Assignment 4: Medical Image Analysis, Image Registration, and Needle Insertion

ME 328: Medical Robotics
Stanford University • Winter 2019

Due on Canvas by 5:00 pm on Wednesday, February 13
Please scan and submit all documents relevant to Assignment 4 via Canvas. (No hard copy)

0. Guest Speaker: After each of the seminars on Friday, March 1 and Friday, March 8, look for questions posted to **Canvas** about the seminars, and answer them online by the time this assignment is due.

1. Readings: You can download these papers from http://www.stanford.edu/class/me328/#readings

G. Fichtinger, P. Kazanzides, A. M. Okamura, G. D. Hager, L. L. Whitcomb, and R. H. Taylor. Surgical and Interventional Robotics Part II: Surgical CAD-CAM Systems. IEEE Robotics and Automation Magazine, 15(3):94-102, 2008.
This review paper describes a set of robot-assisted medical interventions that are analogous to CAD-CAM (and TQM) systems in manufacturing; they involve modeling, planning, robotic implementation of the plan, and post-operative assessment.

N. Hata, J. Tokuda, S. Hurwitz, and S. Morikawa. MRI-Compatible Manipulator With Remote-Center- of-Motion Control. Journal of Magnetic Resonance Imaging, 27:1130-1138, 2008.
The authors developed and assessed a needle-guiding manipulator for MRI-guided therapy that allows a physician to freely select the needle insertion path while maintaining remote center of motion (RCM) at the tumor site.

Z. Yaniv, and K. Cleary. Image-Guided Procedures: A Review. CAIMR Technical report TR-2006-3, 2006.
Reading this paper is optional. This overview paper provides a practical introduction to image-guided interventions, including history, clinical and technical background, and a perspective on the future of the field.

A. (Fichtinger et al.) Explain the difference between percutaneous and transcutaneous procedures.

B. (Fichtinger et al.) The authors state that, out of three metrics of registration performance (accuracy, consistency, and robustness), accuracy is the least important. Do you agree? Why or why not?

C. (Fichtinger et al.) The authors describe some areas for future research in the field. By the time this assignment is due, you should have some idea for the kind of project that you want to work on. (If not, just pick something for the purposes of this assignment.) Does your project fall into any of the areas mentioned?

- If so, which one? Explain.
- If not, write your own "bullet point" to add to this list that is related to the project you are planning to propose.

D. (Hata et al.) What do the authors mean by a "Virtual" Remote Center of Motion (RCM)?

E. (Hata et al.) Name at least three ways in which the use of MRI imaging impacted the design of their robot.

To submit your individual answers to these questions, use the "Assignment 4 Readings" assignment on canvas.

Image-guided robotic intervention problems

In the remaining parts of this assignment, you will perform an image-guided robotic intervention on an artificial tissue specimen. The tissue specimen consists of cured gelatin and a water-filled balloon representing a cyst within the tissue. We will simulate using a robotically guided needle to access and drain the cyst. Similar techniques are used in many other medical procedures, including ablation and biopsy.

Each group of 3 or 4 students will work with an artificial tissue specimen, which you will get from the CA running your ultrasound lab session. Do not "test" needle insertions on your specimen until the very last step of this lab, as the cyst can only be accessed and drained once. We will have "empty" specimens for you to test on. The group should compose and submit a single assignment together for Problems 2, 3, and 4 below. Please do not "divide and conquer", because each member of the group needs to learn all the material (imaging, registration, path planning, and robot control).

Groups will be formed based on the google sheet sign-up time for the ultrasound lab session. Sign up for an ultrasound lab session here: https://tinyurl.com/ME328-USlab

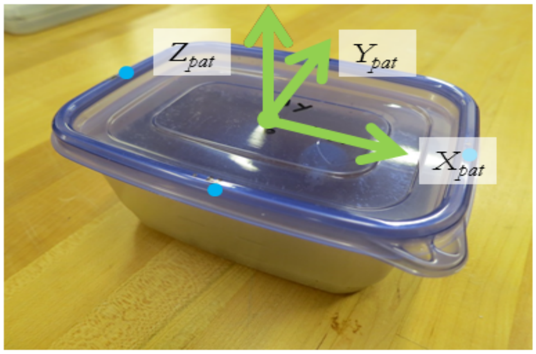
To submit your group answers to these questions, use the "Assignment 4 Ultrasound Lab" assignment on canvas has already been set up for your group.

