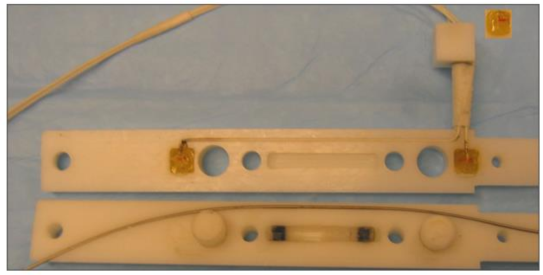
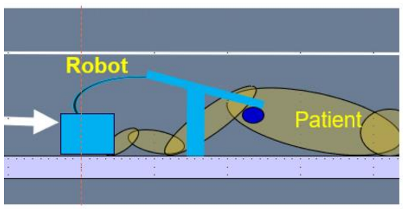
Assignment for CISC/CMPE 330

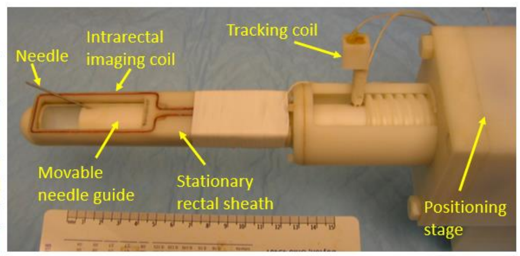
MRI-guided prostate biopsy robot navigation

PROBLEM STATEMENT

We will perform robot assisted transrectal prostate biopsy with MRI guidance with the robotic system shown below and discussed in class.

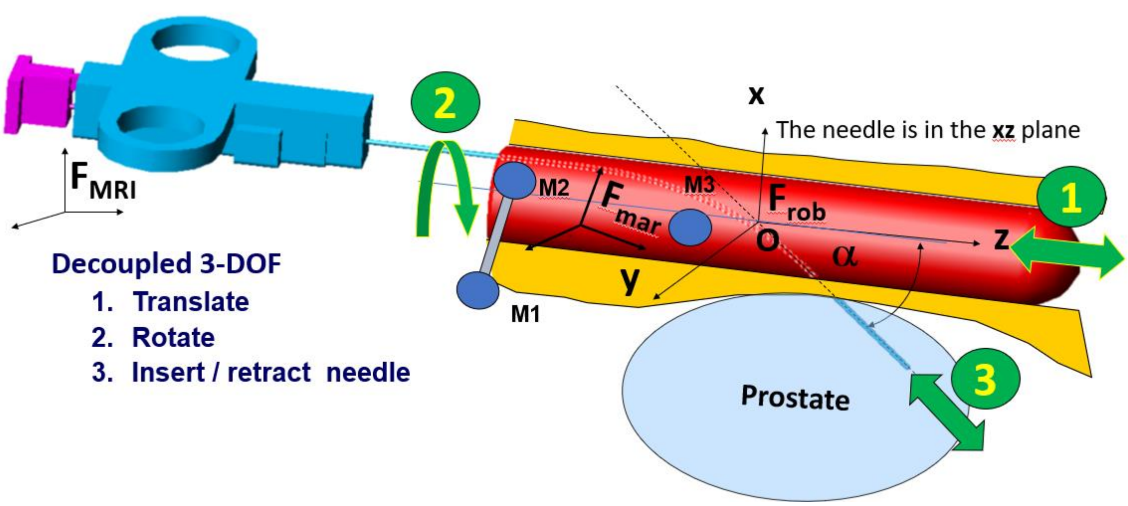






The robot has 3-DOF decoupled motion: we can rotate and translate inside the rectum and insert/retract the needle. "To reduce friction force inside the shaft and to help the needle stay on its trajectory while penetrating through various tissue layers, the needle is twisted while being inserted. The twist angle is not encoded, because the twist angle is not relevant for targeting when the needle is proceeding along a straight trajectory." We instrumented the robot with passive Gadolinium markers from which we compute the position of the robot frame in MRI scanner coordinates. The scheme of robot kinematics and tracking is shown below. (The image above shows a robot with active tracking markers, but we assume that we have disconnected the antennas and use only the passive Gadolinium markers inside the antenna coils.)

