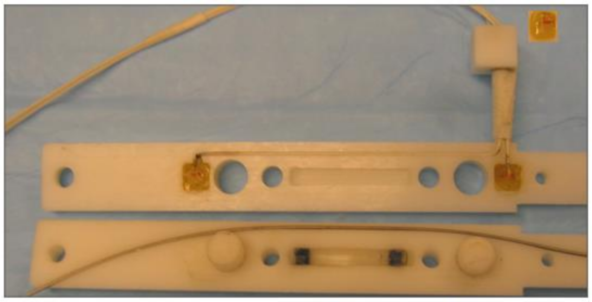
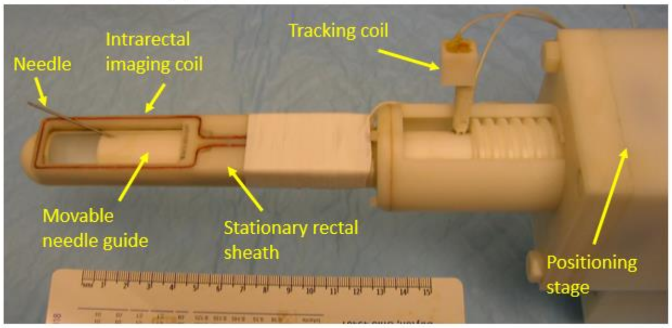
Assignment for CISC/CMPE 330

Transrectal Biopsy Robot Navigation

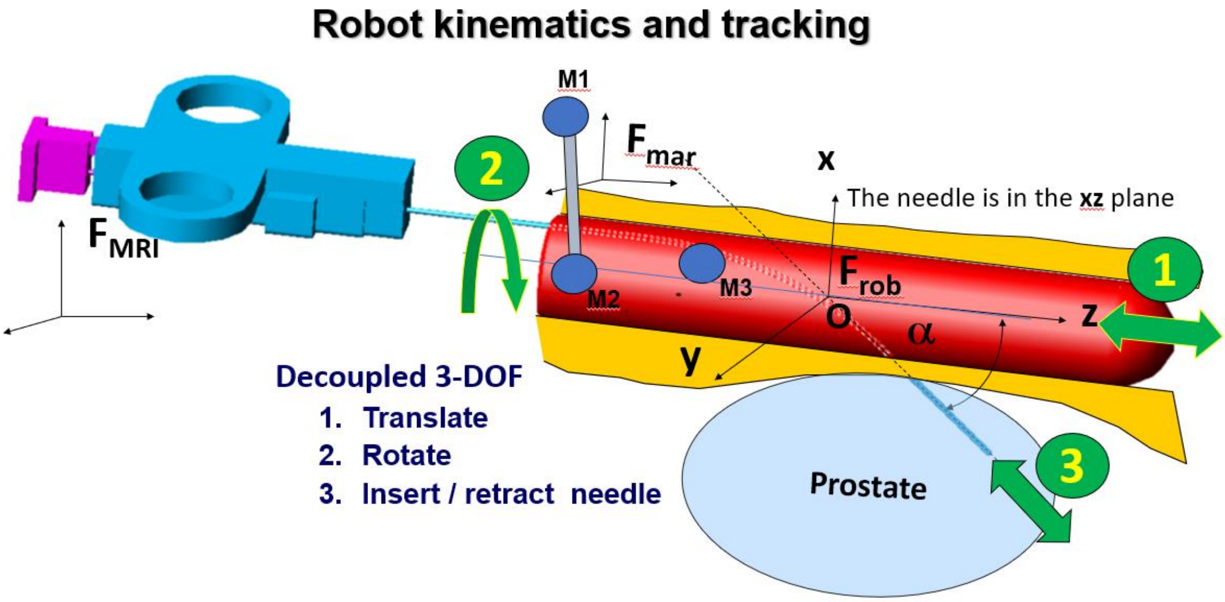
PROBLEM STATEMENT

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. We instrumented the robot with 3 tracking antenna coils (a.k.a. markers) that report the position of the robot's end-effector in MRI scanner coordinates in real-time. The scheme of robot kinematics and tracking is shown below.



