High-Precision Drill Guide Placement with the UR5 using 3D-2D Registration

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1. Introduction

a. Summary

Pedicle screw placement procedures require a high degree of precision and accuracy in screw positioning in order to yield the most successful outcomes. The current standard of care involves a clinician manually placing a pedicle screw in his or her patient based upon knowledge and prior experience; however, often these procedures have a significant failure rate that could be minimized with computer assistance. Dr. Jeff Siewerdsen of the JHMI I-STAR lab has acquired a UR5 robotic arm for potential use in image-guided surgery. Our goal was to combine the versatility of the UR5 robotic arm with the precision of image guided intervention to improve ease, efficiency and accuracy of pedicle screw placement procedures. Ultimately, we aim to universally improve the quality of pedicle screw placement for patients.

b. Background

Pedicles constitute small structures in vertebral segments that are often chosen as a gateway to anchoring pedicle screws that may be embedded for a variety of reasons (spinal stability, correction, etc.) [1].

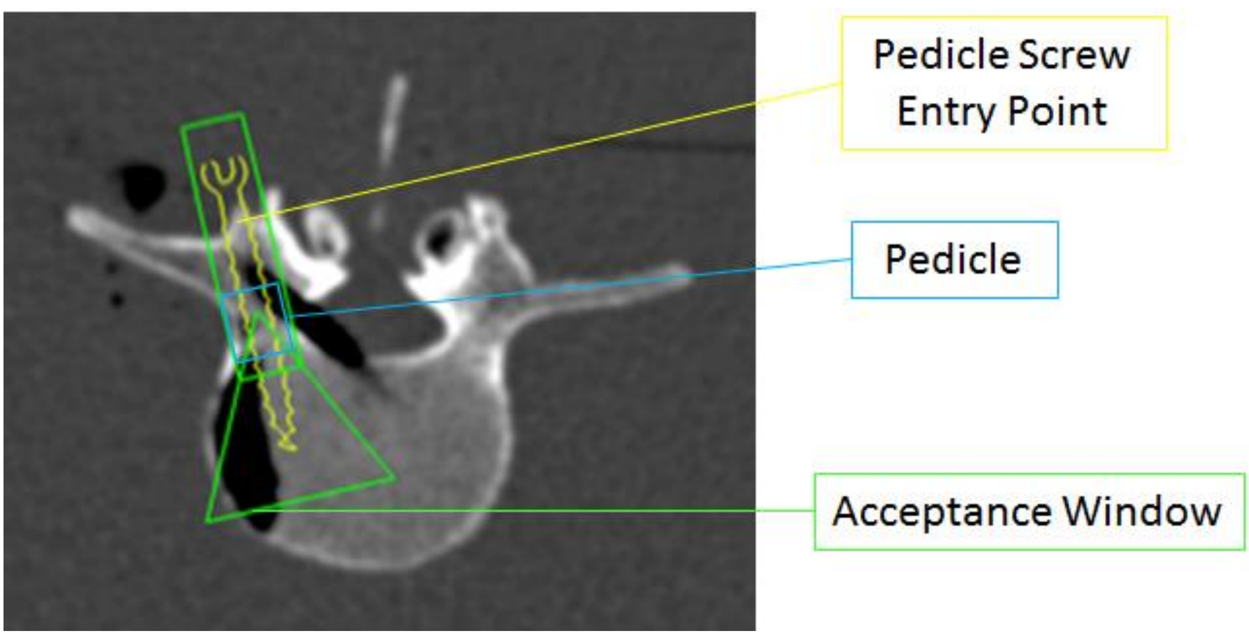


Figure 1. An axial CT slice of a vertebrae with a model pedicle screw secured in place

In pedicle screw placement procedures, a "successful" procedure may be defined as one in which a physician has secured the screw within a surgical "acceptance window" in a vertebrae as shown in Figure 1. Given that the UR5 is a 6-DOF robot arm capable of fluid, forward kinematics, adapting the arm for use in high-precision, image-guided drill guide placement could benefit pedicle screw patients. One can envision the UR5's integration into pedicle screw placement procedures at a high-level in Figure 2 as follows.

