Computational Model to Steer Super-Elastic Needle for an MRI Guided Breast Intervention Robot

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Purpose

To develop a scheme of needle steering for the MR compatible needle intervention robot we devised a computational model to estimate the needle direction with a pivoted super-elastic needle made of Nitinol.

In our previous research, we developed an MR image-guided needle intervention robot system consisted of a bendable needle structure to overcome the space limitations in the MR gantry with MR breast coil [1]. It had 3 degrees of freedom (DOFs) with a fixed needle incision direction. (See Figure 1) In this research we enhanced DOFs without adding any actuating parts. It provides the means to avoid critical structures in front of the lesion.

Methods

We devised a pivot grid plate to increase needle tip's DOFs. Since we utilized a bendable Nitinol needle, it was possible to change the needle direction only with pivot holes without increasing the actuators. A commercial breast compressing plate was modified to make pivot points, and 2.0 mm diameter holes were arranged in a 5.0mm grid pattern. We named it the needle pivoting breast plate. Since each hole works as an initial positioning guidance and a pivot point, we could make additional 2 DOFs needle direction change with no additional actuator.

The needle steering procedure was comprised of the following steps: (1) Initial positioning of the robot to the desired pivot hole; (2) Computing the needle insertion angle for the target position from the given pivot hole; (3) Estimating the robot's future position to make the desired insertion angle of the needle; (4) Proceeding to the future position; (5) Needle insertion.

For steering procedure, we had to estimate the quantity of the needle deflection by the pivot. We focused on the super-elasticity of the Nitinol which allows the straight needle path after the pivot point with the bending angle by large beam deflection theory based on the Euler-Bernoulli beam [2, 3]. To utilize the deflection model, we needed to find the Bending stiffness which is the unique material property. Thus, we found the Bending stiffness with the in-house measurement setup using a precision force gauge (AFG-2, Axis Sensitive Co. Ltd., South Korea) and a digital caliper (CD-10CPX, Mitutoyo, Japan). Finally, we derived an equation with respect to a bending stiffness. It became a closed form equation as $f(\theta_0,\ L, E, I) = \delta_y$, where θ_0 was the angle at the needle end, and L was the perpendicular distance between the needle exit and the pivot plate. E is the material's modulus of elasticity which was 75 Giga Pascal for Nitinol, and I was the moment of inertia of the needle's cross-sectional area which was 0.115 mm^4 for our needle structure.

We utilized the equation to determine the movement of the actuator δ_y to make the desired needle path to the given pivot point to the target point. Because the positions of the pivot point and the target point were given, the angle θ_0 was given. And we knew L from the system dimension and the coordinates of the markers on the robot and the breast plate.

We conducted in vitro experiments to evaluate the proposed estimation model. Our MRI-guided breast needle intervention robot was set up around eight of IR (Infrared) camera (V120 Slim, OptiTrack, US) for 3D motion tracking to trace the positions of the target and needle end. MR fiducial markers to trace the robot position in MRI were also replaced with IR active markers (MTE8600M2, Marktech Optoelctronics, Latham, NY, USA). To evaluate the accuracy of the model we first set a target position by an IR marker; then the needle was steered through different pivot holes; finally, we measured the needle tip position to calculate the difference between the target position and the final needle tip position. In total, 21 different paths to the same target position were traced.

Results

The average targeting error and standard deviation of the 21 measurements was 3.38 ± 1.86 mm. The maximum error was 6.23 mm. Figure 2 shows the experiment setup and the distribution of the measured needle end.

Conclusion

Although the suggested steering method is not a fully steerable needle, it could enable multiple needle paths without increasing the system. We successfully proved the feasibility to steer Nitinol needle using the super-elastic characteristics of Nitinol although there are some hurdles to overcome. We observed the more curvature of the needle made the more error. This error can be induced from three factors: (1) the clearance margin of the pivot holes; (2) the numeric error from the possible nonlinearity of the needle; and/or (3) the robot positioning error because of the precision of the motors and manipulator.

Since we utilized the open loop control to evaluate the computational model only, we are to develop robust feedback loop to control the needle path and the needle end position.