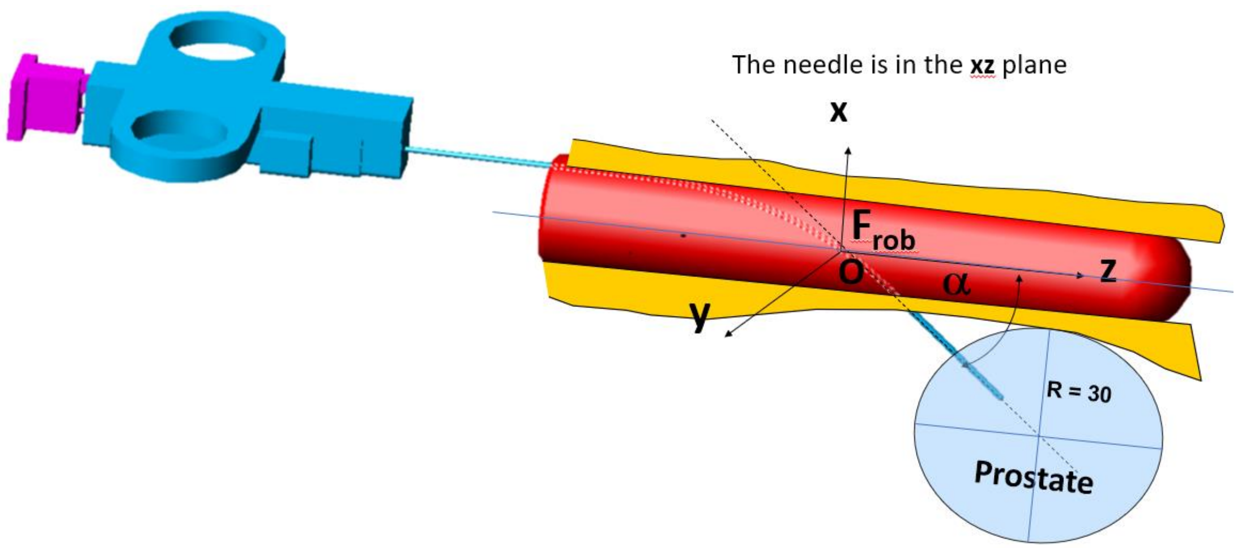
NAVIGATION TRANSFORMATIONS

Your task is to mark the relevant coordinate frame transformations in the sketch above and write up the formula for the transformation of a biopsy target point from F_{MRI} scanner frame to F_{rob} robot frame through F_{mar} marker frame.

WORKSPACE

During design of the device, it is critical to ascertain that all relevant points inside the target zone (the prostate gland in this case) can be safely reached with the robot. We need to compute the minimum range of motion for each degree of freedom and make sure the robot can perform those. For this question, we assume:

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



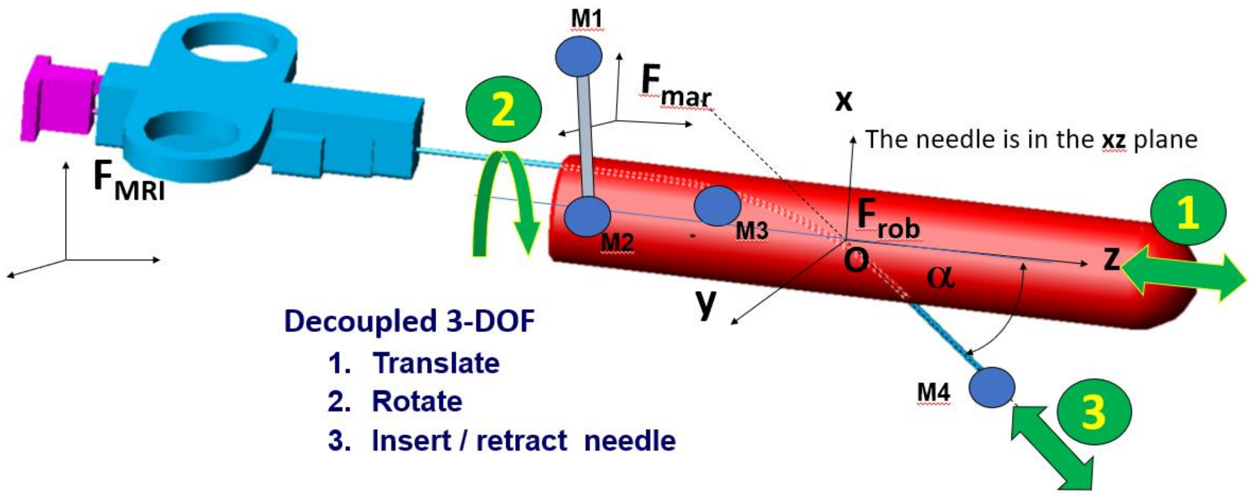
Your task is to derive math formulas to compute the minimum required range of motion for each degree of freedom of the robot to be able to sample the largest prostate. Make a sketch for each degree of freedom.

