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

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1. Introduction

Summary

Pedicle screw placement procedures require a high degree of precision and accuracy in screw positioning in order to yield the most successful outcomes. As the current standard of care often involves a clinician manually placing a pedicle screw in a patient based upon knowledge and experience, there exists a range of placement error that could be minimized with some sort of assistance. Dr. J. Siewerdsen of the JHMI I-STAR lab has acquired a UR5 robotic arm for potential use in image-guided surgery. Though originally designed for a more industrial environment, the 6-DOF robot arm's application will be expanded to non-invasively assist with pedicle screw placement, thereby promoting ease, efficiency, and accuracy of such procedures. Ultimately, we aim to universally improve the quality of pedicle screw placement for patients.

Background and Significance

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].

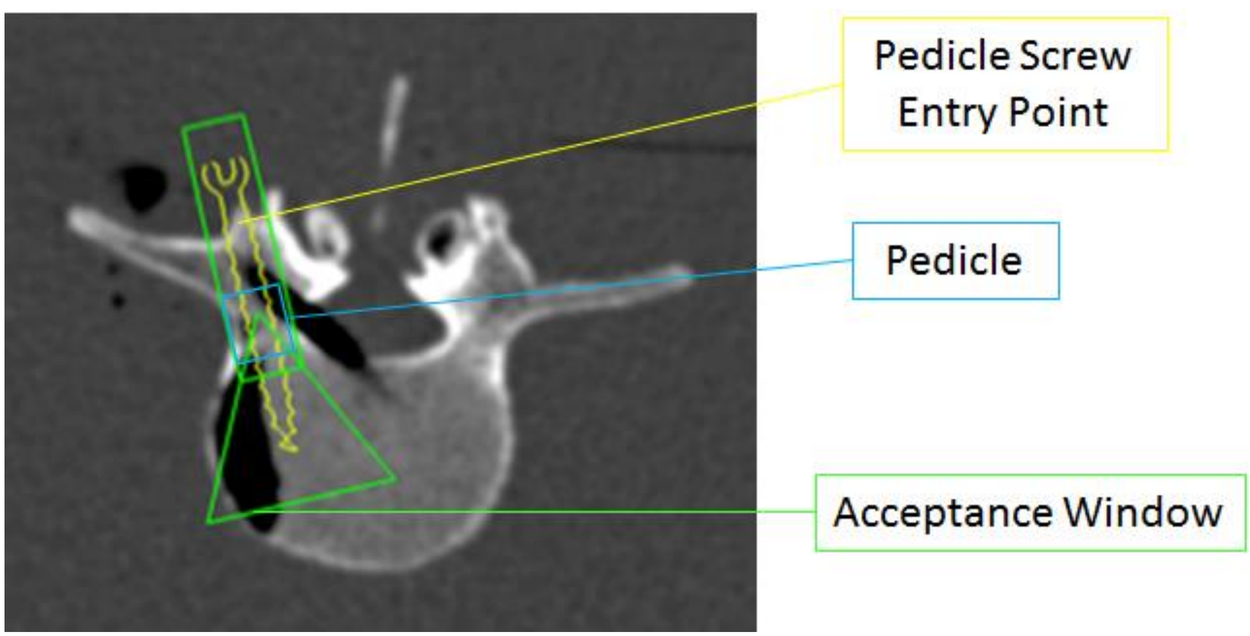


Figure 1. An axial CT slice of a vertebrae with a model pedicle screw secured in place

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. In terms of methodology, a physician will often attempt to manually place a pedicle screw in a patient based upon cumulative experiences [1]. This “free-hand” technique presents an array of errors that could otherwise be minimized with some sort of surgical assistance/guidance. Given that complications include spinal cord breach or dislodgement (which could lead to paralysis or infection) [1], it is imperative that a pedicle screw is properly positioned/secured.

