Active Needle Steering System for Percutaneous Prostate Intervention in High-field MRI

Hao Su, Kevin Harrington, Gregory Cole, Weina Lu and Gregory S. Fischer

***Abstract*— This paper presents the design of a magnetic resonance imaging (MRI) compatible needle steering system actuated by piezoelectric actuators for prostate brachytherapy and biopsy. Our guiding vision is to design a modular needle driver that can be coupled to a generic gross positioning stage to enhance MRI-guided prostate surgery accuracy and decrease operational time. After reviewing pertaining robot assisted needle driver systems in MRI, ultrasound and computed tomography (CT) environments, we articulate the design challenges and requirements of robotic system for close bore interventional MRI surgery. The paper presents a modular 3-degrees-of-freedom (DOF) needle platform coupled with a representative MRI-compatible 3-DOF $x-y-z$ stage. This system is proposed to serve as a slave robot to deliver radioactive seeds in an MRI-guided force feedback teleoperation framework. Moreover, it suffices to be a generic robot platform to provide the needle positioning and orientation task in a diverse array of proposed needle steering scenarios. With a kinematically parallel robot embodiment, the positioning module provides linear position control with high system rigidity. The modular needle driver simultaneously provides needle cannula rotation and independent cannula and stylet prismatic motion. The device mimics the manual physician gesture by two point grasping and direct force measurement of needle axial puncture and lateral forces by two fiber optic force sensors. The CAD model and the fabricated prototype are presented and the experiment with phantom trial is analyzed to demonstrate the system compatibility.**

Keywords: Optical Force Sensor, MRI Compatible, Haptic Feedback, Needle Driver, Prostate Needle Brachytherapy.

I. Introduction

Prostate cancer continues to be the most common male cancer and the second most common type of cancer in human. The estimated new prostate cancer cases $(192,280)$ in 2009 account for 25% incident cases in men [1]. The current "gold standard" transrectal ultrasound (TRUS) for guiding both biopsy and brachytherapy is accredited for its real-time nature, low cost, and apparent ease of use [2]. However, TRUS-guided biopsy has a detection rate as low as $20\% - 30\%$ [3] and the seeds cannot be effectively observed in image. On the other hand, MRI-based medical diagnosis and treatment paradigm capitalizes on the novel benefits and capabilities created by the combination of high sensitivity for detecting seeds, high-fidelity soft tissue contrast and high spatial resolution. The challenges, however, arise from the manifestation of the bidirectional MRI compatibility requirement - both the device should not disturb the scanner function and should not create image artifacts and the scanner should not disturb the device functionality [4]. Moreover, the confined physical space in closed-bore high-field MRI presents formidable challenges for material selection and mechanical design.

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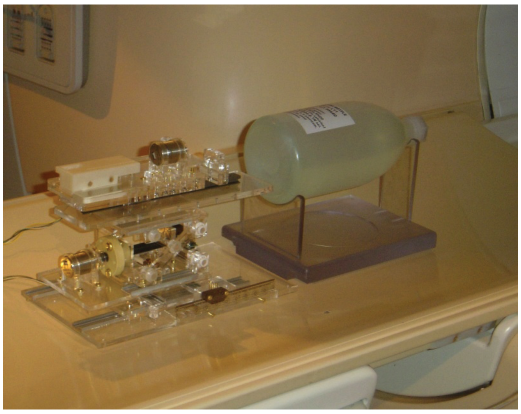

Fig. 1. The prototype robot in the bore of a 3T MRI scanner with a MRI-compatible phantom.

Needle steering becomes an interesting and practical technique to enhance placement accuracy which is deteriorated by needle insertion and tissue deformation in recent years. Bevel needle steering continues to flourish with the combined techniques of nonholonomic modeling and image guided feedback control. Mahvash et al. have [5] experimentally demonstrated that increased needle velocity is able to minimize tissue deformation and damage and reduce position error which is essential for prostate percutaneous therapy. [6] presented a cable driven 5-DOF manipulator with fault-tolerant needle driver for percutaneous needle insertion which functionally satisfies our motion requirement.

