Tele-operated MR-compatible robot for prostate interventions

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1. Introduction

The most common method to diagnose prostate cancer is the transrectal ultrasound (TRUS)-guided biopsy. However, TRUS-guided biopsies have a limited detection rate and accuracy [1]. Magnetic resonance images (MRI) have higher tissue contrast and larger spatial resolution than ultrasound; this entails visibility of the tumor. Therefore, an MR-compatible robot for prostate interventions was developed as part of the MIRIAM (Minimally Invasive Robotics In An MRI environment) project [2]. The MIRIAM robot can perform an MR-guided prostate biopsy autonomously or with minimal input from the clinician. The aim of the current research is to develop a tele-operated system to provide the clinician more control during the procedure. The clinician controls the needle insertion depth while receiving haptic feedback (Figure 1).

2. Methods

The existing MIRIAM control architecture, including its graphical user interface, is modified to include haptic feedback. The feedback is given to the user through the Phantom Omni device (Sensable, Wilmington, USA). A force model is used to provide the haptic feedback (F_h) to the user. The interaction between the needle and the tissue is modeled as an extended Coulomb-viscous friction model plus a cutting force and is defined as follows:

$$F_h = \begin{cases} k_1 sgn(\dot{x}) + k_2\, x\, \dot{x}, & \dot{x} < 0 \\ 0, & \dot{x} = 0 \\ k_3 sgn(\dot{x}) + k_4\, x\, \dot{x} + k_5 x E + k_6 d, & \dot{x} > 0 \end{cases}$$

where x, $\dot{x}$ and d are the needle's insertion depth, velocity and needle deflection, respectively. E is the phantom's Young's modulus. The model parameters k_1, k_2, k_3, k_4 and k_5 are tissue-dependent, which can be estimated online or preoperatively. In this model, the haptic feedback is computed online based on the haptic device position and velocity. The deflection (d) is estimated based on the needle tip position ($\mathbf{p}_{tip}$) provided by the needle tip tracking algorithm. Due to the lack of real-time MRI, needle tracking is done using a needle integrated with fiber Bragg grating (FBG) sensors. Different control architectures are implemented and will be tested using human subjects.

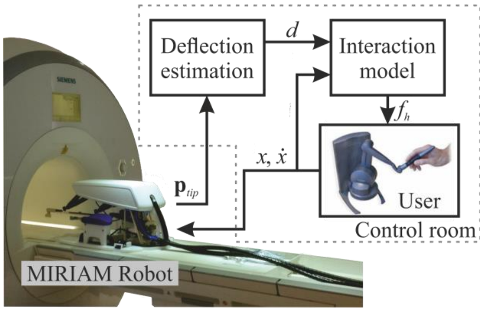

Figure 1: Proposed tele-operation structure for MR-guided prostate biopsies using the MIRIAM robot. The user controls the position (x) and velocity ($\dot{x}$) of the needle. The position of the tip ($\boldsymbol{p}_{tip}$) is tracked and the needle deflection (d) is determined. x, $\dot{x}$ and d provide haptic feedback (f_h) to the user.

3. Preliminary results

A Nano17 force sensor (ATI Industrial Automation, Apex, USA) is attached to the needle base. Experiments inserting the needle into different gelatin phantoms are performed to determine the coefficients of the extended Coulomb-viscous model. The estimated coefficients k_1, k_2, k_3, k_4, k_5, k_6 are $-0.53\,N$, $-0.13 \times 10^{-2}\; Ns/\,mm^2$, $-0.70\,N$, $-0.5 \times 10^{-3}\; Ns/mm^2$, $-0.4 \times 10^{-4} N/\,(kPa\; mm)$ and $55.81 Nmm$, respectively. The tele-operation setup is first tested in the lab environment. The needle moves corresponding to the input from the user.

4. Discussion

This study presents the design and control of a tele-operated needle steering robot with the goal to include the human in the control loop. A shared control architecture where the clinician controls the insertion depth and the robot controls the needle rotation will increase the acceptance of the presented system by the medical community. Next steps in this research include the validation of the tele-operation control architecture, experiments with users and experiments in the MR scanner.

References

[1] Schouten et al., “Evaluation of a robotic technique for transrectal MRI-guided prostate biopsies”, European Radiology, 22(2): 476-483, February 2012.

[2] Moreira et al., "Preliminary evaluation of a robot for MRI-guided needle interventions", 5th Joint Workshop on New Technologies for Computer/Robot Assisted Surgery, Brussels, Belgium, September 2015.