MRI-compatible Haptics: Strain sensing for real-time estimation of three dimensional needle deflection in MRI environments

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Introduction

Conventional closed-bore MRI scanners preclude direct "hands-on" device manipulation. There is a critical need for methods to quickly, accurately and easily manipulate instruments within closed MRI systems. Specifically, catheter, probe, and needle interventions can benefit from optical systems which measure tool positions and forces in real-time. During such procedures, it is useful to track any deviation from the planned trajectory to minimize positioning error and procedural complications. Recently, miniaturized fiber-optic-based force and deflection sensors based on fiber Bragg grating (FBG) technology have been developed and integrated into robotics for force feedback [1]. Our previous work illustrated the feasibility of using Fiber Bragg grating (FBG) sensors to estimate needle deflections in 2D [2]. FBG sensors reflect light with a peak wavelength that shifts in proportion to the strain to which they are subjected. The wavelengths are also dependent on temperature changes, thus the sensors have applications in cryosurgery and tissue ablation procedures. FBG sensors are inherently MRI-compatible, do not interact with the MRI process, and do not cause imaging artifacts. A shape-sensing stylet from an MRI-compatible biopsy needle was fabricated and instrumented with FBG sensors to measure the 3D shape of needle with sub-millimeter accuracy. Calibration, bench-top testing, and an animal experiment were performed with the sensorized needle.

Sensor Placement and Prototype Fabrication

Due to the length and stiffness of the needle used, it was ascertained that sensors at two positions would be sufficient for estimating the final tip position, and to get a reasonable approximation of the bending profile of the needle. The optimal sensor positions were based on minimizing tip deflection error and sensitivity in common bending configurations using cantilever beam theory. For a 15-cm, 18-ga Inconel 625 needle, the optimal sensor positions are at 22 mm and 85 mm from the base.

The outer needle was an unmodified FDA-approved 15-cm 18-ga MRI-compatible needle (E-Z-EM Inc, Westbury, NY). The inner stylet was modified to have three grooves, made by electro discharge machining (EDM), along the neutral axis of the needle at 120-degree intervals. Three fibers with FBG sensors were adhered inside the grooves using a biocompatible adhesive. Each optical fiber has two gratings for strain measurement at two locations along the needle. Therefore, three gratings with different orientations (angular positions) at each location can measure strain in 3D and temperature.

Calibration and Experimental Results

The needle prototype was calibrated for three-dimensional bending using high resolution digital cameras. Two cameras were used for obtaining images of the needle from two orthogonal planes. The images taken by the two cameras were processed using the OpenCV library to obtain the profile of the needle. The calibration results showed linearity and repeatability of the sensor signals.

The initial experiments involved one-point and two-point bending cases in 3D. A tip load was applied in the first case, and a tip load and a point load between two sensor locations were applied in the second case. The deflection and bend shape were estimated (Figure 2) based on the calibration results. The tip position errors were 0.27 mm for one-point bending and 0.665 mm for two-point bending with applied tip deflections of 3.21 mm and 6.8 mm, respectively. The error can be reduced by calibrating for manufacturing errors in sensor placement.

The needle prototype was also tested in a live animal at the Stanford Medical Center. The FBG needle prototype was inserted into a mature male beagle's prostate. The wavelength changes were measured, and a series of MR images was taken. Figure 3 shows oblique and sagittal MR-images of the prostate of the test subject with the needle prototype inserted, along with a graphical reconstruction of the estimated deflection and bent shape, calculated from the FBG sensor signals. The estimation showed deflections of 2 mm and 2.5 mm along the *x* and *z* axes respectively (scale exaggerated to highlight flexing). Thermal compensation of the prototype resulted in negligible errors in the estimated tip position for temperature variations of ±10ºC.

Conclusion

This study shows that FBG sensors can be used to estimate the tip deflection and 3D bent profile of biopsy needles during MR imaging. The three optical fibers with FBG sensors embedded in the needle did not produce any artifact on the images, and the sensor signal was not affected by the magnetic field. Ongoing work is exploring the use of additional FBG sensors to measure forces on the needle from surrounding tissue. Force information combined with image registries can help model tissue properties and deformation, which has applications in surgical planning. The authors thank the US Army Medical Research Acquisition Acitivity (STTR contract, W81XWH8175M677) and the National Institutes of Health (RO1 CA092061, "MRI-Guided Cryosurgery of Prostate Cancer") for financial support for this research.

References

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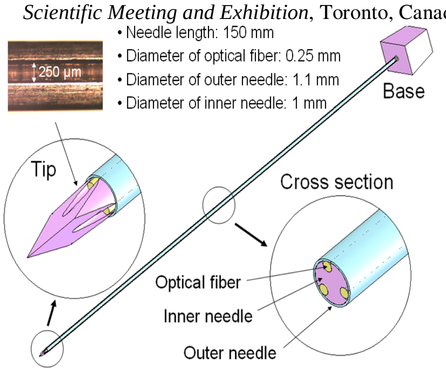

Figure 1. CAD Model of fabricated 18-ga needle, and magnification of one of the needle grooves, 250-µm deep and wide, machined using EDM.

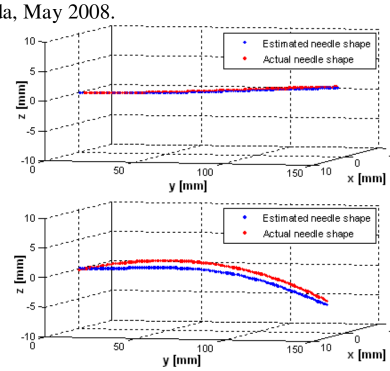

Figure 2. Experimental Results of bend shape and deflection estimation of prototype in 3D: one-point bending (upper) and two-point bending (lower).

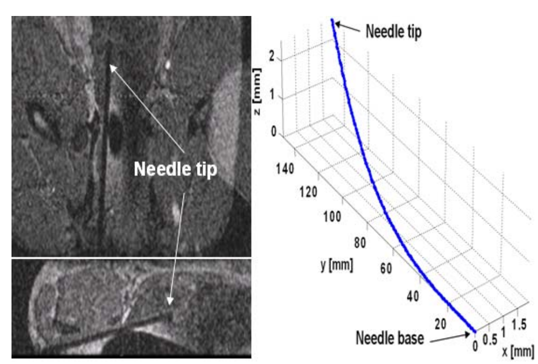

Figure 3. 3T-MRI of prototype in dog prostate on oblique coronal (left, upper) and oblique sagittal (left, lower) reformatted 3D SPGR images. 3D estimation of needle shape (right).