Given that the UR5 is a 6-DOF robot arm capable of fluid, forward kinematics, it would be beneficial to pedicle screw patients if we could adapt the arm for use in high-precision, image-guided drill guide placement. One can envision the UR5’s integration into pedicle screw placement procedures at a high-level in Figure 2 as follows.

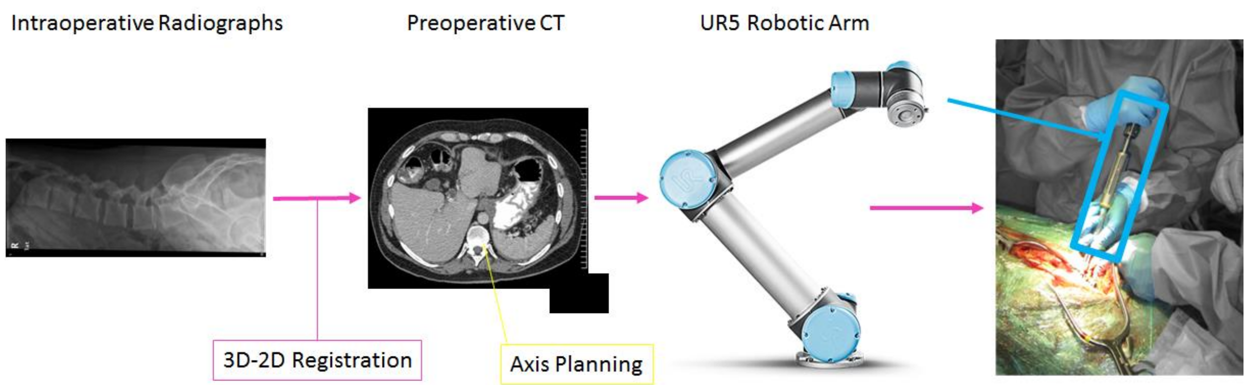


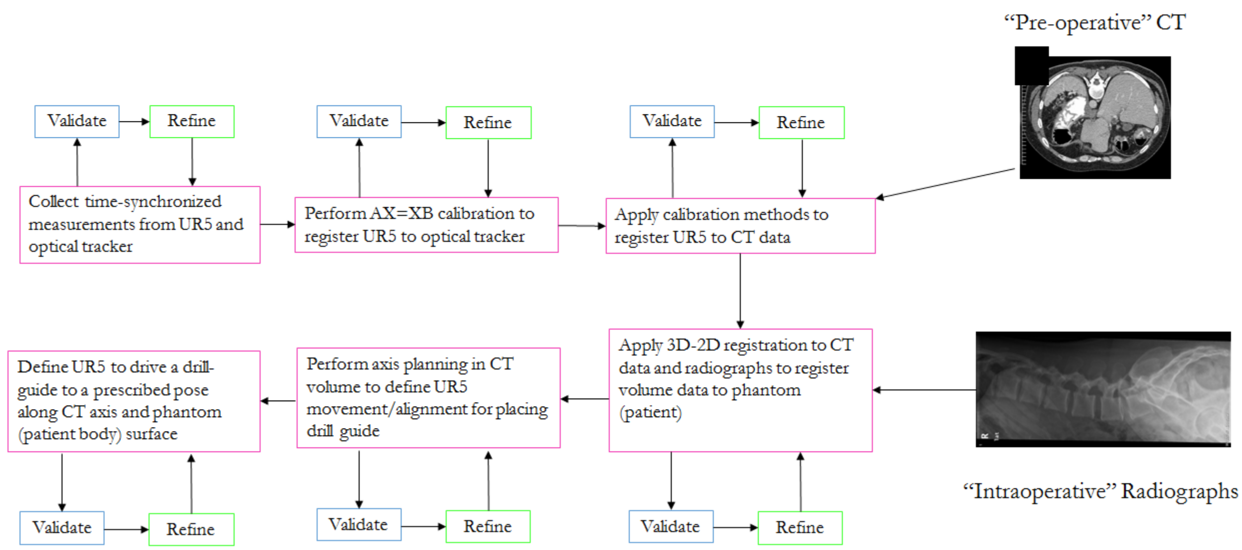
Figure 2. An overview of the UR5’s integration into pedicle screw placement procedures