2. Medical image analysis

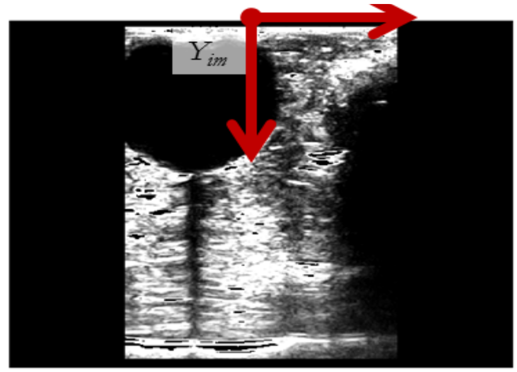
In this problem, you will capture and analyze medical ultrasound images that will be used to guide the needle insertion robot. For Parts 2A and 2B you will work with a CA and postdoc Dr. Giada Gerboni, since misuse can result in damage to the expensive ultrasound transducer. The CAs will run sessions with the ultrasound machine during specific hours – you will sign up for a time on the google sheet and work with the other students who signed up for the same time. Come to Mechanical Engineering Research Lab (MERL) Building, Room 126 at the selected time. If you cannot be present during any of the ultrasound sessions, let the teaching staff know immediately. **Under no circumstances should you handle the ultrasound machine without supervision.**

A. We will give you an artificial tissue specimen and assist you to use the 2D ultrasound transducer to scan the tissue. We will advise you on the best settings for imaging depth, frequency, focus, gain, etc. Use the time to experiment and get a feel for the ultrasound. Once you have achieved sufficient image quality, localize the target within the tissue specimen. The target is a balloon of water roughly 20 mm to 40 mm in diameter, and will appear as a hypo-echoic (dark) region in the image. Record and report the image depth, image width, and ultrasound frequency settings from the ultrasound machine.

B. Capture ultrasound images of the target. Since we will capture only 2D ultrasound data in this lab, we must have information about the orientation and position of the ultrasound transducer in order to localize the target with respect to its container in 3D (see image on next page). Here we will assume the ultrasound image is exactly parallel to the Y-Z plane of the patient frame. (You should manually keep the ultrasound transducer as close to vertical as possible, with the transducer array parallel to the Y-axis of the patient frame.) We will measure the X, Y, and Z components of the image position relative to the patient frame using a ruler. The diagram below shows the patient frame and the image origin. The blue dots are registration fiducial points. Please bring a USB memory stick to store the ultrasound data you capture. Include a copy of the image you capture in your report, along with the 3D position you measured. You might have to flip the image horizontally to match what you saw on the screen. *Hint: See the Matlab help files for the* `fliplr`*,* `image`*,* `colormap`*, and* `gray` *functions.*



Patient frame and registration fiducial points



Ultrasound frame

C. For parts C and D, you can use any computer with MATLAB. Manually segment the target from the ultrasound data. Write a Matlab script to load and display the captured ultrasound image files (.png), using the `imread` function. Then, write additional code to allow a user to select points from the image. You can then either manually select the center of the target (acceptable) or select multiple points along the boundary of the target and take the centroid of the encircled region (better). Subtract the position of the image origin and convert the target coordinates from pixels to millimeters using the imaging depth and width recorded in Part A. Include a printout of the segmented image (selected point(s) overlaid on the ultrasound image) in your report. *Hint: See the Matlab help files for the* `getpts` *function.*

D. Convert the image points to the 3D patient frame using the recorded position of the image origin from Part B. Include the final 3D target position in millimeters (in patient coordinates), and the steps you took to calculate it.