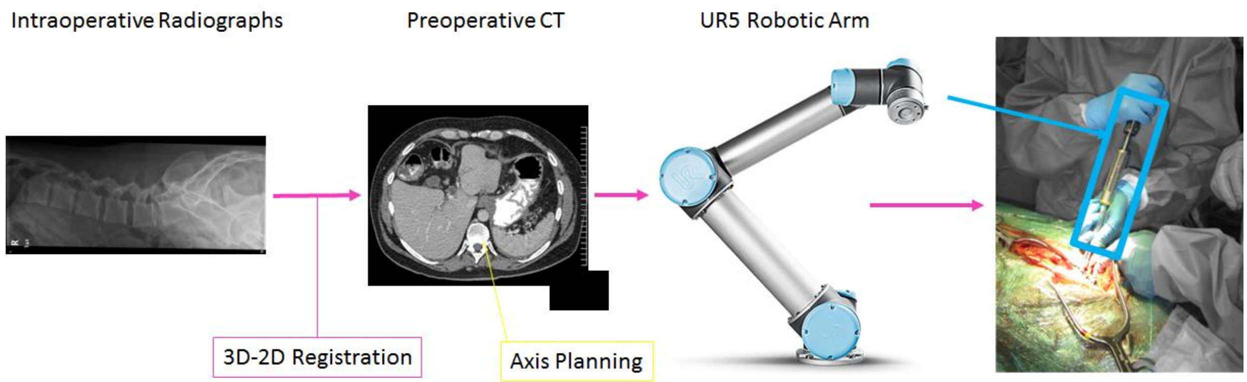


Figure 2. An overview of the UR5's integration into pedicle screw placement procedures

The schematic above highlights how the UR5 robot arm can be used in conjunction with image guidance to improve pedicle screw procedures. In practice, 3D CT volumes are simple to acquire for patients undergoing a procedure such as pedicle screw placement. Furthermore, many operating rooms have fluoroscopy or radiography devices, allowing physicians or some other technician to collect x-rays or radiographs intraoperatively: these images will be 2D images as they are planar. Thus, having these two sets of images, one can use 2D-3D registration to provide feedback to the UR5 about the position and "pose" of the patient. Finally, along with axis planning in the pre-operative CT, the UR5 robot can be used to noninvasively position a drill guide along an axis leading to placement within the acceptance window of a given patient's pedicle. In doing so, we believe that the accuracy of the procedure will be much better than the standard of care, and furthermore, will be easier for the physician to perform.

2. Problem

In terms of methodology, the current standard of care involves free-hand placement of screws into pedicle corridors by physicians based upon prior experiences [1]. This "free-hand" technique presents an array of errors that could otherwise be minimized with surgical assistance/guidance.

Given that the complications of the procedure should it go wrong include spinal cord breach and/or dislodgement (which could lead to paralysis or infection) [1], it is imperative that a pedicle screw is properly positioned and secured. Thus, the risks involved with the current standard of care warrant a means of maximizing screw placement precision to improve patient outcomes

