Development of a Pneumatic Robot for MRI-guided Transperineal Prostate Intervention

S. Song[1], N. B. Cho[1], J. Tokuda[2], N. Hata[2], C. Tempany[2], G. Fichtinger[3], and I. Iordachita[4]

[1]Engineering Research Center, The Johns Hopkins University, Baltimore, MD, United States, [2]Brigham and Women's Hospital, Boston, MA, United States, [3]School of Computing, Queen's University, Kingston, Ontario, Canada, [4]Department of Mechanical Engineering, The Johns Hopkins University, Baltimore, MD, United States

Introduction

Transrectal ultrasound (TRUS) guidance is the most commonly used navigation method for the biopsy and brachytherapy. However, TRUS-guided biopsy has a poor cancer detection rate. In order for greater detection, magnetic resonance imaging (MRI) has been sought for the prostate intervention. Due to strong magnetic field that requires MRI-compatibility of surgical devices and physical limitation of in-bore access and workspace, closed-bore high-field MRI has not been widely adopted for prostate interventions. Recently, a number of MRI-compatible pneumatically actuated robotic systems for in-bore operation have been developed [1]. This study introduces a new pneumatic robot development by understanding advantages and disadvantages of such robots, and investigating new strategic and engineering approaches for enhanced controllability and optimized workflow towards clinical implementation.

Material and Methods

Key requirements that have been discussed from existing pneumatically actuated MRI-compatible robot developments can be summarized in a number of major challenges: design optimization, pneumatic actuator controllability enhancement, and adaptability in currently available clinical environment. A list of engineering and procedural approaches that could resolve such challenges were identified: 1) optimized operational workspace, 2) parallel kinematic configuration with structural rigidity, 3) enhanced pneumatic actuator controllability using timing belt transmission resulting an external damping to the pneumatic actuators. Based on the earlier 'proof-of-concept' robot development by Fischer *et al* [2] and the new approaches, a 4-DOF parallel kinematic structure robot that is capable of guiding widely used biopsy and brachytherapy needles, was designed shown in Fig. 1 (a). Current robot design aims to provide needle guide positioning only, allowing manual insertion. In future, however, this part will be replaced with a remote needle driver unit that even provides haptic feedback. Fabrication materials used for the robot are MRI-compatible. In the CAD model, the blue colored parts are cast acrylic machined by laser cutter and the red colored parts were fabricated from stereolithography apparatus rapid-prototype. The robot consists of a number of detachable modules: base, manipulator, and registration block. The base module provides a rigid flat base for the robot and also it could reduce the necessity of re-registration since the patient is located on the base. The controller described in [2] is also used for the new robot. 3-D Slicer surgical navigation software serves as a user interface with the robot, which is running on a Linux-based workstation in the scanner's console room connecting to the robot via a fiber optic Ethernet connection.

Preliminary engineering evaluation of the new robot was conducted to quantify the outcome of the new pneumatic actuator mechanism and the parallel robot structure. For the robot control accuracy test, each actuator was tuned. First, timing belts were tensioned at an appropriate level by extending the distance between pulleys. Then, control parameters i.e. proportional, integral, and derivative gains were individually set for the highest possible positioning accuracy. Thereafter, a set of nine target positions that are evenly spread around within the robot's Right-anterior planar workspace, i.e. the axial image plane in MRI scan, were chosen. 8 targets are formed in a circle at every 45 degree and a target at the center of the circle. Although the robot can target larger volume by pitch and yaw angling, no such positioning was included in the test, since needle insertion depth information is required. Each actuator's required joint-space displacement was obtained inverse-kinematically. Then, the nine target test was repeated six times at 10 minute intervals in order to evaluate repeatability over the time period that the robot is operational in clinical procedure.