References

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Figure Captions

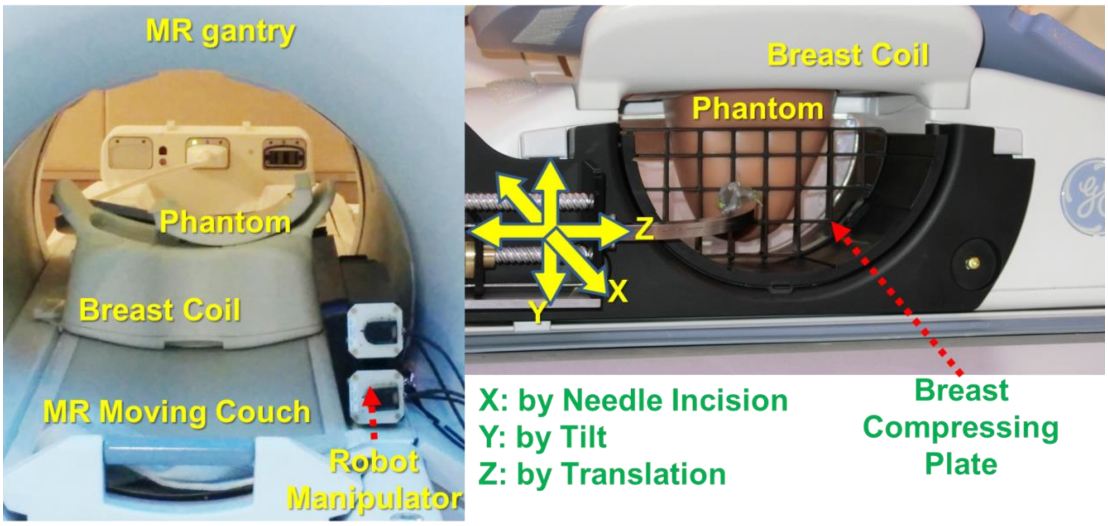

Figure 1. MR image guided breast needle intervention robot platform. It had 3+1 DOFs with the bendable needle approach [1].

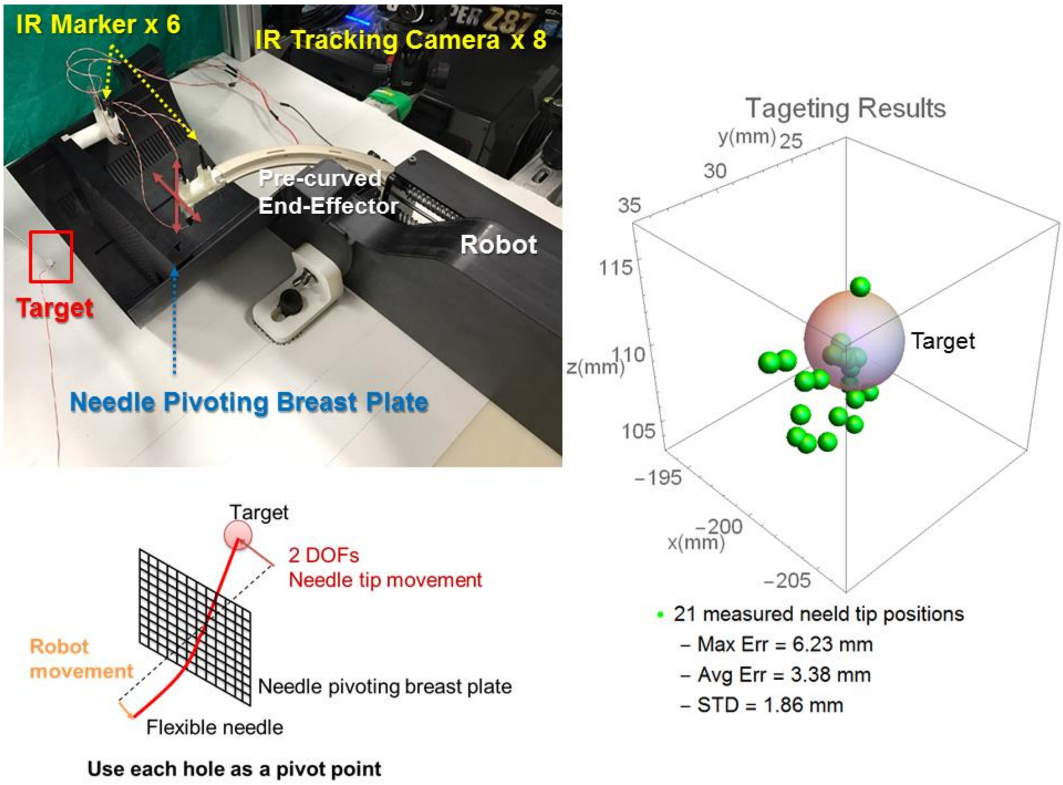

Figure 2. An in vitro experimental setup and the measured results. Two more DOFs were added by the pivoting breast plate without adding actuators.