3. Experimental Approach

a. Technical Design and Approach

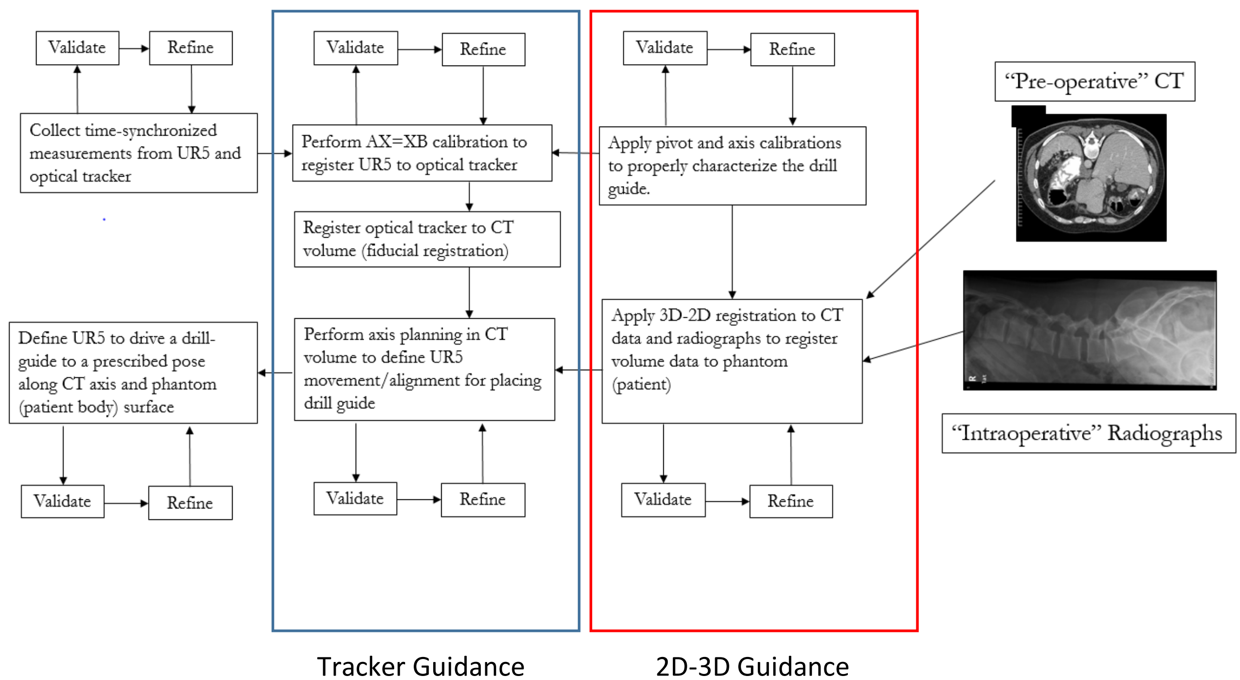


Figure 3. An overview of the project technical flow as a control diagram

The design for the project follows the systems architecture (control) diagram shown above. The first part of the project involved performing a hand-eye (AX=XB) calibration to compute the transformation between the UR5 end-effector and the drill guide attached to the gripping tool. The drill guide has optical markers fastened securely onto it in order to enable tracker guidance (for further details, see section on tool design); therefore, it is important to relate the coordinate system of the robot to the coordinate system of the tracker. To be exact, varying poses of the UR5 (compiled in a list of matrices A) were collected with time-correspondent optical tracker readings of the tool (compiled in a list of matrices B) which were fed into an AX=XB programmatic solver to obtain the X transformation from the UR5 end-effector to the local coordinate system of the drill guide. Corresponding A and B readings were collected in a 3x3x3 grid spanning 30 cm for which the end effector of the robot was perturbed to 5 different poses at each grid point. Repeated tracker measurements were not taken at each grid point initially as this was delayed to the refinement stages.

The X transformation was mathematically validated as shown in the results section, and a repeatability test was conducted to further assess the calibration. In this experiment, we defined a ground truth pose for the UR5 and randomly perturbed the UR5 up to 25° in rotation and 10 cm in translation. Having recorded a tracker measurement at the ground truth target pose, we ask the UR5 to return to the target pose using tracker guidance. Measuring the UR5 pose at each return to the target, we are able to compute the deviations shown in the results section below.

Next, we the CT volume (with accompanying phantom) was registered to the optical tracker via point cloud-point cloud registration specifically involving 16 fiducial points along the phantom. Once this was accomplished, basic axial planning was performed in the “pre-operative” CT volume to drive the robot given the fully registered system. The basic axial planning involved creating an intermediate 6-DOF pose that was translated upwards along the drill guide tool’s primary axis relative to the final 6-DOF pose. In this sense, the final motion that was generated reflected a steady descent upon a pre-planned trajectory axis.