To elaborate, suppose a patient is to have pedicle screws placed into his or her spine. One could consider that the patient is likely to have some spinal, pre-operative CT data. Thus, if the patient’s physical body volume was registered to this CT volume using two, orthogonal intraoperative radiographs via 3D-2D registration, one would effectively have a digital version of the patient to devise path planning with. Following, if one were to register the UR5 to this CT volume and do some initial axis planning, the UR5 could position a drill-guide along said axis to provide a physician with a simple and safe method of placing a pedicle screw into a vertebrae.

2. Technical Approach

Design

The major technical milestones are delineated in the following diagram:



Evaluation

The first course of action is to collect AX=XB calibration data by collecting optical tracker and UR5 positions at varying poses in a given 3 space [2, 3]. This data can then be used to mathematically compute a transformation from the robot tip to gripping tool tip. Following this calibration, experiments to test error in cardinal directions as well as rotational angles will be conducted to verify that our calibration method and AX=XB solver meets our goal of minimizing all translation errors to be < 1.5 mm and rotational errors to be < 1 radian relative to the intended pose.

Once we have verified that we are able to acquire a "good" calibration for our robot, the next step is to repeat the process with a CT volume and accompanying phantom. This process will first entail a similar calibration between the given CT volume and the UR5 robot. Then, we would register the phantom to the 3D-2D registration using two orthogonal radiographs of the phantom [4]. Once this calibration and registration is complete, we would do preliminary axis planning to optimize UR5 path planning. Then, we plan to conduct experiments with the physical phantom itself in order to identify sources of calibration error and attempt to minimize the ones we find.

Finally, once we validate and refine our calibration process -- ie registering the UR5 to a CT volume that is registered to a 2D radiograph -- we can pursue further testing in cadavers to test how well and efficiently the robot can place a drill guide on the pedicle and have the orientation and position be within the acceptance window (see Background). Once this procedure with the robot assistance has a success rate of over 95%, we plan to pursue clinical studies on patients in real time.

3. Project Plan

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 calibration should yield an error < 1.5mm in cardinal directions and < 1 radian error in rotation. We plan to devise an experiment to rigorously quantify and minimize calibration error.

Expected

2D-3D registration

Two orthogonal radiographs and a full 3D CT volume of a phantom will be collected in order to perform 2D-3D registration to identify registration between a CT volume and the phantom.

Registration of phantom with the UR5

Following 2D-3D registration, a similar calibration to the AX=XB from above would be performed to map UR5 to CT volume, and consequently UR5 to phantom.

Experimental verification and refinement

Identify sources of error in 2D-3D registration as well as optimize axis planning to minimize error in UR5 to phantom calibration.