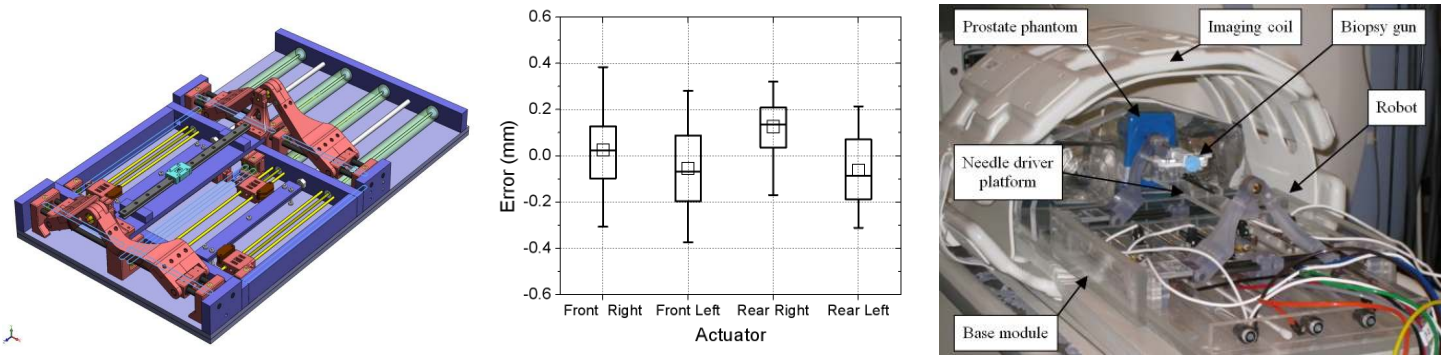

Fig. 1: (a) CAD desgin of the robot, (b) joint-space accuracy test result ('Front' refers superior direction) and (c) a phantom trial setup for MRI guided robotic biopsy.

Results and Conclusion

Each actuator's position error values obtained through the entire experiments are shown in Fig. 1 (b). The maximum error was found at 0.5 mm. The average joint-space (actuator) error was 0.2 mm, which is satisfying for this application, and no significant variation was observed from all four actuators. Repeatability can be a substantial problem for the non-metallic pneumatic actuator because its mechanical behavior varies with changes in temperature and humidity in a short period of time. However, no noticeable change was found in the robot's behavior and accuracy over approximately one hour of entire experiment.

In order to overcome problems of pneumatically actuated MRI-compatible prostate needle placement robots, a new controllability enhanced external damping mechanism was developed. Using the new mechanism and workspace optimization design approaches, a new 4-DOF needle guide robot was developed and a preliminary evaluation of the robot was conducted with satisfying results. Also, an initial phantom trial, shown as Fig. 1 (c), was carried out with focus on overall system integration i.e. communication between robot, planning software and scanner, and procedural feasibility. Minor technical problems were observed mostly from prototype material i.e. low-cost acrylic, which will be replaced for clinical trials. Overall, the new mechanism and other design approaches seem well adopted.

Recently, the robot's MRI compatibility tests using National Electrical Manufacturers Association (NEMA) standard method were conducted with three most widely deployed 3T MRI scanners i.e. GE, Philips and Siemens. The complete study is being analyzed, however, signal-to-noise-ratio (SNR) values and visual outcome suggest that the robotic intervention has no noticeable MRI image degrading.

References

[1] N.V. Tsekos, A. Khanicheh, E.Christoforou, and C. Mavroidis, "Magnetic resonance compatible robotic and mechatronics systems for image-guided interventions and rehabilitation: A review study," Annu. Rev. Biomed. Eng., vol. 9, pp. 351–387, Aug. 2007.

[2] G. S. Fischer, I. Iordachita, C. Csoma, J. Tokuda, S. P. Dimaio, C. M. Tempany, N. Hata, and G. Fichtinger, "Mri-compatible pneumatic robot for transperineal prostate needle placement," Mechatronics, IEEE/ASME Transactions on, vol. 13, no. 3, pp. 295-305, 2008.