Tsekos, et al. [7] presented a thorough review of MRI compatible systems for image-guided interventions. Chinzei, et al. developed a general-purpose robotic assistant for open MRI [8] that was subsequently adapted for transperineal intraprostatic needle placement [9]. Krieger et al. presented a 2-DOF passive, un-encoded, and manually manipulated mechanical linkage to aim a needle guide for transrectal prostate biopsy with MRI guidance [10]. Stoianovici et al. described a MRI-compatible stepper motor and applied it to robotic brachytherapy seed placement [11]. The patient is in the decubitus position and seeds are placed in the prostate transperineally. More recently, the work by [12] and [13] has pioneered the design of teleoperation system in MRI environments.

In this paper, we present a 3-DOF needle driver equipped with fiber optic needle interaction force sensors as slave robot to provide haptic feedback. Fig. 1 shows a prototype robot in the bore of a 3T MRI scanner with a phantom. This paper is organized as follows: Section II describes the system requirement and design consideration. Section III presents the detailed needle driver design including the force sensing module, needle clamping mechanism, needle loading mechanism and Cartesian positioning module. The key contribution of this paper is the generic needle driver with novel clamping mechanism. Finally, a discussion of the system and future work is presented in Section IV .

II. Design Requirements

Besides the stringent MRI comparability requirements and space limit, the design consideration needs to address a couple of issues. First, we need to fulfill the functional requirements of needle insertion, while at the same time, the system should be able to provide simple procedure and practical in clinical application. From the surgeons' perspective, we want to mimic the manual procedure which is relatively uncomplicated [14] and easily adaptable. Some design requirements and methodology to address them are briefly described here.

1) Cannula rotation about its axis with cannula insertion. The independent rotation and translation motion of the cannula can increase the targeting accuracy while minimize the tissue deformation and damage.

2) Stylet prismatic motion to facilitate seed delivery.

3) Safety. Instead of using mechanical stop, the piezo-electric actuators as frictional motors are capable of creating $10N$ of force, when unpowered they can supply up to $16N$ of holding force per motor.

4) Compatibility. The frames of the robot are built up with acrylic. With limited amount of brass fasteners and aluminum rail, it should be compatible in the bore.

5) Operation in confined space. To fit into the scanner bore, the width of the driver is limited to $7cm$ and the operational space when connected to a base platform is able to cover the traditional TRUS 60 x $60mm$ temple. 6) Sterilization. Only the needle clamp and guide make contact with the needle and are removable and sterilizable.

III. Needle Steering System

Usually, a needle steering system requires insertion and cannula rotation motion. This task becomes more complicated for a MRI brachytherapy preloaded needle in terms of extra stylet translational motion to mimic the physician gesture that first move the cannula and stylet in a coordinated manner and then retract the cannula to deliver the seeds. Based on an early design of a force sensor [15] and a haptic system [16], [17], this section demonstrates an updated needle driver. This driver can be used for 3-DOF brachytherapy, 2 concentric pre-bent cannulas [18] or more generally 2-DOF needle steering.

The patient is positioned in the supine position with the legs spread and raised with similar configuration to that

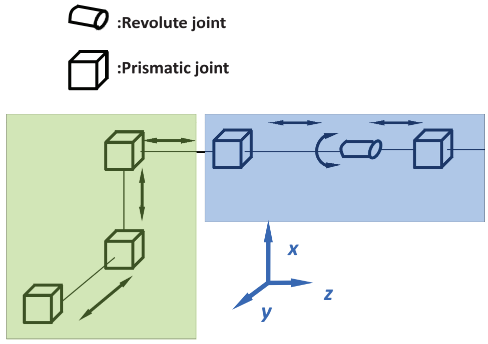

Fig. 2. Equivalent kinematic diagram of the robot: the green shaded is the gross Cartesian stage and the blue shaded is the needle driver.

of TRUS-guided brachytherapy. MRI bore's $60cm$ diameter constraint necessitates reducing the spread of the legs. Considering this configuration and the robot workspace, the width of the robot is limited to $7cm$ with two layer structure. The lower layer embedded with a linear piezoelectric motor drives the linear carriage and the upper layer provides cannulation rotation motion and stylet prismatic motion. This structure aims to minimize the "between-leg" space while the lower Cartesian stage takes advantage of the "under-leg" space.

