

Teleoperated Needle Placement for Real-time MRI-guided Prostate Interventions

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Purpose: Transrectal ultrasound is the most common navigation method for prostate biopsy, however it has a poor cancer detection rate of 20%-30%. MR can provide excellent visualization of anatomical targets and delivery instruments, and offers image-guided surgery with live images. However, spatial constraints of the bore limit access to the patient, and the inability to use conventional sensors and actuators limits availability of assistive technologies. Advantages of deploying a robotic system in prostate interventions include: 1) robot-assistance ensures high procedural accuracy and consistency, and 2) teleoperation provides improved ergonomics over manual insertion while maintaining the ability to view live MR images during the procedure.

Methods: A 6 degree of freedom (DOF) Slave robot and a 2-DOF Master robot have been developed for performing prostate interventions inside the bore of 3T MRI. The Slave robot (Fig. 1, left) provides Cartesian alignment (2-DOF alignment in the X-Y plane and 1-DOF placement of the robotic guide against the perineum) and needle placement with a 3-DOF needle driver module (insertion, cannula retraction or biopsy, and needle rotation). Insertion may be under direct computer control or teleoperated using the Master device (Fig. 1, right). Robot motions are actuated using piezoelectric motors and configuration is sensed using optical encoders. To render proprioception, a Fabry-Perot interferometer (FPI) based fiber optic strain sensor is integrated to the Slave robot to provide high-resolution needle insertion force measurement. The haptic Master robot uses strain gauges integrated into a shielded aluminum load cell to track slave side insertion force. A custom-developed MRI robot controller operates both devices from within the scanner room (Fig. 1, left). The controller can operate both resonant and nonresonant piezoelectric motors under closed loop position, velocity, and force control during live imaging while not degrading image quality. The robot controller is self-contained, scanner-independent, and communicates to navigation software (such as Slicer) via fiber optics.

Results: MR compatibility was evaluated in a 3T Philips Achieva using four imaging protocols: T1-weighted fast gradient echo (T1 FGE/FFE), T2-weighted fast spin echo (T2 FSE/TSE), fast gradient echo (FGRE) and functional imaging spin echo-planar imaging (SE EPI). Results showing subtraction images and signal to noise (SNR) degradation are shown in Fig. 2. SNR degradation proved to be visually unidentifiable, statistically insignificant, and resulted in a mean SNR variation of 2.1% in the worst case. Resolution of the linear optical encoders integrated into the robot is 0.0127 mm/count. Based on independent measurement (which includes deflection, misalignment, etc.), the joints can be reliably controlled to within 30 μ m.

Conclusions: The system provides a clinically viable approach to extending the standard workflow for template-guided prostate interventions to take advantage of intra-operative MR imaging. The teleoperated needle guide allows the physician to maintain control over needle insertion from inside the scanner room while providing improved ergonomics. The robot can actively manipulate standard MR-compatible needles under live imaging.

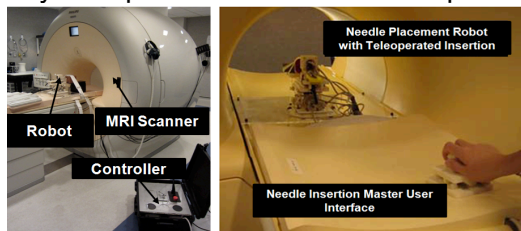


Figure 1: Teleoperated robot system. Needle placement robot for prostate interventions inside 3T MRI scanner and the robot controller is inside the scanner room beside the scanner (left). The needle is inserted using a master device that lets the clinician stand beside the patient, view real-time MR images aligned with the needle axis (right).

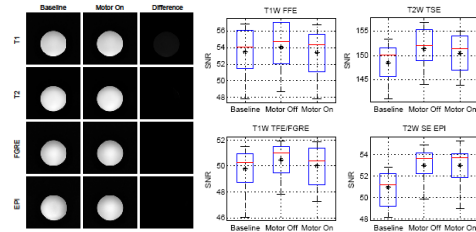


Figure 2: Results demonstrating MR compatibility of the custom piezoelectric motor actuation system that produces no statistically significant image degradation when the robot is moving during imaging. Qualitative results demonstrate no distortion (left). Quantitative analysis of SNR for four imaging protocols with robot absent, off, and moving (right).