Robotic System for MRI-guided Prostate Intervention: Feasibility Study of Tele-operated Needle Insertion

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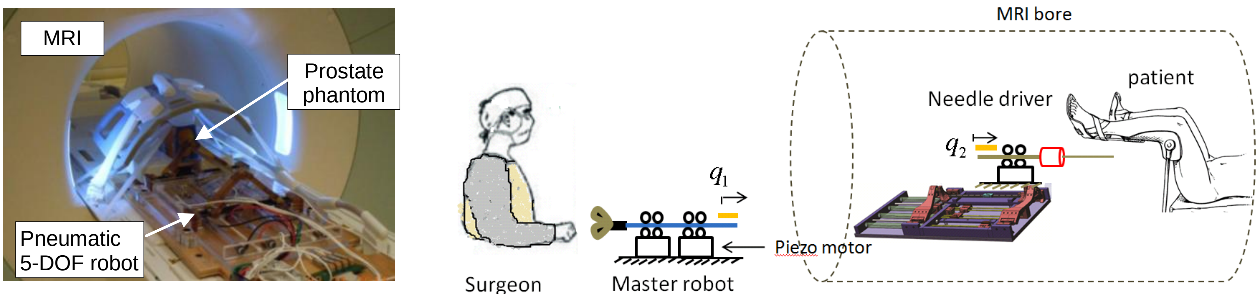
Keywords Prostate Intervention, MRI-compatible, Pneumatic Robot, Teleoperation;

Purpose

In order to integrate the advantages of Magnetic Resonance Imaging (MRI) and robotic technology in medicine, we have developed a high field 3T MRI-guided prostate intervention system for transperineal needle placement procedures. Fig. 1-(a) shows the latest robot prototype that provides 4-DOF surgical needle alignment in MRI coordinate with a platform for manual needle insertion (5^{th}-DOF).



(a) (b)

Fig. 1 (a) Robot prototype during mock procedure. (b) Schematic of the overall master-slave system for remote needle insertion.

Although the robot is able to align the surgical needle toward a predefined target inside prostate, the needle needs to be inserted manually. For this reason, the patient has to be pulled out of the scanner bore, once for manual insertion and once after taking confirmation image at each needle insertion. In order to shorten the procedure time and improve patient comfort, we proposed adding a teleoperated needle driver module on the robot. As depicted in Fig. 1-(b), the surgeon is standing in MRI room, next to the patient and operates an MRI-compatible master device that mimics realistic needle insertion. The slave, which is installed on top of the robot, does the real insertion.

Methods

In our design, the needle driver or the slave robot, Fig. 2-(c), is located close to the scanner’s iso-center and MRI-compatibility becomes the first concern for actuator selection. Based upon previous experience, pneumatic actuators are hard to control especially when they are configured as a master-slave system. As a result, Nanomotion piezo motor was selected as it provides not only enough thrust for penetrating prostate (almost 8.9 N) but also MRI-compatibility.
For needle insertion, a pair of HR4 Nanomotion motor, which are axially pre-loaded against each other on a ceramic drive strips, were used with optical encoders. All materials are non-metalic (Ultem, plastic, or ceramic) except the motor plate that was made of Aluminum for increased rigidity. In initial prototype, the master device, Fig. 2-(a), is not yet actuated. It consists of a MRI-compatible slide and rail (Igus Inc., East Providence, RI) which mimics the needle insertion. In the next step, a linear module similar to the needle driver will replace the current master device in order to generate haptic force feedback. The control unit, Fig. 2-(b), consists of Nanomotion AB5 motor

amplifiers, a DMC-21x3 Ethernet motion controller (Galil Motion Control, Rocklin, California), and a PC workstation on which GalilTools (the software to command the controller and to monitor sensor signals) runs. A 24 V DC power supply is used to run the controller and amplifier.

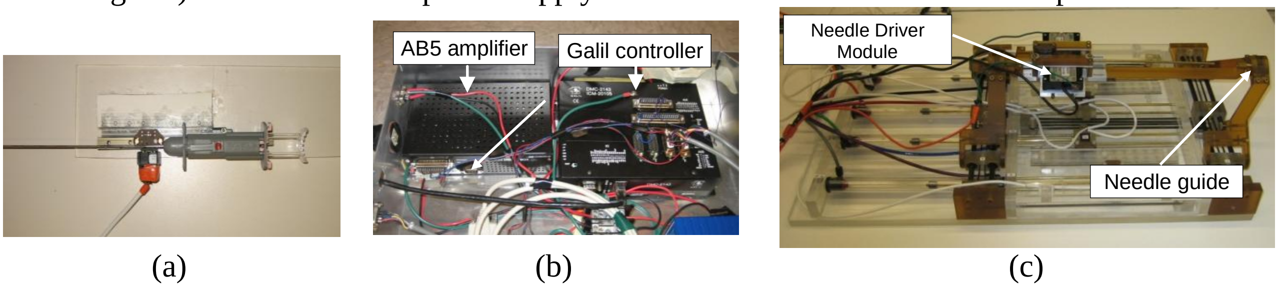


Fig. 2 (a) Master device (b) Control box (c) Needle driver installed on the 4-DoF pneumatic robot.

Results

The position tracking of the master-slave needle driver was assessed. For this reason, a Proportional-Integral (PI) controller was implemented on the Galil controller with the KP=100 and KI=20.The master was moved back and forth over a 40 mm range of motion for 20 sec. It is expected that the slave follows the master without any delay. Fig. 3 shows that needle driver was following the master accurately without noticeable delay. The average error was 0.03 mm. This experiment was repeated 3 times and the error was below 0.1 mm in all cases.

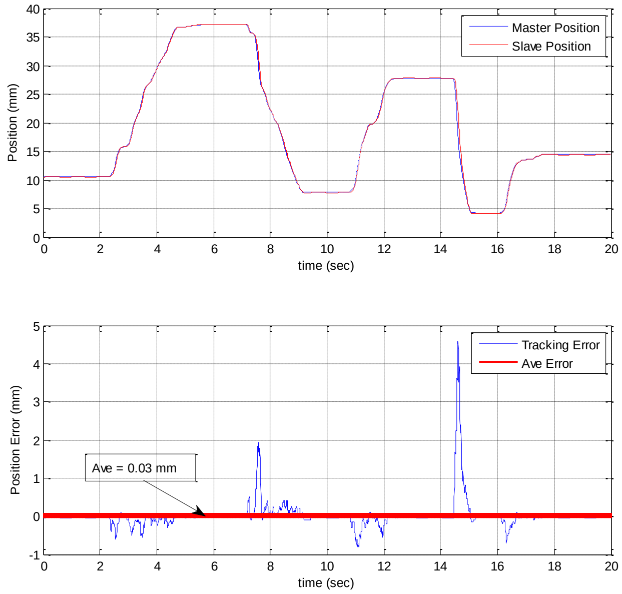


Fig. 3. Position tracking results of the master and slave over 40 mm displacement for 20 sec.

Conclusion

Previously, the accuracy of the base robot in needle alignment was evaluated [1]. Those results showed that the robot can align the needle toward the targets with an average accuracy of 0.2 mm. Also, this study showed that the master-slave needle driver position tracking was satisfactory. These results together suggest an accurate 5-DOF needle placement.

Acknowledgments

This work was funded by National Institute of Health Grants: 5R01CA111288-04, 5R01EB002963-05, 5P01CA067165, and 5U41RR019703. Gabor Fichtinger was supported as Cancer Care Ontario Research Chair.

References

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