Robot kinematics



Q1: NAVIGATION TRANSFORMATION

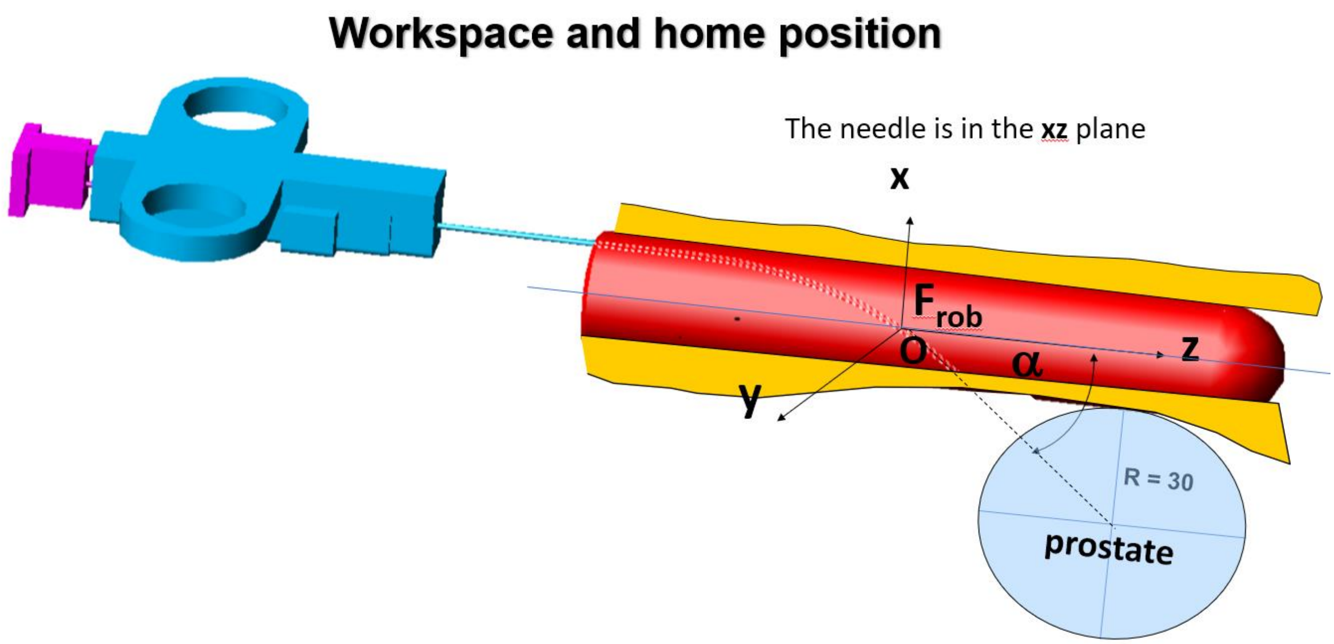
Write up the math formula to transform a biopsy target point from MRI scanner frame (F_{MRI}) to robot frame (F_{rob}). **Hint**: Refer to the course's slide deck.

Q2: WORKSPACE

Before starting a procedure, it is critical to ascertain that all relevant points inside the target zone (the prostate gland in this case) can be reached with the robot. In the home position, the robot translation, robot rotation, and needle insertion are all set to zero as shown in the figure below. **Your task** is to calculate the required range of motion for each degree of freedom to be able to sample the prostate. You explain your approach in a sketch and do a quick hand calculation. **Hint**: Look at the scene from the y axis and z axis.

For this question, we assume that:

