Preliminary Evaluation of Robotic Transrectal Biopsy System on an Interventional Planning Software

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***Abstract*— Prostate biopsy is considered as a definitive way for diagnosing prostate malignancies. Urologists are currently moving towards MR-guided prostate biopsies over conventional transrectal ultrasound-guided biopsies for prostate cancer detection. Recently, robotic systems have started to emerge as an assistance tool for urologists to perform MR-guided prostate biopsies. However, these robotic assistance systems are designed for a specific clinical environment and cannot be adapted to modifications or changes applied to the clinical setting and/or workflow. This work presents the preliminary design of a cable-driven manipulator developed to be used in both MR scanners and MR-ultrasound fusion systems. The proposed manipulator design and functionality are evaluated on a simulated virtual environment. The simulation is created on an in-house developed interventional planning software to evaluate the ergonomics and usability. The results show that urologists can benefit from the proposed design of the manipulator and planning software to accurately perform biopsies of targeted areas in the prostate.**

Keywords—MRI-guided intervention, prostate biopsy, intervention planning software, robot-assisted interventions

I. Introduction

MR-guided prostate biopsy (MRgPBx) has come out as a preferred method for detecting prostate cancer, and recent studies have shown it to provide better results than the conventional transrectal ultrasound-guided prostate biopsy [1]. MRgPBx can be performed in two ways. First, it can be used with an MR-compatible intervention system placed inside the MRI gantry with intraoperative MRI [2–4]. Secondly, it can be used with an MRI-ultrasound (MRI-US) fusion system, which fuses preoperative MR images with intraoperative ultrasound for guidance [5–7]. With either system, a probe is inserted into the patient's rectum, and a needle, guided through an inner compartment in the probe, is used to take tissue samples. MRgPBx may further benefit from controlled actuated motions of the transrectal probe which allows urologists to target prostate tissue more accurately. As a result, there has been a recent increase in the development of MR compatible robotic systems [8–14] that require special actuation mechanisms, such as piezoelectric motors [15–19] or pneumatic actuators [10, 11, 13], and supporting arms with steppers and encoders that can be used in an MRI-ultrasound fusion suite [8, 9, 14] that are either semi-automatically or manually controlled [15–19].

Hospitals may incorporate a transrectal MRgPBx system for prostate cancer diagnosis depending on (1) the availability of the MR scanner, (2) the type of actuation mechanism preferred in the MR scanner for MR-compatible MRgPBx, and (3) the cost associated with the clinical workflow. As a result, much of the transrectal MRgPBx is designed to work in a specific clinical setting and is not adaptable to changes applied to the aforementioned factors. Consequently, a modular and customizable system could assist various clinical needs of the hospital, offering a solution suitable for hospitals of different scales. To make the transrectal MRgPBx system modular, the work presents a preliminary design of a cable-driven manipulator, broadening its usage in clinical practice, with two key features: (1) compatibility with DC servo motors, piezoelectric/ultrasonic motors, and pneumatic actuation and (2) support for different transrectal probe designs and two modes of operation, that can be changed depending upon the patient's position (standard lithotomy, prone, or lateral position) and the location of the malignant tissue. To assess the usability of the manipulator, the work presents an initial evaluation of the manipulator for targeted transrectal MRgPBx in a simulated environment. An interventional planning software is implemented to simulate the planning required for the interventions during a prostate biopsy.

II. METHODS

A. The Manipulator

The cable-driven manipulator, depicted in Fig. 1, has four degrees of freedom (DoF): three rotations and one translation. Each DoF is actuated by the cable-driven mechanism which connects to shafts in the controller box. These shafts can be attached to other actuation mechanisms that depend on whether the manipulator will be used in an MR-ultrasound fusion suite or an MR scanner room. One can attach a transrectal probe to the manipulator distal end. In practice, the probe is first partially inserted into the patient's rectum. Then, the manipulator's distal end is adjusted manually so that the probe can be attached to it. This requires the adjustment of DoF-1 and DoF-2 to move the manipulator's distal end. Once the probe is attached, the interventional planning software is used to analyze and adjust the position of the probe inside the patient's rectum.