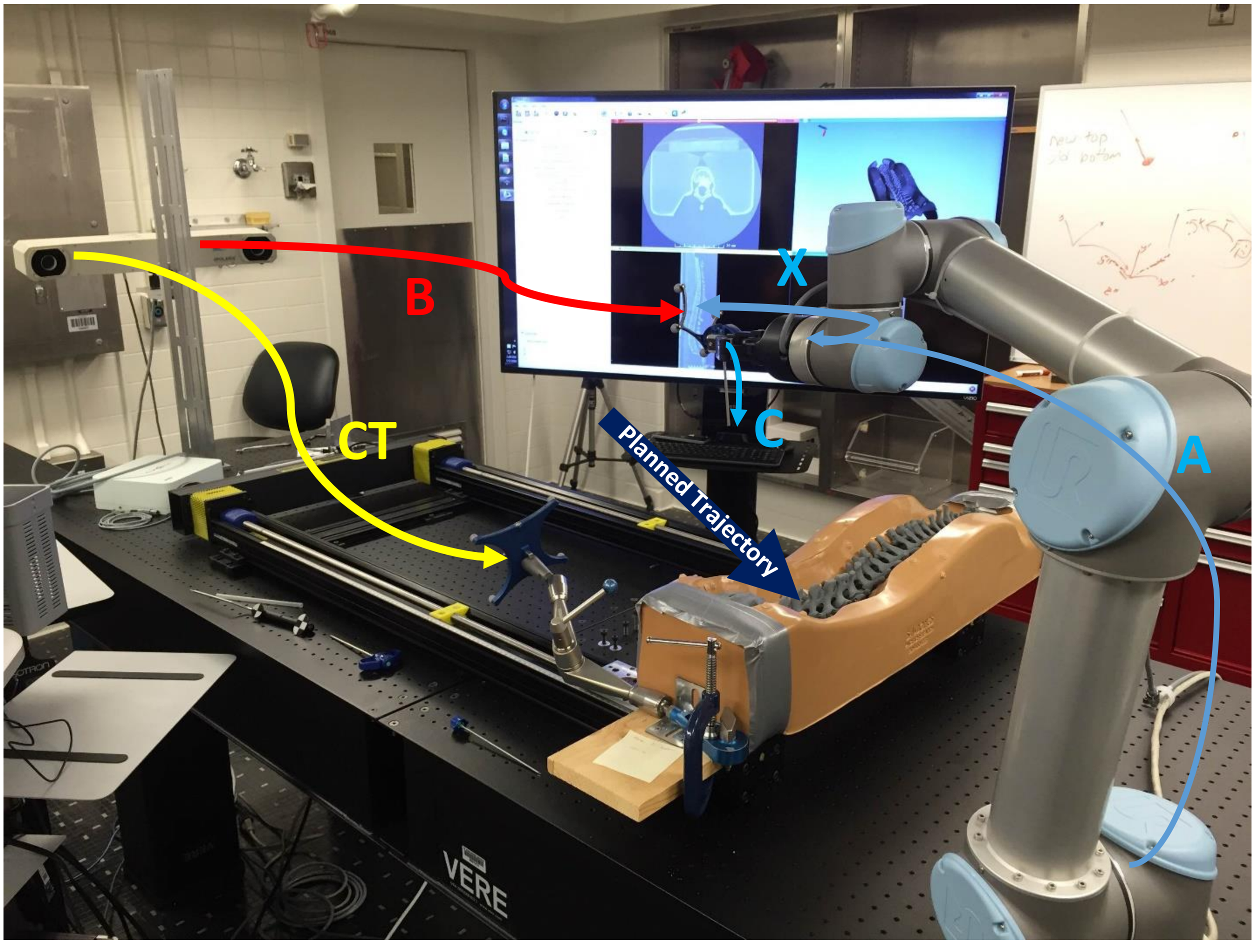


Figure 4. The physical setup of our optical tracking solution

Note that as our ultimate goal is to drive the UR5 to a pose defined in CT space, we can compute the pose of the robot using the transforms depicted in Figure 4:

$$\boldsymbol{A_2 = new\ target\ pose\ for\ robot = A_1 * X * B^{-1} * CT_{reg} * CT_{target} * C^{-1} * X^{-1}}$$

Where, A_1 is the starting pose of the robot, B is the position of the tool with respect to the tracker, C is the tool-tip calibration, X is the hand-eye calibration, CT_{reg} is the fiducial registration between the optical tracker and the CT volume, and CT_{target} is the pre-defined axis along which the UR5 will position the drill guide.

To determine the preliminary target registration error (TRE) associated with the tracker-based solution, we opted for a “leave-one-out” method where target poses were defined by fiducial points that were left out of the intermediate fiducial registration one at a time. Specifically, the fiducial points in CT space constituted ground truth data from which we measured the deviation of the drill guide’s tool tip when attempting to reach the target fiducial. 100 averaged tracker measurements were taken to determine the final position of the drill guide tip to reduce tracker error. Modifications were made to the drill guide for purposes of determining TRE in a manner that would reduce the risk of puncturing the spine model.

As our final step (outlined further in future plans), we can “substitute out” tracker guidance, and “plug-in” image guidance: i.e. use 2D-3D registration to identify patient pose and drive the robot [3]. These three steps correspond to the three deliverables discussed in the project plan. For all functionality involved in the project, documented code was developed to streamline calibration/registration processing and regularly backed up to a git repository and local lab server.