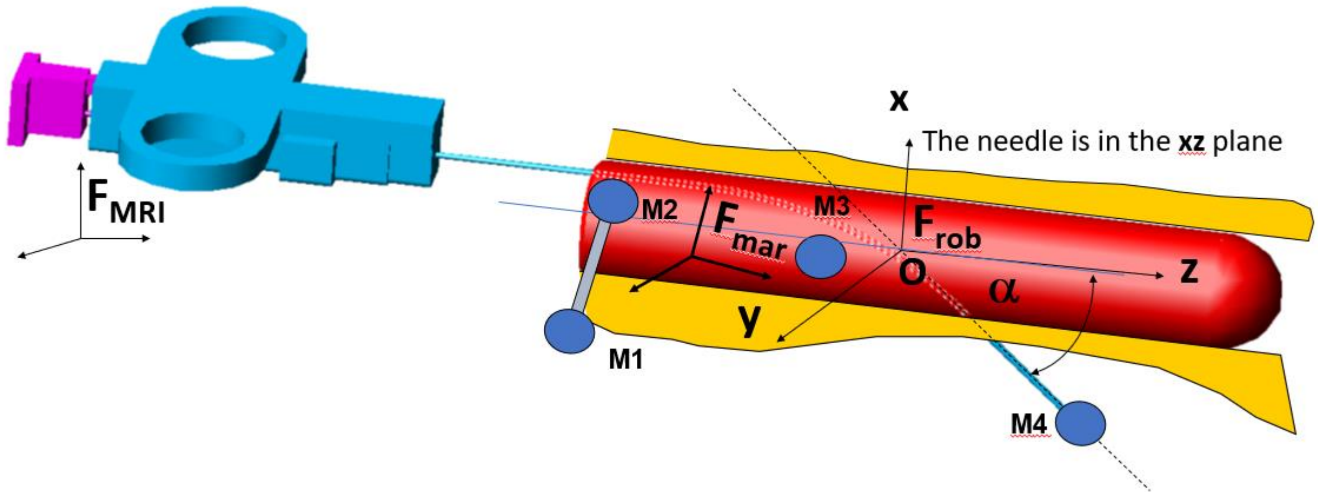
- The diameter of the robot's cylindrical end effector 30 mm.
- The needle's exit angle is 45 degrees.
- The shape of the prostate is spherical, with 30 mm radius.
- The thickness of the rectum wall is uniformly 5 mm.



Q3: ROBOT CALIBRATION

Upon construction of the robot, the exact positions of the tracking markers with respect to the F_{rob} robot frame is not guaranteed; we cannot automatically assume that the M2 and M3 markers lay on the rotation axis of the robot, or we cannot assume that M1-M2 line is perpendicular to the rotation axis of the robot, etc. The exit angle of the needle may not be exactly known, and we cannot be certain that the needle advances along a straight line into the prostate. All these need to be experimentally determined. For calibration, we usually try to place the robot in the MRI scanner approximately in the same position and orientation as it will be during the biopsy procedure, but without the patient. To observe the needle's motion during calibration, an extra tracking marker (M4) is placed in the needle tip.

Calibration setup



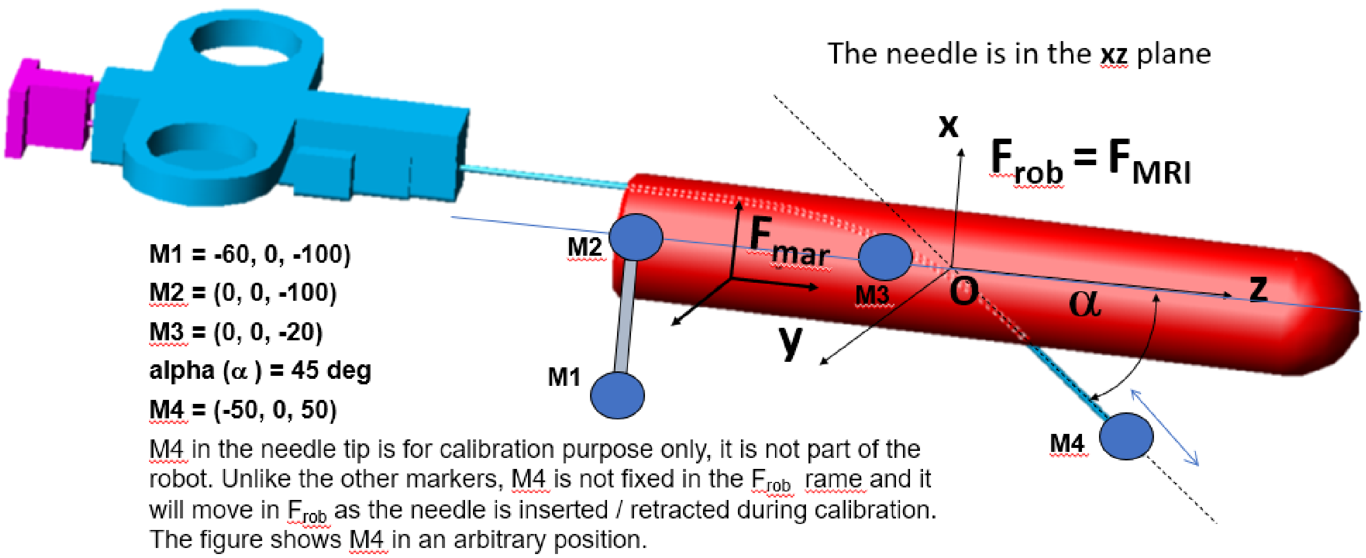
Q3.1 Needle Bending: During manufacturing of needles made of Nickel–Titanium shape memory alloy, heat treatment releases the internal strain of the alloy, allowing the needle to regain its original straight form after exiting the robot shaft. This heat treatment, however, is not always perfect and, as a result, the needle may bend away from the straight trajectory. This manufacturing defect causes inaccurate needle guidance, and it must be detected and quantified prior to using the needle in a patient. Usually, we check a small batch of needles, reject the ones that cause excessive targeting error at the maximum insertion depth. We send the faulty needles back for another heat treatment and the good ones for sterilization. **Your task** is to design a method to detect if the needle bends away from the straight trajectory and quantify by how much the needle would miss the biopsy target at maximum insertion depth. Explain your approach, use text and sketch as you find appropriate. You do not need to implement this in software.

