Interactive Training of Teleoperated Robotic System for Real-time MRI-Guided Steerable Needle Intervention

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1. Narrative

Introduction

Needle-based interventions, also known as percutaneous interventions, are common approaches for diagnostic and therapeutic procedures including tissue biopsy, delivery of therapeutic agents and tumor ablation. Needle steering, controlling the rotation of needle while inserting, is a clinical technique to produce a curved path to avoid anatomical obstacles (e.g. vasculature and bones) or compensate for placement errors. But, it requires delicate skills and long-term training to accurately steer the needle, due to difficult control of the needle path and lack of intraoperative image feedback. Magnetic resonance imaging (MRI) is an ideal imaging modality for image-guided interventions thanks to its ability to provide high resolution, excellent soft tissue contrast and real-time images. However, manual operation inside the tightly constrained closed-bore scanner leads to awkward ergonomics and placement errors.

The objective of the proposed project is to develop a clinician-controlled teleoperated robotic system to train and perform steerable needle intervention under real-time MRI-guidance, with visual-haptic feedback.

Results

To address the issues related to MRI electromagnetic compatibility and mechanical constrains of the confined physical space, our team have developed a robotic system for MRI-guided stereotactic neurosurgery [1] that has the best reported MRI compatibility results to date and a 6-DOF robot manipulator for prostate intervention [2]. A teleoperated system with haptic feedback developed in our previous efforts [3] is adopted in this work with appropriate modification as a testbed.

The major results achieved from this work supported by the Link Foundation include:

1. Developed and implemented needle steering model:
   - Proposed a novel asymmetric tip needle steering method based on the nonholonomic kinematic model, named Gaussian-based ContinUous Rotation and Variable-curvature (CURV) steering model, which enables variable curvature of the needle trajectory with independent control of needle rotation and insertion [9]. As it is inserted into the tissue, the needle rotates continuously with Gaussian-based angle-dependent velocity motion profile. Continuous rotation with smooth transition could attenuate the static frictional effects, and variable curvature improves the steering capability. Decoupling control of insertion motion from the curvature control readily enables active control of the needle path for particular tasks that precise coordination of insertion and rotation is hard to achieve, such as shared autonomy (autonomously controlled rotation with manual insertion).
   - Verified and validated the CURV steering model in open-loop with camera-based phantom studies in 2D, and then further evaluated in 3D with high resolution CT images. The 2D validation of CURV model includes 2 steps, 1) calibrating model parameters and assessing simple curve track with constant parameters, and 2) assessing complex curve track with changing parameters. The results demonstrate that the commanded steering effort could effectively affect the curvature, and the Root Mean Square (RMS) errors of the trajectory fitting are around 0.50 mm.
2. Designed 3D visualization and navigation interface:

- Designed a user interface that can visualize and track the needle path in a continuously acquired MRI volume. The visualized needle path will provide clinicians intraoperative visual feedback, and the tracking data of updated needle tip position will be fed back to controller for generating next control command, which could compensate modeling error and increase the positioning accuracy.
- Evaluated the targeting accuracy of closed-loop control of CURV steering with phantom studies inside a 3T MRI scanner. During insertions, the needle tip position is autonomously tracked with continuously acquired MR images at a frequency of 1.3fps. The experiment demonstrates that the RMS error of 3D targeting accuracy is 0.75 mm.

3. Incorporated teleoperation with visual feedback
    - Integrated the needle steering controller with teleoperated master device to train the user for steering along the desired needle path with visual feedback. The needle insertion speed is an independent control input which could be performed in a teleoperated fashion, while the rotation is generated by the CURV steering model.
    - Assessed the targeting accuracy of needle steering with teleoperated insertion with phantom studies under continuous live MRI-guidance. The experiment demonstrates that the RMS error of 3D targeting accuracy is 0.78 mm.
4. Designed simulator for teleoperated needle steering:
    - Designed a model of needle path with the 3-DOF inputs of master device based on the CURV kinematics model. Built a benchtop testbed for providing haptic user feedback for needle insertion in a non-clinical environment. Currently, our team have been studying the anatomical features and working with clinicians on identifying the most relevant forces to reflect to the user, segmenting tissue boundaries to use for tactile feedback and help with localization.