For the problems below, you will again add your code to the main.cpp file of the code template provided for Assignment 4. For Problem 4, the template includes a function to display the 3D position of the needle tip in the robot frame. You can access this function by pressing 'A'. You should not need to alter this code, other than to change the length of the needle, if yours is longer or shorter than the default length in the code (remember that the length is measured to the distal wrist point of the Phantom Omni). For Problem 5, you will again add your code to the correct part in the switch statement in the function called "Control", within the switch statement under case 'B'. You can also add variable definitions and any other necessary code anywhere between the comments that say "START EDITING HERE" and "STOP EDITING HERE". In addition, you may need to add code to record any additional data you desire that is not already set up to be recorded. There are places in the code labeled "DATA RECORDING EDIT HERE" – these are the areas where you can change which variables are recorded.

3. Image registration. In this problem, you will register 3D medical image data to the kinematic frame of a robotic system (Phantom Omni), by identifying six common "fiducial" points in both the patient and robot coordinate frames. For Problems 3 and 4, you will need to use the computers/Phantom Omnis (Station 1, 2, or 3 only) in 550-108.

A. Define the fiducial points in the patient frame. Based on measurements of your patient that you take with a ruler/calipers, identify the 3D coordinates of the fiducial points in the patient frame and identify these in your report. To make the problem simpler, we have numbered the fiducial points. Be sure to use units of millimeters.

B. Define the fiducial points in the robot frame. Here, use the *empty* patient container placed near the Phantom Omni corresponding to a "patient", so that you can access all fiducial points. Put empty container in the holding bracket as shown below. Use the thinnest rubber band that still holds the container in place, and use plenty of tape to secure the holding bracket. Also, mark out the Omni's position so that you can easily reset the Omni if it is accidentally moved. As described above, you can view the position of the needle tip by running the template and pressing 'A'. Record and report the positions of the fiducial points with the correct labeling.

C. Determine the homogenous transformation from the robot frame to the patient frame that minimizes the sum of the squared Fiducial Registration Errors (FRE) as your disparity metric. (In other words, use the SVD method described in class.) Include the transformation you calculate, as well as the method you use to solve for it, in your report. Don't worry about introducing constraints on the transformation matrix. You should renormalize the columns of the rotation matrix you find, and ignore the fact they may not be perfectly perpendicular. *Hint: In the next part, you will use this homogenous transformation for planning a needle insertion trajectory. Since the registration is invalidated by relative motion of the robot and tissue specimen, you should use the fixation jig, or plan to complete this part immediately before Problem 4.*

D. Transform the target from patient coordinates to robot coordinates. Submit your method and the resulting robot coordinates.

4. Needle insertion. In this problem, you will use a Phantom Omni that has been modified to behave like an RCM needle insertion robot. A metal wire attached to the stylus is constrained to pass through a hole in the tissue specimen container representing the body wall of the patient. The goal is to hit the target at the previously determined location in robot coordinates.

A. Describe your algorithm/trajectory generation process and plot data demonstrating that the needle moved along a straight path from the entry point to the target in free space (i.e., do not test in the artificial tissue specimen initially, rather use the *empty* patient for this). Your controller should work for any initial configuration of the Omni, with the needle just slightly inside the port. Ensure that your needle is inserted along a straight line, and that the tip is reaching the desired position in free space. *Hint: The path should consist of 2 steps: (1) align the needle to the target and (2) insert the needle into the tissue.*

B. Once you are satisfied with your trajectory, position the artificial tissue specimen, and insert the needle towards the target. If you successfully access the cyst, you might see clear water draining out of the tissue specimen. Once the insertion is complete, manually move the needle back and forth, and see if you can feel the tip of the needle hitting the cyst. If you hit the target, say so in the report. If you do not hit the target, try to explain why not. There are many potential sources of error in this procedure – list at least three of them.