b. Tool Design

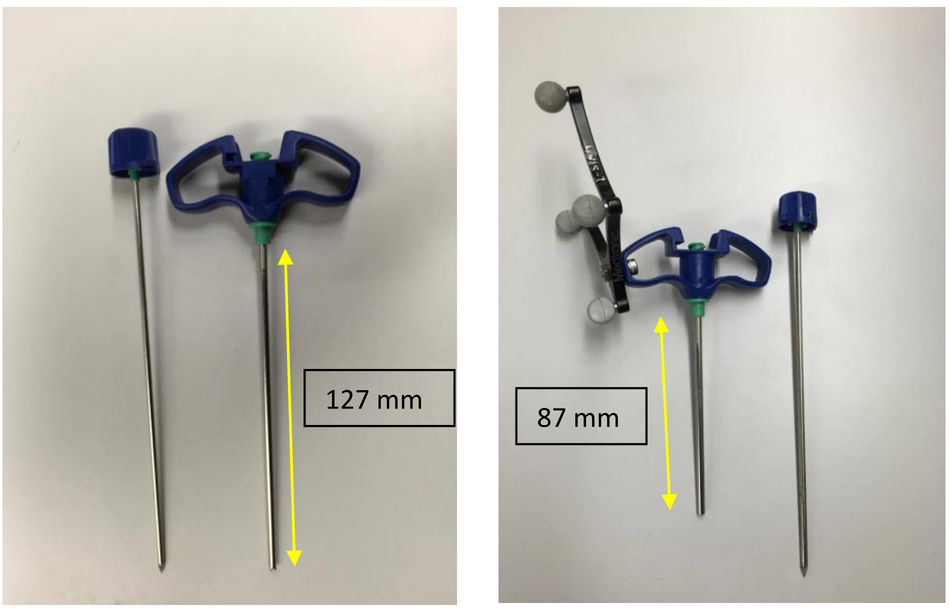


Figure 5. Drill guide design (base tool on left, custom tool on right)

In designing the custom tool guide, we started with a base tool supplied by the I-STAR Lab as seen on the left in Figure 5. The needle component shown in Figure 5 emulates a drill of arbitrary length while the corresponding cannula was modified to allow for a TRE computation with low risk of damage to the setup. Optical tracking markers were rigidly secured to the blue “handle” portion of the cannula, and 40 mm of cannula were sawed off with the assistance of our mentors. In this manner, the cannula alone could be used in the TRE computation as the tool was calibrated with the needle component inserted allowing for the tip position to be virtually known.

4. Results

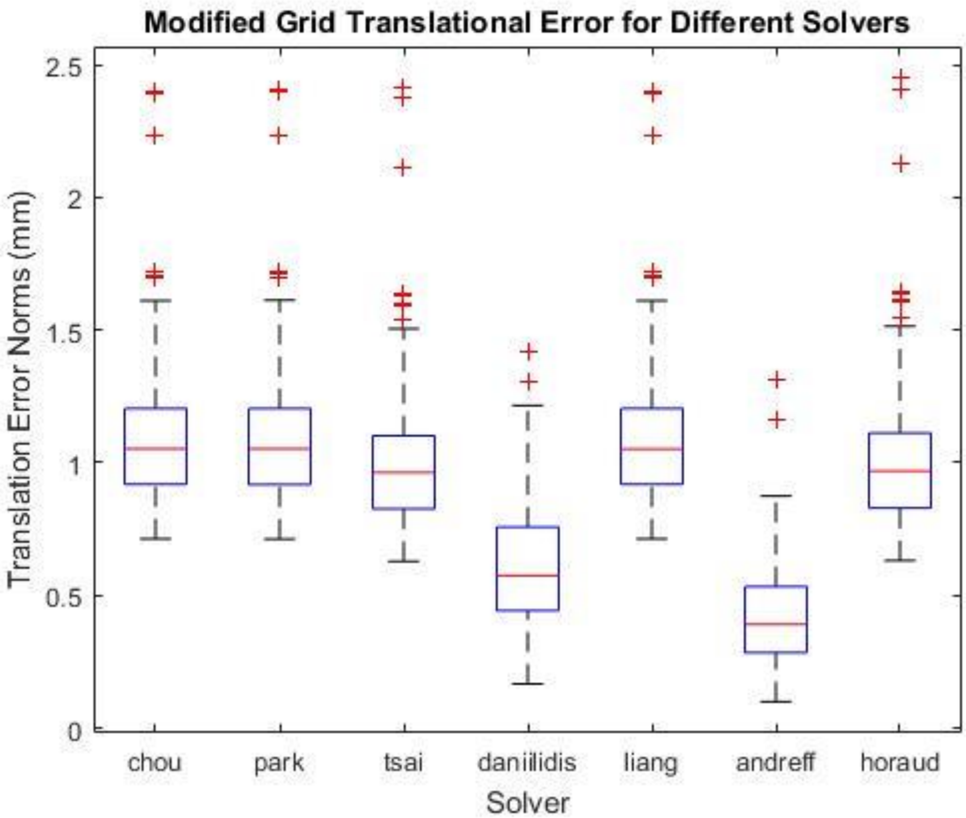
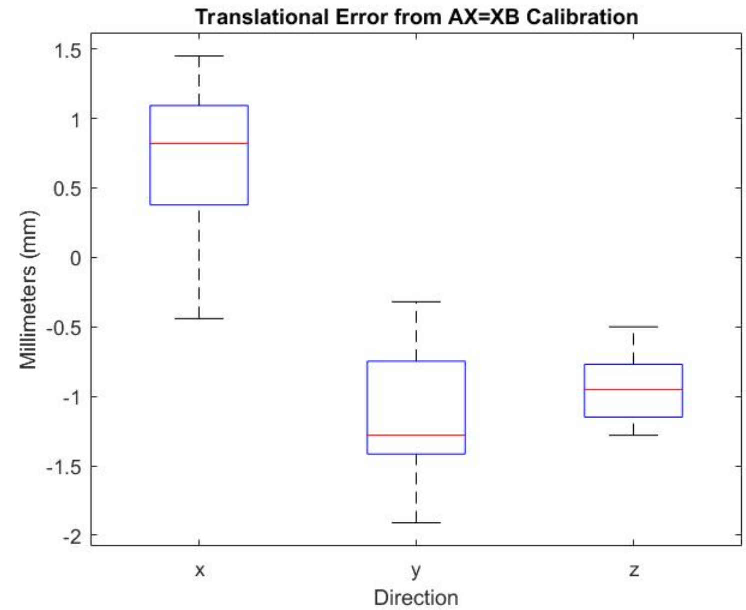
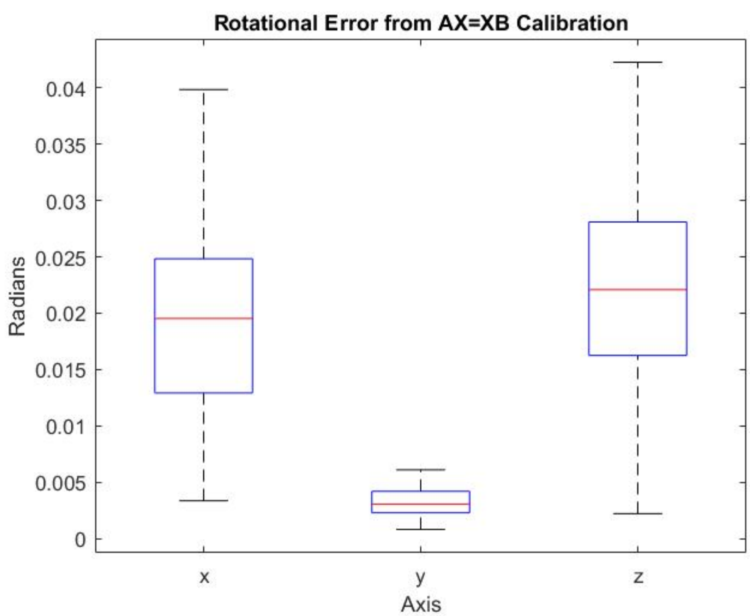