Q3.2 Calibration Design: For computing the constant transformation between F_{rob} robot frame and F_{mar} marker frame, we need to determine the (x,y,z,O) and the a (alpha) exit angle in the F_{MRI} scanner frame. To achieve this, we bring the robot to home position and execute predesigned motion sequences with the robot, observe the positions of the tracking markers in the F_{MRI} scanner frame, and from these observations compute the unknown parameters of the F_{rob} robot frame (x,y,z,O). **Your task** is to design appropriate sequence of robot motions and explain how you will compute the required robot frame (x, y, z, O, alpha). You should make use all available and appropriate motions and tracking markers to maximize accuracy and robustness. In this exercise, you are not required to implement outlier removal in curve fittings. Explain your approach. Use text, math for formulas, pseudo code, figures - whatever you find appropriate. Feel free to mark up images from the class notes or from this document. **Hint**: Start with determining the z axis…

Q3.3 Calibration Implementation: Implement the calibration sequences in software.

Q3.4 Calibration Software Test: Your next task is to test the calibration software on the ideally constructed "ground truth" robot. **Your task** is to simulate the appropriate motions with the ground truth robot, generate simulated marker positions. You can translate the robot across the workspace in 5 mm steps, rotate the robot in a 360 deg range in 30 deg increments, and insert/retract the needle across the workspace in 5 mm increments. Run the calibration, and prove that you can reproduce the ground truth $F_{ro\ b}$(x, y, z, O, alpha) calibration parameters.

Ideally constructed “ground truth” robot



Q3.5 **Marker-to-Robot Frame Transformation**: To complete the calibration process, we bring the robot back to home position, once more acquire and MRI image of the markers, and compute the $F_{rob\leftarrow mar}$ frame transformation, which will be constant for the rest of robot’s life. **Your task** is to compute the $F_{rob\leftarrow mar}$ transformation. **Input**: M1, M2, M3, F_{rob}(x,y,z,O). **Output**: $F_{rob\leftarrow mar}$ transformation. **Test**: Run the module for the ideal ground truth robot, show that you got the result you expected. **Hint:** Implement and test what you wrote for Q1.

Q 4: KINEMATICS

Q4.1 Forward kinematics: We need to be able to compute the resulting location of the needle tip upon moving the motion stages (translation, rotation, insertion) of the robot from its home position. This is called forward kinematics. ***Your task*** is to develop a develop a method to compute the forward kinematics. Use text, equations, drawings to convey your approach. Implement this in software. Input: translation, rotation, insertion. Output: location of the needle tip. **Hint**: execute a translation by Δz, a rotation by $\Delta\gamma$ and an insertion by Δi and see where those motions take the needle tip.

