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Design of a Robotic Tool for Percutaneous Instrument Distal Tip Repositioning

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Abstract **– Manually performed image-guided percutaneous procedures are limited by targeting errors due to instrument misalignment, deflection and an inability to reposition the distal tip of the instrument after it has been percutaneously inserted. These limitations result in suboptimal instrument positioning that limits diagnosis and treatment for a variety of procedures as well as excessive procedure time and radiation dose (in the case of x-ray based imaging). Hence we are developing a robotic tool capable of repositioning the distal tip of a percutaneous instrument after a single insertion into the body. It is based on the concept of deploying a super-elastic pre-curved stylet from a concentric straight cannula. The proximal end of the cannula is attached to the distal end of a screw-spline that enables it to be translated and rotated with respect to the casing. Translation of the stylet relative to the cannula is achieved with a second threaded screw with a splined groove. The device is made of mostly plastic components and actuation is achieved using micro-stepper motors. Measurements of the maximum axial force for the cannula screw-spline and stylet screw were found to match those from design calculations. Evaluation of the mechanism positioning capability demonstrated sub-millimeter and sub-degree translation and angular accuracy. We foresee this robotic tool having wide application across a range of procedures such as biopsy, thermal ablation and brachytherapy seed placement.**

***Index Terms*— percutaneous, needle, steerable, screw-spline, robotic tool.**

I. Introduction

Minimally invasive percutaneous procedures are routinely performed for both the treatment and diagnosis of disease. In medical parlance, percutaneous needle insertion refers to any medical procedure where the skin is punctured with a rigid needle to access inner organs or other tissue as opposed to an open surgical approach. Typically the procedures are performed under image-guidance such as computed tomography (CT), fluoroscopy, ultrasound and magnetic resonance imaging (MRI) that provide high resolution images of the patient anatomy. Example techniques for treating cancer are brachytherapy, where small radioactive seeds are deployed through a needle and implanted into the tumor, and ablation, where thermal energy is applied through a thin probe to destroy the tumor. While there are clear benefits to locally treating disease, the number of procedures that can be performed in this way is limited in part due to the challenge in accurately positioning needles and probes within the target organ. Physicians are often forced to take large safety margins and as a result these ultra-minimally invasive techniques cannot be used near sensitive anatomy. Once inserted, repositioning the distal tip of a straight percutaneous instrument in tissue is challenging, if not impossible, because of forces along its length from the tissue that resist its pivoting motion. Thus, if an instrument is incorrectly placed, a radiologist is forced to retract it and attempt to re-insert it along the correct trajectory. To generate larger or irregularly shaped treatment zones multiple probes are inserted which increases procedure difficulty further. All of the above factors result in these procedures being iterative, time-consuming and having limited accuracy. Thus there is a need for means to accurately and efficiently reposition the distal tip of a percutaneous instrument after insertion into the body.

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II. Related Work

Over the last two decades a number of medical robots have been developed in an attempt to improve needle placement in soft tissue. These robots are mounted on the CT scanner bed [1-3] or the patient [4-6] and provide some method for remote needle orientation and insertion. The majority of these manipulators provide a remote center of rotation so that the needle can pivot about the skin surface. More recently researchers have developed needle steering robots that can control the trajectory of a percutaneous instrument as it is inserted into tissue. The two main strategies that have been employed to achieve steering utilize asymmetric forces at the needle tip (e.g. due to bevel) [7-9] or rotation and translation of concentric pre-curved tubes [10] [11, 12].

The advantage of bevel-based steering is that existing needles can be used; however, this approach relies on a reaction force from the tissue. Controlling the amount of time that the bevel spends in a particular orientation by rotating the needle in a spin-stop-spin-stop manner, a range of curved trajectories can be generated. Webster *et al.* built a compact two degree of freedom mechanism that could advance and rotate a needle with an increased level of control compared to a human [8]. A traction drive was used to advance the needle and this stage was rotated by a gear driven by a second motor.

Two commercially available, passive devices for spinal procedures, such as vetebroplasty, are based on the concept of a superelastic pre-curved stylet with a stiffer concentric outer cannula [13, 14]. These devices offer the physician the ability to target points lateral from the distal end of an instrument. Recent exciting work has extended this concept to control multiple overlapping concentric pre-curved tubes; both to modify needle curvature as it is being inserted into tissue [10] and to navigate around obstacles in the body [11, 12].

