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A TESTBED FOR MULTI-LUMEN STEERABLE NEEDLE EXPERIMENTS

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ABSTRACT
Steerable needles offer the potential to "turn corners" during insertion, thereby avoiding obstacles, reducing tip placement error, and enabling less-invasive access to challenging anatomical locations. In this paper we describe an experimental testbed designed to facilitate experiments with several popular steering mechanisms. One such mechanism makes use of asymmetric forces generated by a bevel tip for actuating steerable needles, and another uses multiple concentric pre-curved tubes that can change needle shaft shape by rotating within one another and extending telescopically. The experimental testbed consists of a new robotic actuation unit for controlling axial rotation and linear translation of multiple tubes. It also includes stereo optical cameras and a magnetic tracking system for feedback of needle shape and tip location. The setup can be used in future work for model validation and closed-loop feedback control of steerable needles and cannulae.

INTRODUCTION
Surgical needles provide one of the least invasive methods of accessing sites within the human body. They are useful for a wide variety of diagnostic and interventional procedures including biopsy [1], neurosurgery [2], regional anesthesia and brachytherapy [3], among many others. In needle-based procedures, clinical outcomes are closely related to the accuracy of needle tip placement to the desired site. However, precise targeting is challenging because of needle deformation during insertion, registration error, and tissue deformation, among other factors. These can cause the needle to miss the desired target, and such trajectory errors can often be visualized using intraoperative medical images.

This has motivated the recent development of a number of needle steering strategies to enable control of needle trajectory and shape within tissue. One popular mechanism for steering needles is to harness asymmetric tip forces (e.g., a bevel tip – see Figure 1) to controllably deflect the needle. Another popular method of steering needles (or more precisely, changing shaft shape) is to use a needle composed of multiple precurved flexible concentric tubes (see Figure 2). Like a bevel tipped needle, these active cannulas composed of concentric tubes are actuated by the axial translation and rotation of the proximal end of each component tube.

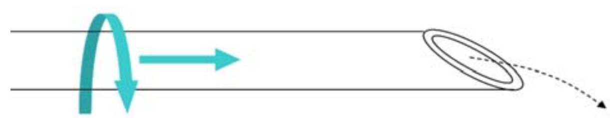

Figure 1: When a bevel tipped needle is inserted into tissue, asymmetric tip forces cause it to bend in a curved path as it cuts through the tissue. Correction for error and obstacle avoidance can be achieved by controlling axial rotation at the needle base during insertion.

In both tip-steered and concentric tube needles, an experimental testbed is needed to verify kinematic modeling and closed-loop control results. In this paper we describe the most recent experimental testbed we have developed to enable experiments with both tip-steered needles and concentric tube active cannulas and combinations of the two. Our testbed consists of a novel robotic actuation unit for controlling the axial rotation and linear translation of several tubes, the innermost of which may be a bevel-steered needle if desired. Feedback in our system comes from stereo optical cameras and a magnetic tracker, enabling experiments in both transparent and opaque media.

Related Work in Needle Steering Testbeds
A variety of noteworthy needle steering testbeds have been developed over the past few years. One of the first needle steering testbeds was the one created by DiMaio and Salcudean, who developed a method of steering traditional steel needles with symmetric tips by applying lateral forces and torques on the needle base during insertion [4]. Their testbed consisted of a modified planar 3-DOF haptic interface [5] to manipulate the needle or a tissue indenter, and an overhead optical camera for data collection. Glozman and Shoham subsequently implemented a similar basic steering concept

Figure 2: An active cannula composed of 3 concentric precurved nitinol tubes. The shape of the device can be changed by the relative rotation and translation of component tubes at their respective bases.

(with different modeling approaches) using a 6-DOF parallel robot under fluoroscopic imaging [6]. The needles used in both of the above studies were standard, clinically used, stainless steel needles.

Tip-based steering can be achieved using either a precurved tip [7] or a bevel [8, 9], to create asymmetric forces that bend the needle during insertion. The direction of bending can be controlled by axially rotating the tip. In the experimental setup of Okazawa *et al*. [7] a precurved stylet can be extended or retracted with respect to an outer cannula that straightens it when it is retracted. The distance of stylet extension controls the curvature, and the axial angle the direction, of forward needle progression during insertion. In [7] a hand-held robot is described to control the stylet, and image feedback was from an overhead optical camera.