Figure 6. An analysis of translational error associated with the AX=XB solvers

To determine the best hand-eye calibration solver to use, we assessed the robustness of the X transformation outputted by different solvers. We multiplied the list of input poses A and B by X such that we obtained a list representing products AX and XB. Figure 6 shows the differences between the translational components of corresponding products $(AX)_i$ and $(XB)_i$. As shown in Figure 6, the median translational errors were all less than 2 mm, indicating that the solvers were able to output X transformations accurately related A and B. Although the simultaneous solvers Daniilidis and Andreff presented the lowest median errors, we opted to use Tsai's separable solver instead because it is not affected by the rotational-translational solving artifact associated with simultaneous solvers, and has offered the lowest average error in prior studies [2].



- Average Translational Error:
    - 0.667 mm in x (std. dev. 0.541)
    - 1.045 mm in y (std. dev. 0.459)
    - 0.894 mm in z (std. dev. 0.228)



- Average Rotational Error:
    - 0.02 rad in x (std. dev. 0.01)
    - 0.003 rad in y (std. dev. 0.002)
    - 0.02 rad in z (std. dev. 0.01)

Figure 7. Errors for Repeatability Experiment

Shown here were the results of the repeatability experiment described above. Given that these deviations also fell below our target error of < 1.5mm in the xyz directions and < 1 radian error in rotation, we proceeded to further steps in our project.