III. Telerobot Design

In this paper we present the design of a compact three degree-of-freedom robotic tool that can be used to reposition the distal tip of a percutaneous instrument to adjacent points in a volume. This is achieved through translation and rotation of a cannula and translation of a super-elastic pre-curved stylet relative to the cannula (Fig. 2). Such a device would be useful for correcting targeting errors, reaching multiple points in a volume or directing the instrument tip around obstacles when a straight line trajectory cannot be taken.

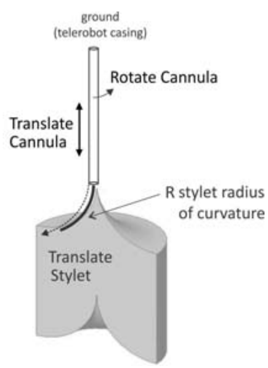

Fig. 1 Illustration of the motions of a cannula and stylet that can be actuated to enable targeting of a volume in the body after a single cannula insertion.

A. Defining Device Specifications

The first step in the design of the mechanism was to define the functional requirements. This was done in collaboration with radiologists and it was determined that the device should

- have sufficient force to insert cannula into tissue (15.6 N),
- provide sufficient force to move stylet relative to the cannula (14 N),
- actuate the appropriate degrees of freedom (3) with 1 mm translation and 1 degree angular accuracy,
- be compatible with CT machines
- and be sufficiently lightweight for patient mounting.

Previously we performed experiments to measure the force required to retract various size pre-curved stylets into a variety of cannulae. We found a maximum force of 14 N to retract a curved Nitinol stylet into a cannula [15]. Previously reported results of inserting needles into tissue range from 2.3 N to 15.6 N [16, 17] and depend of the size and type of needle used; thus, these maximum values were used as design specifications.

B. Mechanism Design

The mechanism design, largely of plastic components for CT compatibility, is shown in Fig 3. The device has a protruding cannula and a stylet with a curved distal tip pre-assembled inside. The proximal end of the cannula is attached to the distal end of a hollow screw-spline and the proximal end of the stylet is attached to the distal end of a screw nested inside the screw-spline. Each attachment is achieved via aluminum threaded inserts that are bonded to the proximal end of the shafts. The length of the cannula and stylet were chosen so as to be positioned at the distal tip of a 10 cm access cannula. The axial travel of both the cannula screw-spline and stylet screw are 40 mm and the cannula screw-spline is capable of 360 degrees of rotation. Three identical clamps were used to secure the stepper motors to their respective mounting plates. The system height and diameter are 15 cm and 5 cm respectively with a weight of approximately 180 grams.

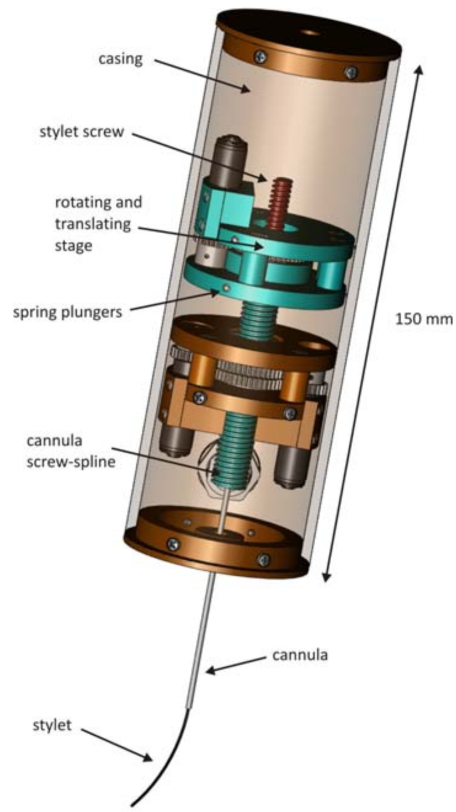

Fig. 3 CAD image of the telerobotic needle steering system. The cannula is attached to a screw-spline (turquoise) that can be translated and rotated through control of two stepper motors grounded to the casing (brown). The stylet is attached to a screw (red) that can be translated with respect to the screw-spline through control of a motor that is grounded to the screw-spline.