Webster, *et al.* developed a bevel-tip needle steering experimental setup, describing two different robotic mechanism designs for controlling insertion and rotation. One design grips the needle near the skin, and another pushes it from the base [8, 9]. These robots manipulate a single flexible, beveled nitinol needle. Feedback is from stereo optical firewire cameras, and closed-loop control has been implemented [19] and combined with planners [20]. Minhas *et al.* at Carnegie Mellon increased the size of the bevel tip with respect to the needle shaft to increase curvature, and applied bevel steering in cadaver studies in brain tissue under fluoroscopic feedback [21]. Their experimental setup involved encoded, manually controlled insertion, with motorized, computer controlled bevel rotation. A similar strategy was implemented in a teleoperated setting by Romano *et al.* [18] using the robot of [9]. Ding *et al.* have implemented bevel steering under fluoroscopic imaging [22]. Abolhassani *et al.* [23] have applied bevel steering to reduce unwanted deflection of steel needles during insertion by using force/torque data at the needle base to determine when to activate a single 180 degree rotation of the bevel during insertion. A magnetic sensor was used to acquire needle tip position data, an optical camera provided information on needle deflection at the tissue entry point, and an ultrasound system was used to image the needle within tissue.

All of the above work has been accomplished with a single stylet, or needles consisting of a stylet and single straight outer cannula. Recently, several groups have developed designs whereby the needle shaft shape can be directly controlled using multiple concentric precurved tubes that can be rotated within one another and extended telescopically. Terayama *et al.* demonstrated coupling such a device to a needle guide to access locations in an ultrasound image [24]. The research groups of Dupont at Boston University [25-28] and Webster at Vanderbilt [10-17, 29-31] have focused on applying beam mechanics to develop in-depth models of concentric tube robots. However, thus far little attention has been devoted in published material to the actuation units that control these devices.

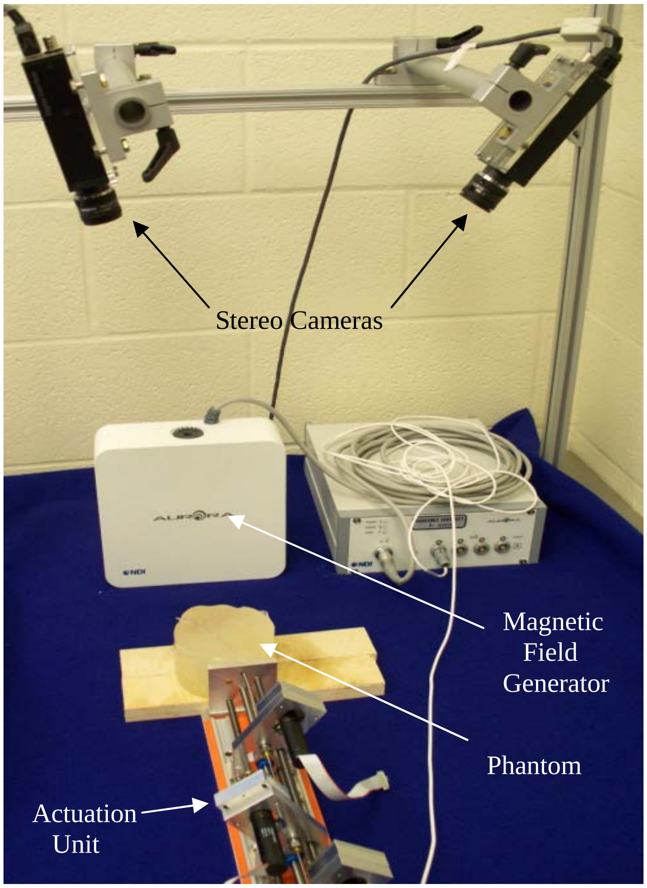

Figure 3: Photo of experimental setup showing the robotic actuation unit, and the optical and magnetic sensing systems. A magnetic tracking coil is embedded within the tip of the steerable needle.

In this paper, we describe our latest experimental setup, which combines many features of prior needle insertion testbeds with a new robotic actuation unit that can control several tubes simultaneously, the innermost of which may optionally be a bevel-tipped needle.

EXPERIMENTAL TESTBED

Our experimental testbed shown in Figure 3 consists of 1) stereo firewire cameras, 2) a magnetic tracking system, with tracking coil embedded near the needle tip, and 3) a robotic actuation unit. These components are addressed in the following subsections.