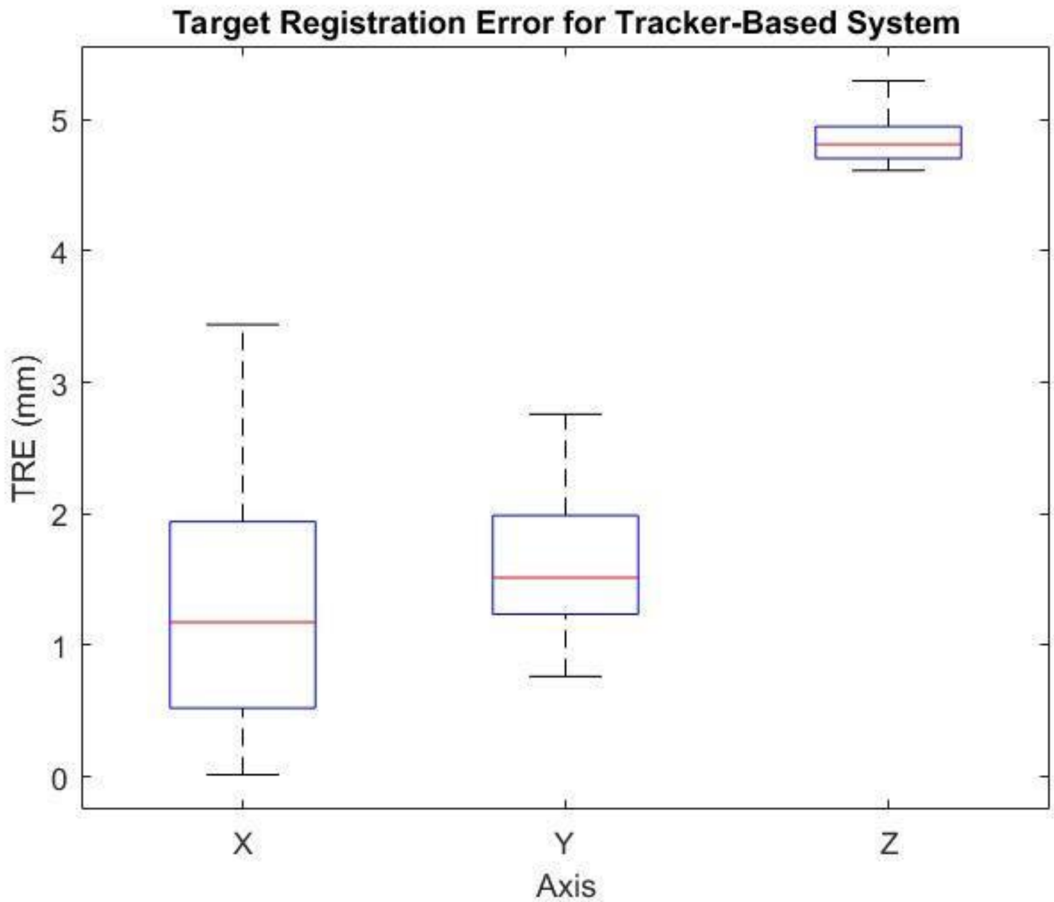


Figure 8. Target Registration Error (TRE) for optical tracker guided system.

As shown in Figure 8, the TRE associated with our tracker-based solution was 5.07 mm. This is result of the propagation of errors associated with tracker-robot registration, tracker-CT registration, tool calibration, and use of the optical tracker in general. In future experiments, the error could be reduced by obtaining an updated CT volume of the spine model to decrease fiducial registration error, and further increase optical tracker stability to reduce jitter. Specifically for the optical tracking setup, optical tracking markers could be attached to the UR5 itself such that calibrations would not have to be re-performed if the drill guide tool was perturbed.

5. Significance

Thus far, we have developed a system that can use an optical tracker along with pre-operative CT data to drive the UR5 robot to a target position determined in the CT volume. As we continue to refine the project – minimize tracker registration errors, minimize calibration error, and optimize path planning — as well as start the implementation of the 2D-3D guidance for the UR5, we believe we can make a significant contribution to improving pedicle screw placement procedures. Given that approximately 488,000 spinal fusion cases are performed annually in the U.S. (dependent upon pedicle screw placement), with about 70% growth in the last decade [4], the potential impact of the solution remains large.

6. Management Summary

Outlined below is a list of deliverables that we planned to complete throughout the course of the semester:

Deliverables

Minimum

~~UR5 to optical tracker registration~~

Identify a working "X" for AX=XB calibration between an optical tracker and the UR5 robot. This would give us the ability to send the robot to a desired pose as specified by the optical tracker.

~~Experimental verification and refinement~~

After consulting our mentors, the initial calibration should yield an error < 1.5mm in cardinal directions and < 1 radian error in rotation.

Expected

~~Optical Tracker to CT Volume Registration~~

Use phantom with fixed fiducials to register CT volume and optical tracker.

~~Experimental verification and refinement~~

Identify sources of error in fiducial registration, as well as conduct repeatability tests to verify robustness and accuracy of TRE.

~~Axis and path planning~~

Devise simple path planning for the UR5 to travel along an axis to position the drill guide. Furthermore, make robot robust in handling 5-DOF targets (axis) by safeguarding against stray rotations in the 6^{th} DOF.