B. Software Simulating Interventional Planning Environment

The interventional planning software was implemented in C++ using the Visualization Toolkit Library (VTK) [20]. The interface provides an OpenGL widget for visualization of data in the form of a three-dimensional (3D) scene. All stereotactic planning parameters are adjusted through a graphical user interface (GUI) programmed using the Qt framework [21].

The urologist interacts with the planning software (shown in Fig. 2) through a set of GUI elements, comprised of sliders, checkboxes, and buttons, and with the 3D scene using the mouse buttons. The left button lets the physician rotate the camera, the middle button is used to pan the camera, and the mouse scroll is used to zoom in and out of the scene. The feedback text box is used to provide information on events and metrics. The right pane contains all the GUI elements used to modify the interventional planning parameters, known as the interaction

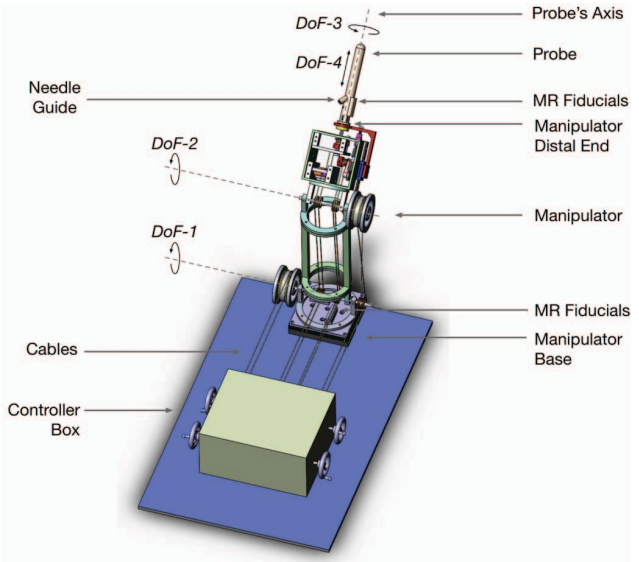

Fig. 1. Preliminary design of the cable driven manipulator used for transrectal MRgPBx. A detachable transrectal probe is attached to the manipulator's distal end. Actuation of the four DoF adjusts the probe inside the rectum.

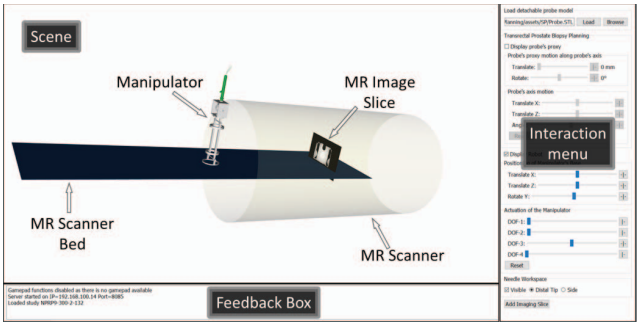

Fig. 2. Snapshot of the interventional planning software. The user adjusts the intervention planning parameters in the interaction menu, the visuals are rendered in real time in the 3D scene, and feedback on simulation events is provided in the feedback box.

menu. These interactions are further explained in their corresponding sections below. There are also GUI elements that let the physician hide/show certain visuals and render them only when needed. There are two types of data sets that the system can handle: triangular meshes and patient imaging data. The imaging data is loaded from the DICOM images using vtkDICOM, a module of VTK [22].