The screw-spline is a custom plastic ACME threaded screw that also has a splined groove along its length. It is functionally similar to the ball-screw spline that is produced by THK that is used in some SCARA robots (e.g. EPSON RS3-Series, EPSON Robots, CA 90746) and other robotic applications where the combination of translation and rotation are required in a compact design. Fig. 4 shows nuts 1 and 2 engage the screw threads and spline respectively. Nut 1 has a bore that is threaded to match the lead of the screw and nut 2 has a slot broached into the inside diameter for a small plastic 1.5 mm wide key to be inserted that engages the splined groove on the screw-spline. Translation of the stylet is achieved in a similar way with a keyed feature on the inside of the screw-spline constraining the stylet rotation relative to it.

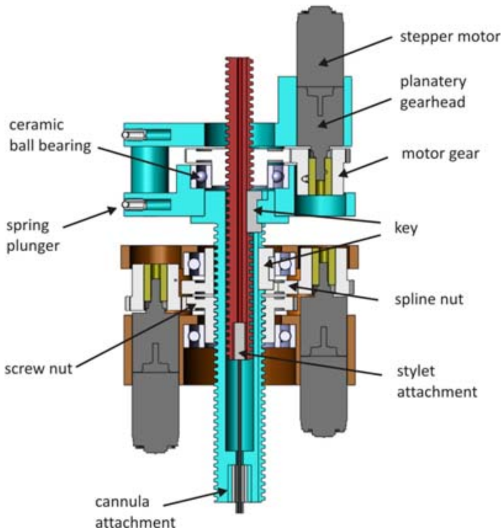

Fig. 4 Section view of the drive mechanism. A spline nut and screw nut engage the spline and threads of the screw-spline respectively. Another threaded nut engages the screw that rides inside the screw-spline. The nuts are bonded to the inside race of ceramic ball bearings and have teeth that engage spur gears on the corresponding gearhead shafts.

By appropriate control of the two nuts, three modes of operation of the screw-spline, and hence cannula, with respect to the casing could be obtained as shown in Fig. 5.

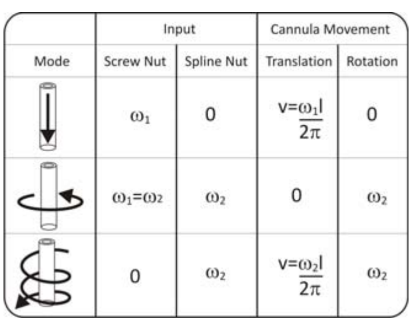

Fig. 5 The cannula axial and rotational position is controlled by the screw-spline..The helix mode is not required for this application.

C. Mechanism Actuation and Transmission Selection

Neglecting friction forces arising from bearings, the general equation for calculating the torque to raise a load and overcome frictional forces due to sliding contact between the threads is

$$T = \frac{Fd_m}{2}\left(\frac{l + \pi\mu d_m \sec\alpha}{\pi d_m - \mu l \sec\alpha}\right) \quad (1)$$

Where F is the desired maximum force, d_m is the pitch diameter of the lead screw, l is the lead, μ is the coefficient of friction between the threads and α is the ACME thread angle (i.e. 29°). Using a simple sliding test, the coefficient of sliding friction of Acetal on Acetal was found to be 0.2. By choosing an appropriate lead and diameter for the screws the cannula can retain its axial position when the stylet is being translated and vice versa. Other important considerations when sizing a power screw transmission are efficiency and the maximum stress it will experience. If T_0 is the torque achievable assuming no frictional losses due to sliding contact between the threads the efficiency, e, for power transmission with a screw is given by

$$e = \frac{T_0}{T} = \frac{Fl}{2\pi T} \quad (2)$$

Assuming a stress concentration of 2 due to the threads, the equivalent von Mises stress in the screws can be estimated by combining the axial and shear stresses

$$\sigma_{equivelent} = 2 * \sqrt{\left(\frac{4F}{\pi(d_r - d_i)^2}\right)^2 + 3\left(\frac{16T}{\pi d_r^{\,3}}\right)^2} \quad (3)$$

where F is the axial load and d_r and d_i are the root and inside diameter of the leadscrew respectively. A larger diameter or lead will reduce the stress in the screw (the latter by reducing the torque requirement); however, it will also result in a reduced efficiency and increase in the required input torque. Given this trade-off, a lead of 1/16 inch (1.5875mm) was chosen for the stylet screw and cannula screw-spline. A stylet diameter of 6 mm was chosen so that its bending stiffness would be sufficient for prototyping on a lathe. The screw-spline diameter was chosen to be 11 mm so that it just allowed the stylet screw to concentrically nest inside it. A summary of the results of the design calculations are shown in Table 1.

