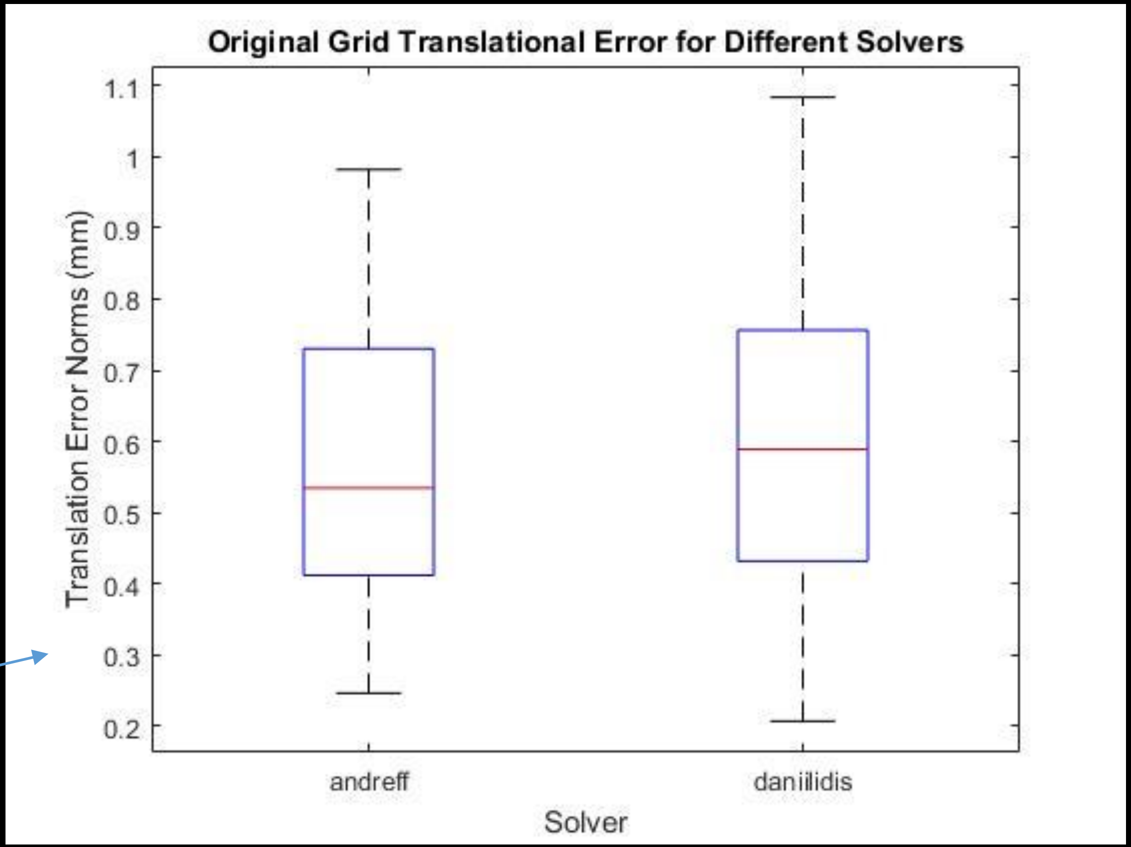
- Register tracker to CT data
- Complete assembly of drill guide
- Test ability of UR5 to align drill guide along pre-planned axis relative to phantom (with system including optical tracking system)
- Ultimate goal is still a system without an optical tracker



Questions?

Validation of AX=XB Solvers (Initial Grid)





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Tsai-Lenz Method

$$\begin{aligned} \mathrm{Sk}\left(k_{\mathbf{R}_{A_i}} + k_{\mathbf{R}_{B_i}}\right) k'_{\mathbf{R_X}} &= k_{\mathbf{R}_{A_i}} - k_{\mathbf{R}_{B_i}} \\ k_{\mathbf{R_X}} &= \frac{2k'_{\mathbf{R_X}}}{\sqrt{1 + \left|k'_{\mathbf{R_X}}\right|^2}} \end{aligned}$$

where the skew-symmetric matrix

$$\mathrm{Sk}(\mathbf{x}) = \begin{pmatrix} 0 & -\mathbf{x}(3) & \mathbf{x}(2) \\ \mathbf{x}(3) & 0 & -\mathbf{x}(1) \\ -\mathbf{x}(2) & \mathbf{x}(1) & 0 \end{pmatrix},$$

and the angle of rotation θ for $\mathbf{R_X}$ by setting

$$\theta = 2\mathrm{atan}\left|k'_{\mathbf{R_X}}\right|.$$

Tsai-Lenz Method

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

$$\begin{pmatrix} \mathbf{R}_{A_1} - \mathbf{I} \\ \vdots \\ \mathbf{R}_{A_n} - \mathbf{I} \end{pmatrix} \mathbf{t_X} = \begin{pmatrix} \mathbf{R_X t_{B_1}} - \mathbf{t_{A_1}} \\ \vdots \\ \mathbf{R_X t_{B_n}} - \mathbf{t_{A_n}} \end{pmatrix}$$