CALIBRATION

The tracking system reports the coordinates of the three tracking markers built into the robot in F_{MRI} scanner imaging frame in which the relevant anatomy is observed. Biopsy needle is controlled in the F_{rob} robot frame. The robot can rotate about the z axis, and translate along the z axis, and the needle can be advanced/retracted. We assume the needle is in the xz plane of the robot frame and the needle is fully retracted into the center of the F_{rob} robot frame.

Upon construction of the robot, the exact positions of the tracking markers with respect to the F_{rob} robot frame is not known with respect of the tracking markers is not known. For example, we cannot assume that the M2 and M3 markers lay on the rotation axis of the robot, and we cannot assume that M1-M2 line perpendicular to the rotation axis of the robot, etc.) Upon construction, exact exit angle of the needle is also not exactly known, we cannot even be certain that outside the robot the needle advanced and retracted in a straight line. The chief objective of the calibration to experimentally determine frame transformation between F_{mar} maker frame and F_{rob} robot frame in which the motion of biopsy needle is controlled.

Robot calibration setup



For calibration, we place the robot in the MRI scanner roughly in the same position and orientation it will be during the biopsy procedure, but without the patient. We bring the robot joints into a nominal home (resting) position; we typically set the rotation angle halfway between min and max rotation, set the translation halfway between min and max translation. We insert the needle halfway into the imaginary prostate. To observe the needle motion during the calibration process, 4th tracking marker (M4) is placed in the needle tip.

The needle is made of Nickel–Titanium (NiTi) shape memory alloy. During manufacturing, heat treatment releases the internal strain of NiTi, allowing it to regain 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 when exiting the robot's shaft 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 NiTi needles, reject the ones that cause excessive targeting error, typically larger than 1 mm at the maximum insertion depth. We send the bad needles back for heat treatment and the good ones for low-heat gas or liquid sterilization which will not alter their mechanical properties.

Your task is to design a method to detect is a NiTi needle bends away from the straight trajectory and quantify by how much the needle would miss the biopsy target at a given insertion depth. Explain your approach, use text and sketch. (You will not need to implement this in software.)

Our next task is to figure out where the F_{rob} robot frame is with respect to the F_{mar} marker frame, i.e. we need to determine the (x,y,z,O) and the α (alpha) exit angle of the needle. To achieve this, we bring the robot to home position and execute predesigned motion sequences with the robot, observe the positions of the 4 tracking markers in F_{MRI} scanner imaging frame, and from these observations compute the unknown parameters of the F_{rob} robot frame (the (x,y,z,O, α). Finally, we bring the robot joints to their home position, observe the three robot markers in F_{MRI} scanner imaging frame and transform them to F_{rob} robot frame – which finally completes the calibration process.