The 3D Scene: There are two types of rendered visuals in the scene: models, which render triangular meshes, and slices representing MR images. Each object in the scene is positioned and oriented with respect to the MR scanner coordinate system. The visuals rendered as part of the planning software are summarized in Table I. The MR scanner is represented by a cylinder with a radius of 60 cm and a length of 160 cm. It is used to orientate the physician with respect to the real MR scanner. The MR scanner bed can be translated in and out of the scanner. The base of the manipulator is fixed to the surface of the bed. The imaging data is always positioned and oriented with respect to the MR scanner's coordinate system where the origin is located exactly in the middle of the scanner. The location and orientation of the patient imaging data are obtained directly from the DICOM information. The probe is attached to the manipulator. For our studies, we are using a standard probe that is part of the preliminary design of the manipulator. The probe allows the physician to inject a biopsy needle which either comes out from its distal end or side. Once the probe is loaded, the system automatically creates a workspace defining the maximum reach of the probe's needle based on its DoF-3 and DoF-4 range. Additionally, a proxy position of the probe is also displayed (explained in section II.C).

TABLE I. INTERVENTIONAL PLANNING ENVIRONMENT

Simulated Entities	Purpose
MRI Scanner	Simulate the MRI scanner where the patient is laying
Bed	Simulate the bed where the patient is laying
Manipulator	The manipulator used to perform the biopsy
Probe	The probe inserted into the patient's rectum
Proxy	A ghost of the probe that can be freely moved to test probe placements
Imaging Data Slices	Imaging data from the patient
Probe Workspace	The workspace of the probe, i.e., the reach of the needle
Proxy Needle	A virtual needle used to simulate the real needle and rendered as part of the proxy

Imaging Data: Imaging data can be loaded directly from the DICOM medical format. The imaging data is in the form of 3D grid, and one plane in the grid represents a 2D slice, which is rendered in the scene. The physician can render multiple slices from the same or a different image set. Each slice of the data is uniquely identified by a slice index and its orientation: transverse, sagittal, or coronal. The selected slice is rendered relative to the MR scanner's coordinate system.

Additionally, each rendered slice is visualized on a separate window, which we call Slice Viewer, that provides a 2D view of the image. Fig. 3 shows a Slice Viewer displaying an MR image set. The urologist can hover over the image and obtain coordinate information about each pixel with respect to the MR scanner. The current slice index and orientation are shown in the bottom corners of the view. The physician can select the slice and orientation using the GUI controls above the view. Changing the slice and orientation will automatically change the rendered slice in the 3D scene, i.e., the rendered slice and the slice in the Slice Viewer are both synchronized. Thus, one can manipulate the rendered slice in the 3D scene using the Slice Viewer.

Probe: The probe is attached to the distal end of the manipulator and is inserted into the patient's rectum. The urologist can select from different probe designs. These probe designs are loaded into the system using the GUI by selecting the appropriate model. The designs are stored in STL, PLY, or OBJ 3D format.

Virtual Manipulator: The virtual manipulator represents the physical robotic manipulator in the simulated environment of the 3D scene. The DoF values are altered through the GUI elements in the interaction menu.

Probe's Proxy: The virtual manipulator in the interventional planning software will be synchronized with the physical manipulator. Thus, the values of the DoF computed on the software will be directly sent to those of the physical manipulator placed inside the MR scanner. To check whether a given configuration of DoF is achievable to target a region for biopsy, the physician is provided with a proxy of the probe. The proxy is rendered in yellow color and initially coincides with the probe's position and orientation when enabled. The GUI elements allow the probe's proxy to move and rotate in the same fashion as the probe. When the proxy is enabled, it is also visualized as projections on the slice viewers, which shows the intersection of the probe's proxy with MR images. This assists the physician to perform interventional planning in 2D and 3D space and test the positioning of the probe before moving the physical manipulator. If the probe's proxy position is valid, then only the actuation command is sent to the robotic manipulator. Fig. 4 shows the proxy's placement in the scene and the mark it makes on the slice viewer. Additionally, the proxy can be translated on the x- and z-axis relative to the manipulator and rotated along the manipulator's xz plane. When one of these three actions are executed, the manipulator tries to inversely adjust its DoF to attempt overlaying the probe onto the proxy. If the configuration can be achieved, the probe's color will remain green. If the configuration cannot be achieved because of constraints imposed by the DoFs, the probe's color will turn red and the manipulator will remain in its last valid configuration. The calculations made to check if the configuration is possible are explained in the following sub-section.

