Precision Pneumatic Robot for MRI-Guided Neurosurgery

David B. Comber
Diana Cardona
Robert J. Webster, Ph.D.
Eric J. Barth, Ph.D.

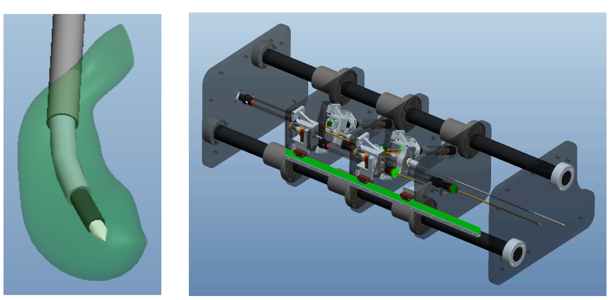
Department of Mechanical Engineering
Vanderbilt University

1 Background

Thermal ablation is an interventional technique that promises to enable percutaneous treatment of many cancers and other disorders throughout the human body. Acoustic ablation offers the possibility of steering thermal energy electronically [1], and is known to be MRI compatible, and thus amenable to real-time thermal dose monitoring through MR thermometry. We propose a pneumatically actuated robotic approach for delivering the ablator tip to a desired target, since a robot has the potential to be more accurate than humans, and can work within the confined space of a standard MRI machine. Our robot is designed to deliver a steerable needle made from precurved elastic concentric tubes.

2 Methods

Our concentric tube needle is made from three precurved concentric nitinol tubes; a CAD design is shown in Fig. 1a. It required five degrees of freedom: translation of the outermost, rigid tube; rotation and translation of the middle, precurved nitinol tube; and rotation and translation of the innermost, ablator-carrying nitinol tube. To simplify manufacture, we designed a modular robot having one module per needle tube. Modules translate the tubes on a common pair of guide rods, so more modules can easily be added in the future if desired.



(a) (b)

FIGURE 1. (a) ABLATOR TIP IN A LESION (b) ROBOT CAD MODEL

For pneumatic actuators, piston-cylinders were selected; they comprise MRI compatible materials and do not introduce image artifacts. Rod locks were integrated into the design for safety. In designing the mechanism, we focused on reducing overall robot size while minimizing friction, in order to improve the precision of control of the pneumatic actuators.

A detailed CAD design is shown in Fig. 1b. In component design, material selection focused on reducing image distortion. To minimize eddy currents, nonconductive components were used as much as possible. Aluminum and brass were chosen for parts that must undergo higher stresses.

Each active cannula tube is translated via an acrylic plate supported by two plain linear bearings. Two carbon fiber guide rods support all three sliding plates. Each of the two curved elastic tubes rotates via one pneumatic actuator and transmission mounted to its respective acrylic plate. The reciprocating motion of the piston-cylinder is converted to rotation using a grooved timing belt and two pulleys.

3 Results

Figure 2 is a photograph of the prototype. The overall dimensions are 12x28x8 in. The maximum initial insertion depth is 7 in. The mechanisms are free of binding, thus minimizing friction at the linear bearings and piston rod seals. With the robot in a 3T scanner, images of an Alzheimer's Disease Neuroimaging Initiative phantom were collected. Geometric image distortion was within scanner calibration limits. Most of the distortion was localized to a small region of the phantom nearest the robot.

A high precision nonlinear controller for the pneumatic actuators has been developed in a parallel work [2]. Using this control algorithm on the new prototype, we have achieved a maximum steady-state error of 0.005 mm (the resolution of the encoder). Each actuator requires one 4-way spool valve, two pressure sensors, and one optical encoder.

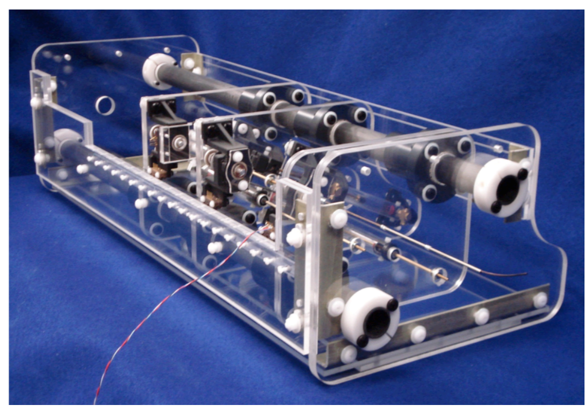


FIGURE 2. ROBOT PROTOTYPE

4 Interpretation

The controller results imply the robot will be sufficiently accurate at typical MRI resolutions. We do not believe that the minor image distortion observed will be problematic, since we envision considering clinical targets outside the distorted region. If required, in future work, metallic components can be replaced with high-strength plastics.

References

[1] Kinsey, A. M. et al, 2008, "Transurethal ultrasound applicators with dynamic multi-sector control for prostate therapy: *In vivo* evaluation under MR guidance," *J. Med. Phys.*, 35(5), pp. 2081-2093.

[2] Comber, D., and Barth, E. J., 2011, "Precision Position Tracking of MR-Compatible Pneumatic Piston-Cylinder Using Sliding Mode Control," DSCC2011-5960, *Proc. DSCC & Bath/ASME Symp. Fluid Power and Motion Control*, Arlington, VA, pp. 1-7.