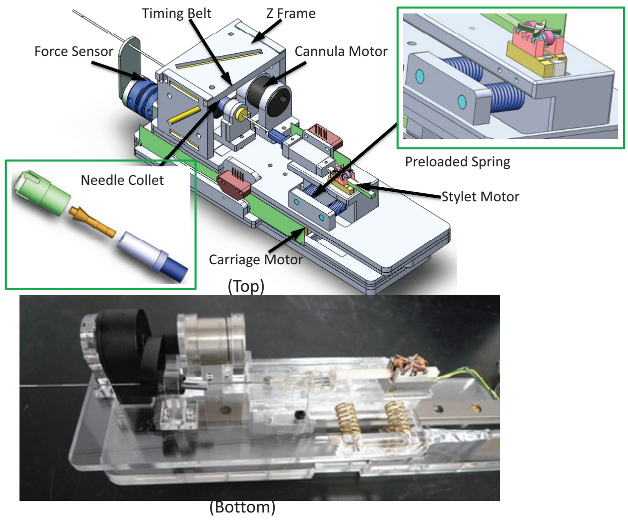

Fig. 3. (Top) CAD model of 3-DOF needle driver with the left corner depicting the universal clamping mechanism and the right corner depicting the needle loading mechanism and (bottom) needle driver physical prototype.

To create the force and motion in an MRI compatible system, we selected the piezoelectric motor (PiezoMotor, Uppsala, Sweden) and optical encoders (U.S. Digital, Vancouver, WA) with shielded differential signal lines [19]. A CAD model of the needle driver and the physical prototype are shown in Fig.3. The underlying mechanical design principle is to make the motion DOF decoupled and simplified. Since for preloaded needle brachytherapy, the needle cannula and stylet should be inserted and retracted independently. We follow the coarse to fine manipulation design method, and the kinematics of the system is shown in Fig. 2. The blue shaded is the needle driver which includes a revolute joint to perform needle rotation (discussed in subsection III-A) and two collinear prismatic joints to independently actuate the needle canula and stylet. The green shaded is the gross Cartesian stage with 3-DOF (discussed in subsection III-C).

A. Needle Rotation Mechanism

Rotation of the needle about its axis may be implemented to drill the needle in to limit deflection as described by Masamune, et al. [20] and Wan, et al. [21]. On the other hand, by taking advantage of the intrinsic asymmetry property of bevel needles, the needle driver may be used to steer the needle similar to traditional treatment for mobile robots and some mobile manipulators in [22]. Webster, et al. [23] explored the modeling and control of bevel steering techniques along trajectories defined using techniques described by Alterovitz et al. [24]. For different needles (brachytherapy and biopsy application), the rotation part can be the cannula for the brachytherapy needle or the whole shaft of diamond shape biopsy needle.

B. Force Sensing Module

We have developed a 3-DOF fiber optic force sensor that provides in-vivo measurement of needle insertion forces to render proprioception associated with brachytherapy procedure [16]. Even though the sensor can monitor axial force and two lateral forces, to guarantee fast and convenient needle loading, the sensor is connected with an offset plate to measure only the lateral forces at the needle tip. A separate 1-DOF sensor is used to measure axial insertion force. This setting is preferable than the design [6] that the needle assembly held an off-the-shelf 6-DOF hollow force sensor (not MRI compatible) by mechanical fastening. The latter design is difficult for needle loading because of the configuration of putting the needle through the center.

C. Cartesian Positioning Module

The modular needle driver is designed to work on a variety of platforms. We have developed a generic Cartesian positioning stage that may be used with it. To guarantee the MRI compatibility, the linear stage is mainly made of cast acrylic machined by laser cutter and some high strength plastics PEEK. The scissor structure can support the needle rigidly and ensure high stability. Each linear axis is constructed by linear slide and carriage (Igus, Inc., CT) which are made of anodized aluminum, a proven MRI compatible material.

This driver is modular for percutaneous intervention in the sense that it can be conveniently integrated with generic positioning stage like the Cartesian positioning stage that we have developed or orientation stage developed by our collaborator [25] which provides insertion pitch and yaw motion and is especially desirable to overcome pubic arch interference problem.