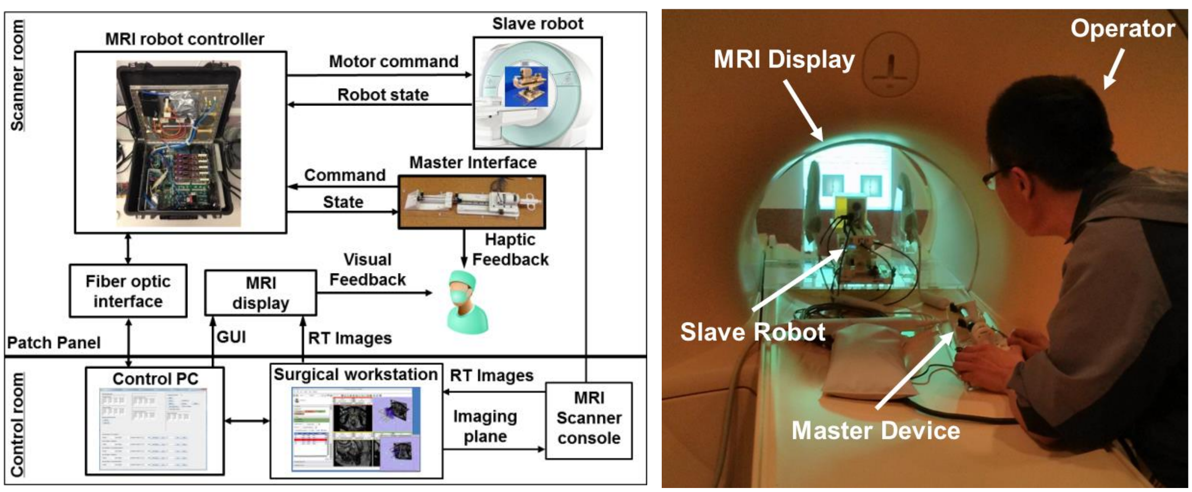

Figure 1: (Left) System architecture of teleoperated robotic system for interactive training of MRI-guided steerable needle intervention. The clinician/trainee manipulates the master device outside the scanner bore with real-time visual-haptic feedback. (Right) System setup inside MRI scanner room showing clinician/trainee perform insertion with master device while observe the updated intraoperative images.

Significance and impact

The proposed system is a unique and innovative integration of MRI-compatible teleoperated robot control, needle steering modeling and real-time MRI needle tracking, designed to facilitate the training and performance of steerable needle interventions with increased accuracy, enhanced ergonomics and improved workflow. By utilizing a modular design approach, the system can readily be configured for varying clinical applications including percutaneous prostate interventions and stereotactic neurosurgery.

Where might this lead?

By integrating the teleoperated robotics with advanced MR imaging modality, the system is able to improve the training performance of clinicians to conduct steerable needle intervention, in the aspects of safety, accuracy, and ergonomics. The clinical version with manual needle insertion is currently approved by the Institutional Review Board (IRB) for clinical trials [8]. In the near future, we will work on applying this MRI-guided teleoperated robotic system in the real clinical studies, which would further improve the clinical workflow and procedure outcomes [4].

Reference

[1] G. Li, H. Su, G. A. Cole, W. Shang, K. Harrington, A. Camilo, J. G. Pilitsis, and G. S. Fischer, "Robotic System for MRI-Guided Stereotactic Neurosurgery", IEEE Transactions on Biomedical Engineering, vol. 62, no. 4, pp. 1077-1088, 2015.

[2] G. Li, H. Su, W. Shang, J. Tokuda, N. Hata, C. M. Tempany, and G. S. Fischer, "A Fully Actuated Robotic Assistant for MRI-Guided Prostate Biopsy and Brachytherapy", SPIE Medical Imaging (Image-Guided Procedures, Robotic Interventions, and Modeling Conference), Orlando, USA, Feb. 2013.

[3] W. Shang, H. Su, G. Li, and G. S. Fischer, "Teleoperation System with Hybrid Pneumatic-Piezoelectric Actuation for MRI-Guided Needle Insertion with Haptic Feedback", IEEE/RSJ International Conference on Intelligent Robots and Systems - IROS, Tokyo, Japan, Nov. 2013.

[4] M. Wartenberg, N. Patel, G. Li, and G. S. Fischer, Towards Synergistic Control of Hands-on Needle Insertion with Automated Needle Steering for MRI-Guided Prostate Interventions, IEEE EMBC 2016, Orlando, FL, USA, Aug. 2016. (Accepted)

2. How did the fellowship make a difference?

The Link Foundation Fellowship provides me indispensable financial support for my research project and PhD dissertation. The fellowship allows me to devote myself full time to the research project, and thus accelerated the progress of my dissertation. The fellowship also provided me the opportunity to attend several international conference and workshop, which allows me to get connection and communication with many outstanding researchers in the society of robotics and image-guided therapy. Moreover, the fellowship provided me the opportunity to conduct research project with our collaborator at Johns Hopkins University, which offered great contributions on this research. It is my honor to be a Link Foundation Fellow.

3. Future Plans

I just finished my PhD dissertation on June and started research on modeling and simulation of industrial robot for automotive assembly at General Motors as a researcher. In the near term of my career, I will apply the scientific knowledge, technologies and experience learned from my PhD study to the industry and create valuable benefits to the society.

4. Publications, Presentations, and Other Outputs.

[5] Gang Li, PhD Dissertation, Worcester Polytechnic Institute, “Robotic System Development for Precision MRI-Guided Needle-Based Interventions”, 2016

[6] H. Su, G. Li, D. C. Rucker, R. J. Webster III, and G. S. Fischer, “Concentric Tube Continuum Robot with Piezoelectric Actuation for MRI-Guided Closed-loop Targeting”, Annals of Biomedical Engineering, 2016 (Accepted).

[7] M. Li, G. Li, B. Gonenc, and Iordachita I., “Towards Human-Controlled, Real-Time Shape Sensing Based Flexible Needle Steering for MRI-Guided Percutaneous Therapies”, International Journal of Medical Robotics and Computer Assisted Surgery, 2016 (Accepted).

[8] G. Li, N. A. Patel, W. Shang, M. Wartenberg, T. Heffter, E. C. Burdette, I. Iordachita, J. Tokuda, N. Hata, C. M. Tempany, and G. S. Fischer, “A Clinically Integrated Robotic System for MRI-Guided Transperineal Prostate Biopsy: Preliminary Clinical Evaluation”, Annals of Biomedical Engineering, 2016 (under review).

[9] G. Li, N. A. Patel, W. Shang, H. Su, and G. S. Fischer “Modeling and Control of Gaussian-based Continuous Rotation and Variable Curvature Needle Steering: An MRI-guided Approach”, IEEE Transactions on Robotics, 2016 (In Preparation).