Maximum

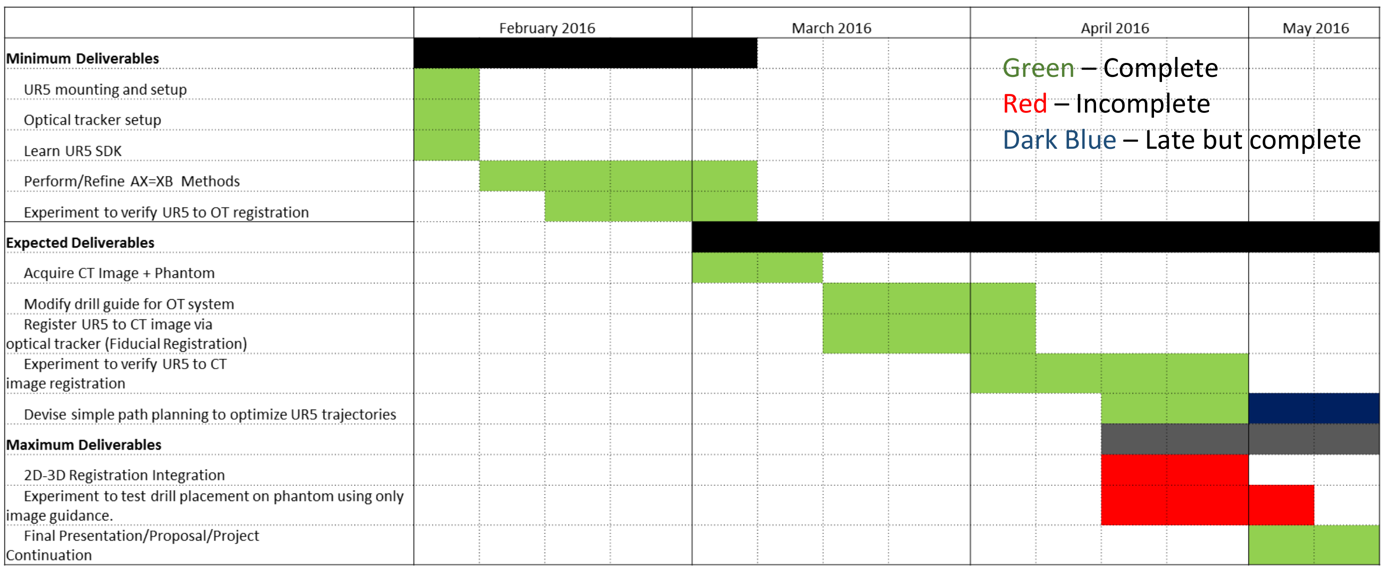
2D-3D registration

Acquire 2D radiographs of robot end-effector and testing phantom in order to align pre-operative CT volume to the 2D radiograph. Devise experiment to test TRE and PDE (projection distance error).

Image guidance

Use the information from the 2D-3D registration to drive the UR5 to a target axis by applying similar "path planning" and motion control used in tracker-based guidance.

Timeline (for CIS II)



As shown above in the timeline, we were successfully able to complete our minimum and expected deliverable, albeit being two weeks late on the expected deliverable. As a consequence, we were not able to commence work on the maximum deliverable; however, we both plan to continue with the project in the future and have already orchestrated plans with our mentors as to how we will implement the maximum deliverable in the coming future. Our end vision is still a solution that does not rely on tracker-based guidance, instead relying upon 3D-2D registration techniques to unify our system.

During the semester, we split the project up to maximize the utility of both group member's strengths. To be exact, Vignesh headed the majority of mathematical validations/analyses throughout the course of the project while Thomas implemented most UR5-driven processes in a custom TREK module. Overall, both of us learned the complexities of processes involved in bringing multiple systems and objects together to relate different coordinate systems as well as the fundamentals underlying known software builds and mathematical/experimental validation.

7. Acknowledgements

This project is supported by Dr. Jeff Siewerdsen and Ali Uneri of the JHMI I-STAR Lab. We would like to thank them for their continued support and enthusiasm.

8. References

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[2] 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.

[3] Markelj, P. et al. "A Review of 3D/2D Registration Methods for Image-Guided Interventions". Medical Image Analysis 16.3 (2012): 642-661. Web. 4 Feb. 2016.

[4] Weiss A J and Elixhauser A A R 2014 Characteristics of operating room procedures in U.S. hospitals, 2011 *Healthcare Cost and Utilization Project (HCUP) Statistical Briefs* (Rockville, MD: Agency for Healthcare Policy and Research) #170

9. Technical Appendices

All of our software development is stored under the git repository for the Laboratory for Computational Sensing + Robotics (LCSR) in the I-STAR sub-group:
https://git.lcsr.jhu.edu/groups/istar