Q4.1 Inverse kinematics: To use the robot in surgery, we need to compute the values of translation, rotation and needle insertion that will take the needle tip to this desired target point from the home position of the device. ***Your task*** is to develop a method to compute the inverse kinematics. Use text, equations, drawings to convey your approach. Implement this in software. Input: desired location of the needle tip. Output: translation, rotation, insertion. **Hint**: Try to proceed backward from the previous.

Q4.3 Kinematic Test: We need to make sure that our inverse and forward kinematic routines are indeed inverting each other. ***Your task*** then is to generate a handful (N=10 or so) random biopsy target points within the Workspace of the ideal ground truth robot. Move the robot to home position. For each biopsy target compute the inverse kinematics parameters, feed the results into your forward kinematics routine, and demonstrate that you get your needle tip back into the target position.

Q 5: MARKER TRACKING

To be able to use the robot, we must be able to localize the robot markers in the MRI frame rapidly, at will. Let us assume the markers are identical small caplets filled with Gadolinium solvent. As discussed in class, we can localize bright markers by frequency encoding with the x, y, and z gradient magnetic fields. We excite the subject volume slice by slice in each gradient direction separately. Since the markers are very bright, we can identify the corresponding gradient location where the signal is brighter than other gradient locations that contain no marker. When none of the markers are in overlap, then each marker is showing at a different gradient location along each axis. When multiple markers overlap at a gradient location, their signal intensity also multiplies, allowing us to determine how many markers share that given gradient location.

Your task is to develop a method and software to reconstruct the 4 markers used in the "ground truth" robot from their gradient locations. Note that the M4 marker in the needle tip is not fixed with respect to other markers, it moves during the calibration process. Explain your approach in comments or on paper, as you prefer.

Input: **x** [x1, x2, x3, x4], **y** [y1, y2, y3, y4], **z** [z1, z2, z3, z4] for the x, y, z gradient locations where markers were detected in the MRI signal.

Output: M1, M2, M3, M4 marker positions.

Test: Test your robot tracking solution on the ideally constructed "ground truth" robot.

- ***Case1***: **x** [-60, -50, 0, 0], **y** [0,0,0,0], **z** [-100, -100, -20, 50]. This is a test case when the robot is placed in the scanner such that F_{rob} and F_{MRI} are in coincidence.
- ***Case2***: **x** [0, 50, 50, -10], **y** [50,50,50,50], **z** [-50, -50, 30, 100]. This is a test case when the robot is placed in the scanner such that it was shifted by [50,50,50] in F_{MRI}, with no rotation.
- ***Case3***: **x** [-42, -35, 0, 0], **y**[-42, -35, 0, 0], **z**[-100, -100, -20, 50]. This is a case when the robot is placed in the scanner such that it is rotated by +45 degrees about +z in F_{MRI}, with no translation.

For each test case, compute the expected marker positions and show that your marker tracking software correctly produces the expected marker positions.

Hint: Refer to the course's slide deck re MR frequency encoding.

POINT GUIDE		
Q1. NAVIGATION TRANSFORMATION		
Transforms	2	
Total		2
Q2. WORKSPACE		
translation	2	
rotation	2	
insertion	2	
Total		6
Q3. CALIBRATION		
3.1 Needle Bending	5	
3.2 Calibration design (x,y,z,O,alpha - each 2 pts)	10	
3.3 Calibration software (x,y,z,O,alpha - each 3 pts)	15	
3.4 Calibration test (x,y,z,O,alpha - each 3 pts)	15	
3.5 Marker-to-Robot Frame Transformation	5	
Total		50
Q4 KINEMATICS		
Inverse kinematics		
Method (trans,rot, insertion)	6	
Software (trans,rot, insertion)	3	
Forward kinematics		
Method (trans,rot, insertion)	6	
Software (trans,rot, insertion)	3	
Kinematic tests (rans,rot, insertion)	6	
Total		24
Q5. MARKER TRACKING		
method	6	
software	6	
tests	6	
Total		18
TOTAL		**100**