Stereo Imaging

One method of feedback in our system is stereo firewire cameras (Sony XCDX710) that connect to the control computer. These cameras are capable of capturing 8-bit grayscale images at a resolution of 1024x768 pixels with a rate of 30 frames per second. The cameras are mounted on an adjustable frame so that they can be set up as desired in terms of angle and field of view. The images received from the cameras simulate images that could be obtained clinically using biplane fluoroscopy. This stereo camera setup is substantially equivalent to the one implemented at Johns Hopkins [9, 19, 20].

Magnetically Tracked Needle
We construct needles using tubes and wires made from Nitinol, a superelastic alloy of Nickel and Titanium. To construct a tracked, bevel-steered needle, we begin with a tube and grind a bevel on one end. We then insert the maginetic tracking coil (Aurora 5DOF sensor, NDI, Canada) shown in Figure 4 into the center of the tube, and fix it in place with glue near the needle tip. Note that buckling of such a needle can be prevented using an external telescoping sheath as was done [9]. Precurved tubes can be set to desired shapes by plastic deformation or heat treatment [10-17, 24-31].

Figure 4: Bevel tipped needle with magnetic tracking coil

Robotic Actuation Unit
As mentioned previously, robotic actuation units to control bevel-steered needles and/or multi-lumen cannulas require two actuated degrees of freedom (axial rotation and translation) per tube, applied at the base of each tube. A desirable feature of an actuation unit is modularity, so that it is straightforward to add more tubes. Also, it is desirable to minimize the total lengths of the tubes used, in order to minimize torsional windup effects. To accomplish this, the mechanism must be capable of tightly stacking tube grip points in the axial direction, so that when all tubes are fully deployed, the grip points of the tube bases are as close to one another as possible. An additional challenge is in gripping each tube itself tightly enough that there is no slippage during actuation, while at the same time loosely enough that the tube is not crushed or compressed so far that excessive friction is introduced.

Figure 5 illustrates our most recent actuation unit prototype. It contains several carriages actuated by lead screws (three are pictured, but the particular prototype shown will eventually accommodate four). One tube is attached to each carriage via a collet. The design is in principle modular, in that one can easily add additional lead screws and carriages, and the basic concept remains the same. The design can also be lengthened or shortened as desired based on travel lengths required by a given application.

A close-up image of an individual carriage is shown in Figure 6. The needle is gripped by a custom brass collet which is housed in a rotary bearing attached to the carriage. The collet grips the tube and is fixed to a toothed pulley via two set screws. The gear is driven through a belt drive by the motor attached to the carriage. The belt can be pre-tensioned by adjusting the position of the motor in linear tracks before fixing it in place with screws. The needle progresses forward out of a hole in the front plate of the robot as shown in Figure 7. The translational motion of the entire carriage pictured in Figure 6 (Left) is driven by a lead screw in its bottom left corner. Other carriages contain pass-through holes for this lead screw.

The carriages are stabilized by a central shaft running through a linear bearing in each of the carriages, as well as by two linear slides that run along the base and support the bottom corners of each carriage. Brushed Maxon DC motors drive all axes, and low-level PID control of the motors is implemented by an eight axis motion control board from Galil, Inc. (DMC 4080). Design specifications regarding forces and torques of a mechanism such as this are highly dependent on the tubes one wishes to actuate with it (diameters, precurvatures, tissues, etc.). The latest active cannula models [16, 26, 30, 31] can be helpful for calculating these, and an example of converting application requirements to design specifications can be found in [29].

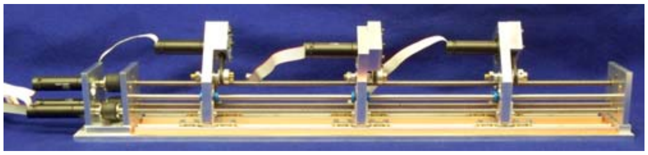

Figure 5: The robotic actuation unit, showing three translational carriages, each of which can move independently when actuated by lead screws coupled to the motors pictured to the far left in the image. One tube is attached to each carriage, and each carriage carries motor and belt drive assembly to rotate the tube axially.