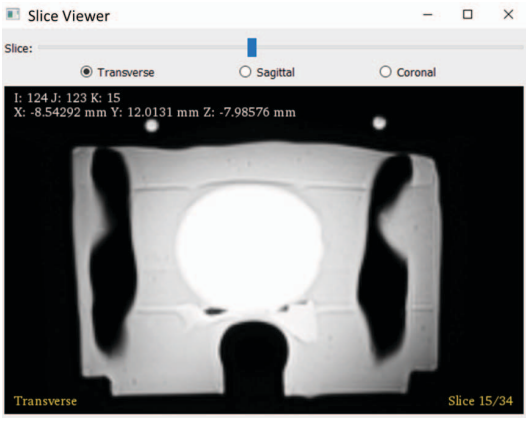

Fig. 3. Example of a *Slice Viewer* rendering a slice with index 15 out of 34 slices in transverse orientation from an MR acquired image of a phantom. The coordinate information shown is with respect to the placement of the cursor on the image.

C. *Probe's Proxy and Workspace Computations*

The manipulator can be adjusted through the GUI which allows the physician to set the probe in a certain position and orientation (defined by P_2 and $\vec{n}$). In many cases, it is desirable to instead place the probe (which behaves as an end-effector of the robotic system) in a certain position and orientation and check if the manipulator (i.e. robotic system) is able to achieve the given configuration by computing its DoF values with respect to a fixed base (P_0). To achieve this, the urologist is given a set of three sliders that translate and rotate the proxy with respect to the XZ axis of the manipulator. The position and angle of the proxy are then used to calculate the DoF values that the manipulator would need to overlay the probe onto the proxy. If these calculated values are within range of the DoF, the manipulator will automatically adjust itself (shown in Fig. 5) and update the GUI elements accordingly.

Fig. 6 depicts the values used from the manipulator and proxy's placement and orientation to compute the DoF values needed to meet the proxy's required configuration. Additionally, Table 2 gives information on the meaning of each variable used as part of the inverse kinematics equations. Using these variables, one can compute the values of DoF-1, DoF-2, and DoF-4. Note that the value of DoF-3 only rotates the probe along its z-axis which does not affect the manipulator when

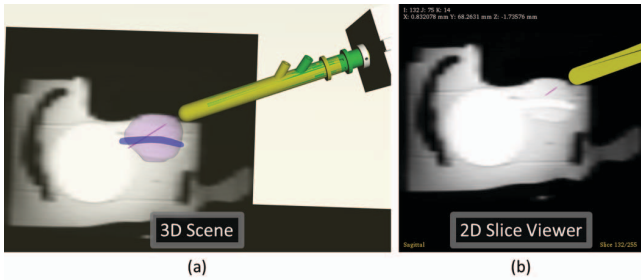

Fig. 4. Rendering of the proxy inserted into the patient's rectum as shown in (a) the scene and (b) the slice viewer with slice number 128 out of 255 in sagittal orientation.

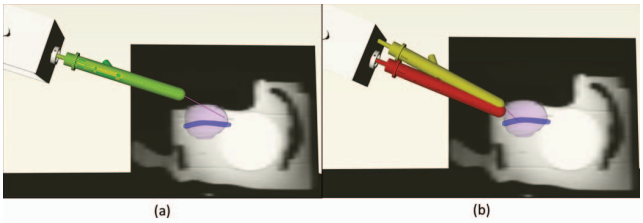

Fig. 5. Probe's proxy positioning in (a) an achievable configuration and (b) an unachievable configuration by the manipulator.