Maximum

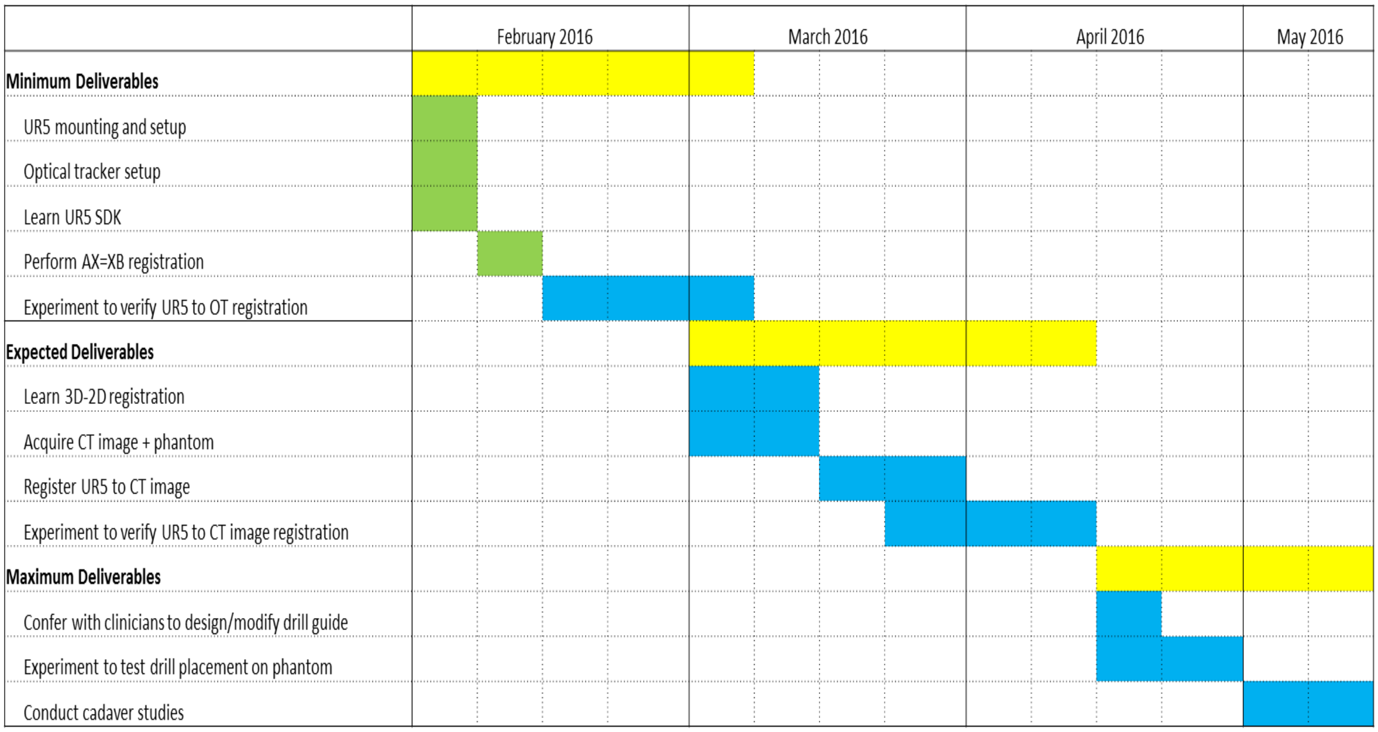
Conduct experiments in cadavers.

Design and conduct experiments to test -- in real-time -- our proposed surgical workflow: 2D Radiograph → CT Volume (with axis planning) → UR5 → Drill guide placement. Once these experiments prove effective in cadavers, the study can be extended to live patients.

Dependencies

Dependency	Resolution
Operational UR5 with programmatic control	✓
Optical tracker along with OT markers	✓
Work bench for UR5 mounting	✓
Computer for UR5 control and direction	✓
Visualization software for optical tracking	✓
3D visualization software (3D slicer)	✓
3D-2D registration software in Trek	✓
CT Data accompanied by corresponding phantom	Plan to obtain by meeting on February 29th with Dr. Siewerdsen.
Machine shop access to modify drill guide	✓
Mentors	✓

Timeline



February 2016
March 2016
April 2016
May 2016
Minimum Deliverables
UR5 mounting and setup
Optical tracker setup
Learn UR5 SDK
Perform AX=XB registration
Experiment to verify UR5 to OT registration
Expected Deliverables
Learn 3D-2D registration
Acquire CT image + phantom
Register UR5 to CT image
Experiment to verify UR5 to CT image registration
Maximum Deliverables
Confer with clinicians to design/modify drill guide
Experiment to test drill placement on phantom
Conduct cadaver studies

4. Acknowledgements

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5. References

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[4] 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.