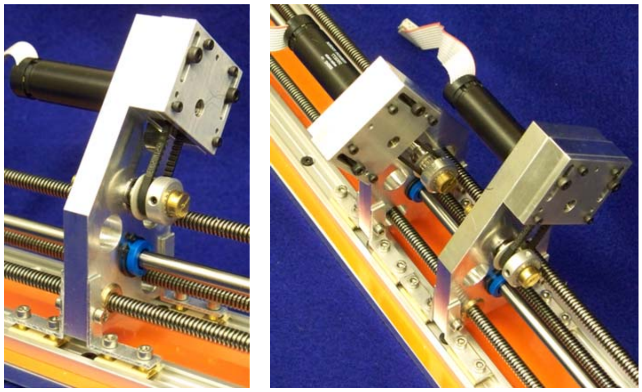

Figure 6: (Left) a close up of a single carriage showing the attached motor and belt drive which turns a brass collet that grips a tube. Also pictured are the central support shaft and the linear bearing that slides on it and the two linear slides that support the bottom corners of the carriage. (Right) the motors of successive carriages are offset and can thus pass by one another permitting carriages to stack tightly in the axial direction.

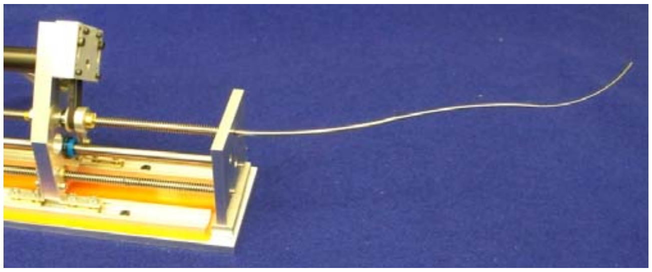

Figure 7: Tubes extend out of the front plate of the device. The concentric tube robot pictured contains four tubes. The outermost is pictured fully retracted (its tip flush with the front plate), and the innermost will be connected to the fourth carriage when it is completed.

DISCUSSION

We are currently using the experimental testbed described in this paper to validate trajectory-following controllers for bevel-steered needles. We are also using it to experimentally validate Jacobian-based control in free-space for concentric tube continuum robots. In the future, our experimental system will also be useful for experiments that combine bevel steering and steering via concentric precurved tubes simultaneously.

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REFERENCES

[1] Tobkes, A. I., and Nord, H. J., 1995, "Liver Biopsy: Review of Methodology and Complications," Digestive Diseases, 13, pp. 267-274.

[2] Rizun, P. R., McBeth, P. B., Louw, D. F., and Sutherland, G. R., 2004, "Robot-assisted Neurosurgery," Semin. Laporasc. Surg., 11(2), pp. 99-106.

[3] Wei, Z., Wan, G., and Gardi, L., 2004, "Robot-Assisted 3D-TRUS Guided Prostate Brachytherapy: System Integration and Validation," Medical Physics, 31, pp. 539-548.

[4] DiMaio, S. P., and Salcudean, S. E., 2003, "Needle Insertion Modeling and Simulation," IEEE Transactions on Robotics and Automation, 19(5), pp. 864-875.

[5] Sirouspour, M. R., DiMaio, S. P., Salcudean, S. E., Abolmaesumi, P., and Jones, C., 2000, "Haptic Interface Control-Design Issues and Experiments with a Planar Device," IEEE International Conference on Robotics and Automation, 1, pp. 789-794.

[6] Glozman, D., and Shoham, M., 2007, "Image-Guided Robotic Flexible Needle Steering," IEEE Transactions on Robotics, 23(3), pp. 459-467.

[7] Okazawa, S., Ebrahimi, R., Chuang, J., Salcudean, S. E., and Rohling, R., 2005, "Hand-Held Steerable Needle Device," IEEE/ASME Transactions on Mechatronics, 10(3), pp. 285-296.

[8] Webster III, R. J., Cowan, N. J., Chirikjian, G. S., and Okamura, A. M., 2006, "Nonholonomic Modeling of Needle Steering," International Journal of Robotics Research, 25(5/6), pp. 509-526.

[9] Webster III, R. J., Memisevic, J., and Okamura, A. M., 2005, "Design Considerations for Robotic Needle Steering," IEEE International Conference on Robotics and Automation, pp. 3588-3595.

[10] Webster III, R. J., Romano, J. M., and Cowan, N. J., "Mechanics of Precurved-Tube Continuum Robots," 2009, IEEE Transactions on Robotics, 25(1), 67-78.

[11] Rucker, D. C., Croom, J. M., and Webster III, R. J., 2009, "Aiming Surgical Lasers With an Active Cannula," ASME Journal of Medical Devices, 3(2), pp. 027506.