D. Universal Needle Clamping Mechanism

To design a needle driver that allows a large variety of standard needles to be used with the system, a new clamping device rigidly connect the needle shaft to the driving motor mechanism is developed as shown in the left corner of Fig. 3. This mechanism is a collet mechanism and a brass hollow screw is twisted to fasten the collet thus rigidly lock the needle shaft on the clamping device. The clamping device is connected to the rotary motor through a timing belt that can be freely fastened by moving the motor housing laterally. The clamping device is generic in the sense that we have designed 3 sets of collets and each collet can accommodate a width range of needle diameters. The overall needle diameter range is from $25Gauge$ to $7Gauge$. By this token, it can not only fasten brachytherapy needle but also biopsy needle or most other standard needles instead of designing some specific structure to hold the needle handle as those in [12].

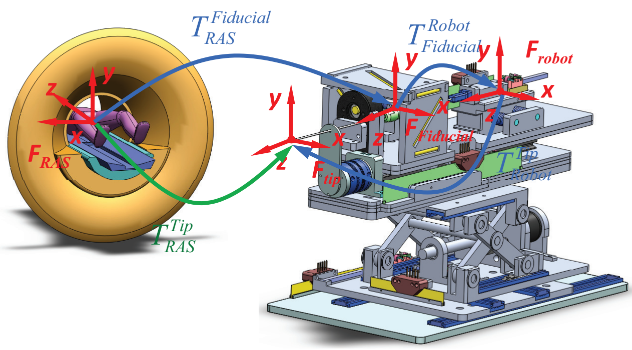

Fig. 4. Coordinate frames of the tracking system.

E. Needle Loading Mechanism

Once a preloaded needle or biopsy gun is inserted, the collet can rigidly clamp the cannula shaft. Since the linear motor is collinear with the collet and shaft, we need to offset the shaft to manually load the needle. We designed a brass spring preloaded mechanism shown in right corner of Fig. 3 that can provide lateral passive motion freedom. The operator can squeeze the mechanism and offset the top motor fixture then insert the loaded needle through plain bearing housing and finally lock with the needle clamping. This structure allows for easy, reliable and rapid loading and unloading of standard needle.

F. Tracking Module

To achieve dynamic global registration between the robot and image coordinates a z-shape passive tracking fiducial [26] is attached on the robot upper plate proximal to the needle tip for convenient imaging purpose (shown in Fig. 4). This Z-frame is capable of providing the full 6-DOF pose of the frame (the robot, with respect to the scanner) with any arbitrary transverse MR image slicing through rods. The end-effector location with respect to the fiducial frame is computed in terms of the kinematics and encoder positions and transformed to the representation in the image coordinate system.

IV. Discussion

We presented a novel needle driver and a plurality of MRI compatible mechatronic devices consisting of a optical force sensor and a linear stage. The needle driver can provide needle cannula rotation and stylet translation motion while the cannula translation is engendered by the 3-axis stage. The design is capable of positioning needle and increase the operation autonomy and thus reduce operation time.

Initial comparability test verified the system architecture and electrical setting. We are in the process of electrical test and building a fully functional prototype to evaluate the MRI-compatibility and targeting accuracy. This compatibility test with the same actuator [19] and control hardware in the scanner room has confirmed that no pair showed a significant signal degradation with a 95% confidence interval. A needle steering system in MRI environment is being tested. Detailed quantitative performance experiments and results would be reported soon.

After the building of physical prototype, a small amount of driver and stage deflection was observed. This could be addressed by replacing acrylic with more rigid plastics materials like PEEK. Because of needle-tissue interaction, needle insertion model (kinematic or dynamic model) should be considered to actively control the needle motion by steering or minor needle tip correction to enhance targeting accuracy with real-time MRI guidance.

V. Acknowledgements

This work is supported in part by the Congressionally Directed Medical Research Programs Prostate Cancer Research Program (CDMRP PCRP) New Investigator Award W81XWH-09-1-0191 and Worcester Polytechnic Institute internal funds. We are also grateful for the generous sample support from Igus, Inc (Providence, RI).

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