inversely trying to overlay the probe onto the proxy. The calculations are as follows:

$$P_1 = P_2 - \vec{n} * L_2 \quad (1)$$

$$L_1 = \|P_1 - P_0\| \quad (2)$$

Substituting (1) into (2) yields:

$$L_1 = \|P_2 - \vec{n} * L_2 - P_0\| \quad (3)$$

Equation (3) is expanded to form a quadratic equation. The manipulator's configuration is only possible when the solutions to the quadratic equation are real, positive, and within the range of the possible values of L_2, i.e., the smallest positive result that is less than the maximum permissible distance between P_2 and P_1. Then, P_1 can be calculated by substituting L_2 into (1).

The probe's workspace is defined by the needle's reach based on DoF-3 and DoF-4. This is visualized by a span of translucent needles. The workspace is useful to assess the current values of DoF-1 and DoF-2 as it lets the physician know whether the region of interest can be reached under that configuration. If so, the urologist can proceed to adjust DoF-3 and DoF-4 accordingly.

III. Experimental Studies

A. Experimental Setup

The usage of transrectal robotic manipulator for targeting lesions inside the prostate was assessed in the virtual simulated environment of the interventional planning software. Studies were designed to measure easiness for the urologist to target the region of interest by adjusting the manipulator's DoF.

A study was conducted with eight subjects with no previous knowledge of the software. The subjects comprised of researchers working in the field of image-guided interventions with both clinical and/or engineering background. Each subject was given a training guide to be familiar with the software and its interface. During training, subjects were asked to use the software to adjust the camera, adjust the manipulator, adjust and maneuver the proxy, and familiarize themselves with the orientations of the 3D scene. When the subject felt comfortable with the usage of the software based on their input, the study was initiated.

Subjects were asked to plan a biopsy such that the needle always follows a specific trajectory to hit a designated target. In practice, this is never the case as the region of interest for biopsy can be approached through different trajectories.

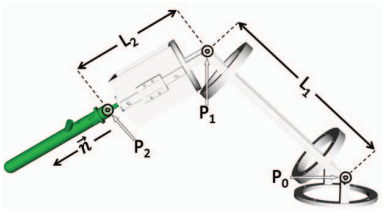

Fig. 6. Visual representation of the probe positioning parameters. The positions are measured with respect to the MR scanner coordinate system.

TABLE II. Probe Positioning Parameters

Variable	Description
$\mathbf{P_0}$	DoF-1 position
$\mathbf{P_1}$	DoF-2 position
$\mathbf{P_2}$	The position of the proxy
$\mathbf{L_1}$	The length of the arm
$\mathbf{L_2}$	The distance between P_1 and P_2,
$\vec{\boldsymbol{n}}$	Unit vector representing the probe's proxy direction

However, during this study, if it can be demonstrated that the urologists are able to plan a biopsy for a specific target using a unique trajectory, it will assist in evaluating the usage of the manipulator on the intervention planning software for MRgPBx.

To quantify the study, a needle trajectory (passing through the prostate region on MR images) was defined as a target. The objective of the subjects is to adjust the four DoF to overlay the probe's needle, which is rendered as part of the proxy, on top of the target needle as close as possible. In other words, the closer these two needles are, the more accurate the participants have achieved the objective. Two metrics were used to determine the accuracy. The first metric is the distance between the rear end of the target needle and the rear end of the proxy's needle. The second metric is the angle between the two needles, i.e., the angle of the direction vectors between the two needle trajectories. In theory, if the subject was to have an accuracy of 0 mm distance and 0° angle, the placement of the needle would be perfect. In reality, this is nearly impossible, so threshold values were set. For our studies, an accurate placement would require a distance less than 1.0 mm and angle less than 1.0°. Fig. 7 shows a geometric representation of how these two metrics are calculated.