[12] Webster III, R. J., Swensen, J. P., Romano, J. M., and Cowan, N. J., 2008, "Closed-Form Differential Kinematics for Concentric-Tube Continuum Robots with Application to Visual Servoing," 11th International Symposium on Experimental Robotics 2008, Springer Tracts in Advanced Robotics 2009, 54, 485-494.

[13] Lyons, L. A., Webster III, R. J., and Alterovitz, R., 2009, "Motion Planning for Active Cannulas," IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 801–806.

[14] Rucker, D. C., and Webster III, R. J., 2009, "Mechanics of Bending, Torsion, and Variable Precurvature in Multi-Tube Active Cannulas," IEEE International Conference on Robotics and Automation, pp. 2533-2537.

[15] Webster III, R. J., Okamura, A. M., and Cowan, N. J., 2006 "Toward Active Cannulas: Miniature Snake-Like Surgical Robots," IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 2857-2863.

[16] Rucker, D. C., and Webster, R. J., 2009, "Parsimonious Evaluation of Concentric-Tube Continuum Robot Equilibrium Conformation," IEEE Transactions on Biomedical Engineering, 56, pp. 2308-2311.

[17] Webster III, R. J., Romano, J. M., and Cowan, N. J., 2008, "Kinematics and Calibration of Active Cannulas," IEEE International Conference on Robotics and Automation, pp. 3888-3895.

[18] Romano, J. M., Webster III, R. J., and Okamura, A. M., 2007, "Teleoperation of Steerable Needles," IEEE International Conference on Robotics and Automation, pp. 934-939.

[19] Kallem, V., and Cowan, N. J., 2009, "Image Guidance of Flexible Tip-Steerable Needles," IEEE Transactions on Robotics, 25(1), pp. 191-196.

[20] Reed, K. B., Kallem, V., Alterovitz, R., Goldberg, K., Okamura, A. M., and Cowan, N. J., 2008, "Integrated Planning and Image-Guided Control for Planar Needle Steering,", 2nd IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics, pp. 819-824.

[21] Minhas, D. S., Engh, J. A., and Riviere, C. N., 2009, "Testing of Neurosurgical Needle Steering via Duty-Cycled Spinning in Brain Tissue in vitro," IEEE International Conference of the Engineering in Medicine and Biology Society.

[22] Ding, J., Stoianovici, D., Petrisor, D., Mozer, P., Avila, R., Ibanez, L., Turner, W., Yankelvitz, D., Wilson, E., Banovac, F., and Cleary, K., 2008, "Medical Needle Steering for Lung Biopsy: Experimental Results in Tissue Phantoms using a Robotic Needle Driver," IEEE International Conference on BioInformatics and BioEngineering, pp. 1-5.

[23] Abolhassani, N., Patel, R. V., and Ayazi, F., 2007, "Minimization of needle deflection in robot-assisted percutaneous therapy," The International Journal of

Medical Robotics and Computer Assisted Surgery, 3(2), pp. 140-148
[24] Terayama, M., Furusho, J., and Monden, M., 2007, “Curved multi-tube device for path-error correction in a needle-insertion system,” International Journal of Medical Robotics Computer Assisted Surgery, 3, pp. 125–134.
[25] Sears, P., and Dupont, P., 2006, “A Steerable Needle Technology Using Curved Concentric Tubes,” IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 2850-2856.
[26] Dupont, P., Lock J., and Butler, E., 2009, “Torsional Kinematic Model for Concentric Tube Robots,” IEEE International Conference on Robotics and Automation pp. 3851-3858.
[27] Mahvash, M., and Dupont, P., 2008, "Bilateral Teleoperation of Flexible Surgical Robots,” New Vistas and Challenges in Telerobotics Workshop, IEEE International Conference on Robotics and Automation.
[28] Sears, P., and Dupont, P., 2007, “Inverse Kinematics of Concentric Tube Steerable Needles,” IEEE International Conference on Robotics and Automation.
[29] R. J. Webster III, “Design and Mechanics of Continuum Robots for Surgery,” Ph.D. Thesis, Johns Hopkins University, December 2007.
[30] D. C. Rucker, B. A. Jones, and R. J. Webster III, “A Geometrically Exact Model for Externally Loaded Concentric Tube Continuum Robots,” IEEE Transactions on Robotics. (Accepted)
[31] D. C. Rucker, R. J. Webster III, G. S. Chirikjian, and N. J. Cowan, “Equilibrium Conformations of Concentric-Tube Continuum Robots,” International Journal of Robotics Research. (Accepted)