TABLE 1
TRANSMISSION CHARACTERISTICS FOR THE SCREW-SPLINE AND SCREW TO ACHIEVE THE DESIRED FORCES OF 15 N AND 29.6 N RESPECTIVELY.

	Screw-Spline	Screw
Torque Required [Nmm]	23.9	28.1
Maximum Stress [MPa]	0.7	6.9
Efficiency [%]	15.9	26.6
Backdrivability	NO	NO

The stepper motors and gearheads selected for this application were 10 mm diameter (AM1020, MicroMo Electronics (Faulhaber Group), FL) and a two-stage planetary gearhead with 16:1 reduction. There was a further gear reduction between the gearhead shaft and the nuts for the screw-spline (2:1) and screw (1.875:1). The stepper motor had a step angle of 18 degrees and so this gear reduction also yielded a minimum step angle for the screw-spline of just over half a degree (18/32), fulfilling the design specifications. Also, the torque transmitted at a pitch diameter, d_p, results in a radial load, F_{radial}, on the shaft on which the gear is mounted, given by

$$F_{radial} = \frac{2T_g}{d_p} \quad (4)$$

Where T_g is the torque at the gearhead shaft. Furthermore, a pressure angle ϕ, between the gear teeth generates a force that acts to spread the gears apart

$$F_{spread} = F_{radial}\tan\phi \quad (5)$$

The radial load on the gearhead shaft was calculated to be 13 N with a spreading force of 4.7 N. Thus, a hubbed spur gear was used so that the gear teeth were placed in line with the sintered brass bearings in the planetary gearhead as shown in Fig. 4. Ceramic bearings were used for attaching each of the nuts to their respective mounting plates (VXB Bearing Inc.). These bearings provided a compact non-metallic package with the advantages of low friction and small axial play (~0.1 mm). The bending stress in the gear teeth was calculated using the basic Lewis equation. The maximum value was 6.9 kN/m^2; well below the maximum allowable stress for Acetal. An image of the constructed prototype is shown in Fig. 6.

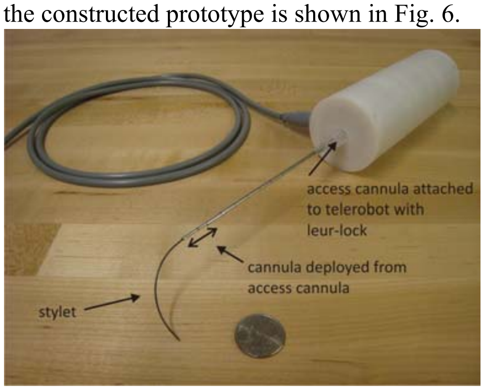

Fig. 6 Prototype of the telerobot shown attached to an access cannula via a standard medical leur-lock. The stylet is shown in its deployed position and the cannula is protruding about 1 cm from the distal tip of the access cannula.

IV. System Evaluation

Bench-level experiments were performed to measure the output force as well as the system accuracy and repeatability. A load cell (LCM200, Futek, CA, USA) with amplifier (CSG105, Futek, CA, USA) was mounted concentric with the screw-spline or screw to measure the maximum axial force and a spring scale (increments of 40 grams) with a lever were used for measuring the maximum torque. A summary of the experimental and predicted values is shown in Table 2.

Table 2
Comparison of the maximum force and torque capacities of the cannula screw-spline and stylet screw to their predicted values.

	Predicted	Measured
Cannula Screw-Spline		
Axial Force [N]	28	26
Drive Torque [Nmm]	37	25
Holding Torque [Nmm]	51	59
Stylet Screw		
Axial Force [N]	43	25

For position measurements, a potentiometer was mounted concentric to the shafts to measure axial rotation and a linear caliper was used to measure the translation of the screw-spine and screw. The typical standard deviation of the 10 readings for any one position was 0.05 mm. The results are summarized in Table 3 demonstrating sub-millimeter and sub-degree accuracy and repeatability. The screw-spline couples the rotation and translation of the cannula and so the degree to which axial position was effected by commanded rotation of the screw spline was evaluated. The deviation of the axial position of the was less than 0.2 mm for up to 15000 rotations.