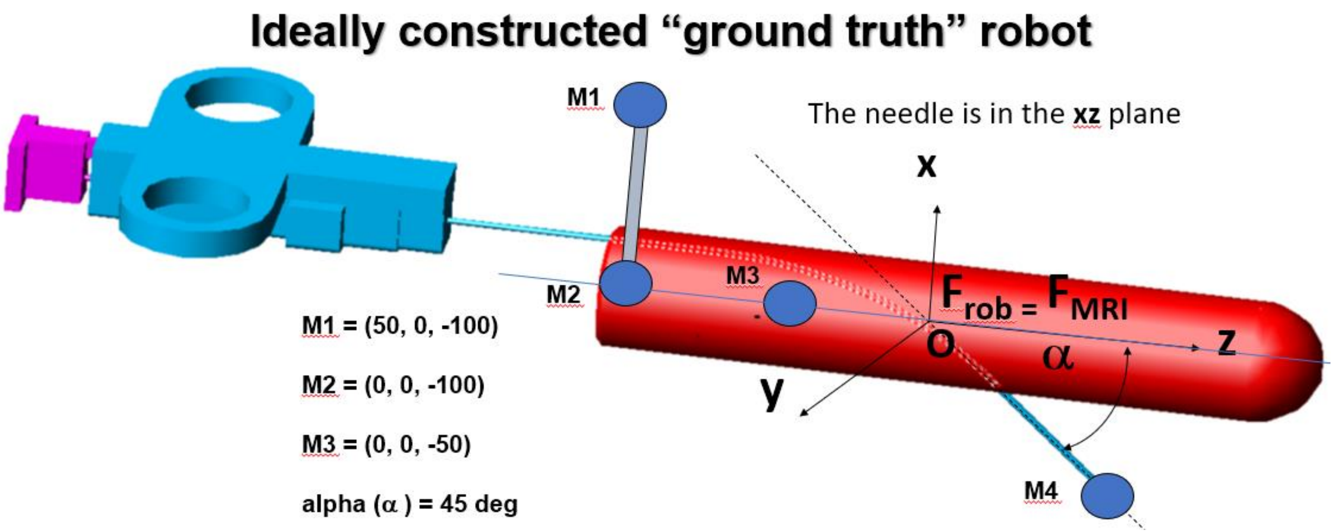
Your task is to design appropriate combinations of robot motions and explain how you compute the required F_{rob} robot frame parameters (x, y, z, O, alpha). You should make use all appropriate available robot motions and tracking markers to maximize the robustness of your approach in deriving the unknown parameters. Explain your approach. (Use text, math for formulas, pseudo code, figures, etc., whatever you find appropriate. Feel free to mark up images lifted from the class notes or from this document.)

Your task then is to implement the calibration sequence in software.

We test the calibration on an ideally constructed "ground truth" robot below. We assume that the robot was placed in the scanner such that F_{MRI} scanner imaging frame and F_{MRI} robot frame coincide. (You have previously developed and tested the transformation from F_{MRI} frame to F_{rob} frame multiple times, therefore it is irrelevant for testing the new calibration routines). We assume that positions of M1, M2, M3 and alpha were pre-designed and the robot is perfectly fabricated, with the F_{rob} parameters being x(1,0,0) y(0,1,0) z(0,0,1), O(0,0,0), alpha=45 deg. We assume that the robot translates in 50 mm range by 1 mm increments, rotates in 360 deg range by 1 deg increments, and the needle advances in 50 mm range in 1 mm increments.

Your task is to generate the appropriate motions with the ground truth robot, generate the marker positions, run the full calibration, and prove that your can reproduce the ground truth F_{rob} (x, y, z, O, alpha) calibration parameters.

Your task is to repeat the calibration with blending sigma=1.0 mm normally distributed random error to each observed marker position, compute the new set of (x, y, z, O, alpha) calibration parameters – which should now be somewhat different from the ideal ground truth calibration parameters. Compute the difference that these calibration parameter errors make in targeting the center of the prostate. (Use the layout from the Workspace figure.)



KINEMATICS

During surgery, we first move the robot to its home position. We pick a desired biopsy target point in F_{MRI} scanner image frame, transform this to F_{mar} marker frame, and further transform this to F_{rob} robot frame. Here we encounter an issue called i*nverse and forward kinematics*.

Inverse kinematics: 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. ***Your task*** then is to implement this in software. Input: desired location of the needle tip. Output: translation, rotation, insertion.

Forward kinematics: To use the robot in surgery, 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. ***Your task*** then is to implement this in software. Input: translation, rotation, insertion. Output: location of the needle tip.

Kinematic Test: We need to make sure that our inverse and forward kinematic routines are indeed inverting each other. ***Your task*** is to generate N=10 or so random biopsy target points within the Workspace of the ideal ground truth robot (in which the alpha needle angle is 45 degree). Move your 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.

POINT GUIDE for Transrectal Biopsy Robot Navigation		
NAVIGATION TRANSFORMATIONS		
Transforms	2	
Total		2
WORKSPACE		
translation	3	
rotation	3	
insertion	3	
Total		9
CALIBRATION		
Needle deflection	5	
Robot frame calibration		
Method x,y,z,O,alpha (3pts each)	15	
Software x,y,z,O,alpha (3pts each)	15	
Calibration test (no error)	15	
Calibration test (with random marker error)	5	
Total		55
KINEMATICS		
Inverse kinematics		
method for trans,rot, ins (4pts each)	12	
software	3	
Forward kinematics		
method for trans,rot, ins (4pts each)	12	
software	3	
Kinematic test	4	
Total		34
TOTAL		**100**