Table 3
Comparison of axial and angular motion in response to respective commands (Average of 10 readings and standard deviation).

	Commanded	Measured
Cannula Screw-Spline		
Translation [mm]	5	5.01 ± 0.02
Rotation [deg]	5	4.97 ± 0.22
Stylet Screw		
Translation [mm]	5	4.96 ± 0.06

V. Conclusions and Future Work

In this paper we have presented the design of a compact robotic tool capable of repositioning the distal tip of a percutaneous instrument, after it has been inserted into the body. The steering mechanism consisted of deploying a pre-curved stylet from a concentric straight cannula. Ultimately this device will be controlled by a point-and-click interface that incorporates medical images and allows for the selection of target points based on the visualized anatomy.

References

[1] A. Bzostek, *et al.*, "A Testbed System for Robotically Assisted Percutaneous Pattern Therapy," *MICCAI'99,* vol. 1679/1999, pp. 1098-1107, 1999.
[2] D. Stoianovici, *et al.*, "AcuBot: a robot for radiological interventions," *Robotics and Automation, IEEE Trans. on,* vol. 19, pp. 927-930, 2003.
[3] M. Rasmus, *et al.*, "Preliminary clinical results with the MRI-compatible guiding system INNOMOTION," *Int J CARS* vol. 2 pp. S138-S145, 2007.
[4] E. Taillant, *et al.*, "CT and MR Compatible Light Puncture Robot: Architectural Design and First Experiments," in *MICCAI 2004*, ed, 2004, pp. 145-152.
[5] B. Maurin, *et al.*, "A robotized positioning platform guided by computed tomography: practical issues and evaluation," in *Robotics and Automation, 2006. ICRA 2006. Proceedings 2006 IEEE International Conference on*, 2006, pp. 251-256.
[6] C. Walsh, *et al.*, "A Patient-Mounted, Telerobotic Tool for CT-Guided Percutaneous Interventions," *ASME Journal of Medical Devices,* vol. In Press, 2008.
[7] S. P. DiMaio and S. E. Salcudean, "Needle insertion modelling and simulation," in *Robotics and Automation, 2002. Proceedings. ICRA '02. IEEE International Conference on*, 2002, pp. 2098-2105 vol.2.
[8] R. J. Webster, III, *et al.*, "Nonholonomic Modeling of Needle Steering," *Int. J. Rob. Res.,* vol. 25, pp. 509-525, 2006.
[9] J. A. Engh, *et al.*, "Flexible Needle Steering System for Percutaneous Access to Deep Zones of the Brain," in *Bioengineering Conference, 2006. Proc. of the IEEE 32nd Annual Northeast*, 2006, pp. 103-104.
[10] S. Okazawa, *et al.*, "Hand-held steerable needle device," *Mechatronics, IEEE/ASME Transactions on,* vol. 10, pp. 285-296, 2005.
[11] R. J. Webster, *et al.*, "Mechanics of Precurved-Tube Continuum Robots," *Robotics, IEEE Transactions on,* vol. 25, pp. 67-78, 2009.
[12] P. Sears and P. Dupont, "A Steerable Needle Technology Using Curved Concentric Tubes," in *Intelligent Robots and Systems, 2006 IEEE/RSJ International Conference on*, 2006, pp. 2850-2856.
[13] R. L. Pakter and E. M. Morris, "Hollow, curved, superlastic medical needle," vol. US Patent No. 6,592,559 B1.
[14] W. R. Daum, "Deflectable Needle Assembly," vol. US Patent No. 6,572,593.
[15] C. Walsh, *et al.*, "Material Selection and Force Requirements for the use of Pre-Curved Needes in Distal Tip manipulation Mechanisms," in *2010 Design of Medical Devices Conference*, Minneapolis, MN, 2010.
[16] A. M. Okamura, *et al.*, "Force modeling for needle insertion into soft tissue," *Biomedical Engineering, IEEE Transactions on,* vol. 51, pp. 1707-1716, 2004.
[17] T. Podder, *et al.*, "In vivo motion and force measurement of surgical needle intervention during prostate brachytherapy," *Medical Physics,* vol. 33, pp. 2915-2922, 2006.