Additionally, time was recorded for each subject to achieve an accuracy within the aforementioned thresholds. The metric values were computed in real-time as the participant interacted with the proxy and were displayed in a label on the top right corner of the scene. Each subject performed three trials for each of the two modes. For all the trials, the base of the manipulator was pre-placed on the bed which had at least one possible configuration to accurately overlay the proxy's needle on the target.

B. Results

The times and accuracies recorded are summarized in Fig. 8. Based on these results, we can conclude the following:

- The time required for interventional planning on the software by the subjects improved as more trials were

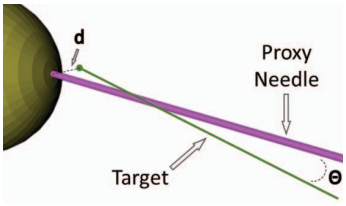

Fig. 7. The accuracy of the user's actions is quantified by the distance between the needles' heads denoted as d and the angle between the needles denoted as Θ.

completed. The pattern was observed for six subjects where the average time was reduced on average by 62% after trial 1 for Mode-I, whereas Mode-II showed no apparent improvement for subsequent trials.

- Subjects were able to achieve higher accuracy for Mode-II (Mode-I average distance was 0.82 mm and angle 0.60 degrees whereas Mode-II average distance was 0.64 mm and angle 0.68 degrees). However, it took more time for Mode-II (average time 188 s) as compared to Mode-I (average time 159 s).

The following trends were also observed during the trials:

- Subjects who relied mainly on the accuracy rendered as a textual label completed the trials faster over those who relied mainly on the visuals.
- Subjects who did not modify the perspective of the 3D scene took significantly longer
- Subjects who used the probe's proxy positioning completed the trials faster
- Subjects who had previous experience interacting with 3D space using a mouse as an input device were faster

Based on these observations, it is clear that the subjects would need improved training session and familiarization with the software to improve the speed and accuracy of these trials. Nonetheless, all participants were able to complete the tasks under the required accuracy, which shows that the proposed manipulator of the transrectal prostate biopsy system along with the interventional planning software has the potential for safe prostate biopsy interventions.

IV. Discussion

We note that the studies we present here are not completely representative of the manipulator's deployment and use in an actual clinical setting. These studies were performed to assess the usability of the interventional planning software which is to be used as an interface between the urologist and the real manipulator. Hence, we performed this study under the scenario of an interventional paradigm that required as high an accuracy as possible to access the targeted location following a specific trajectory. We plan to investigate other scenarios of the interventional planning software before interfacing it with the real manipulator. More studies need to be conducted to document the extent of the device's flexibility to access different locations and anatomies of the prostate with different types of patients. These studies will be conducted with collaborating urologists with different levels of expertise. Additionally, certain constraints, such as the patient's position, will be considered as constraints for the manipulator's adjustments applied by the urologist. These studies will include an interactive training session to ensure that the urologists understand and master the manipulator's kinematics, its workspace, and the interventional planning software resulting in more reliable feedback.

In addition, part of our future work entails the development of interventional planning using augmented reality as an extension of our current interventional planning software. By visualizing the 3D scene in true 3D using holographics, we can immerse the urologist into the patient's data to make biopsy planning more intuitive and interactive. Works in other clinical settings have shown that the use of holographic augmented reality, such as in [23–25], can facilitate the work performed by physicians for the preparation and execution of interventions.

V. Conclusion

The use of MR compatible robotic systems for MRgPBx is emerging and progressively establishing itself as a preferred method over the conventional transrectal ultrasound-guided prostate biopsy. However, most MRgPBx systems are tailored to a specific clinical setting, workflow, and logistics. In this work, a cable-driven manipulator is proposed that is adaptable to operate with both MR-compatible interventional systems and MR-ultrasound fusion systems. We show that the designed manipulator can provide accurate positioning and orientation for MRgPBx using the described interventional planning software. Additionally, we demonstrated that using the interventional planning software in conjunction with the preliminary design of the manipulator can offer urologists the freedom to perform safe biopsies in a timely and ergonomic manner.

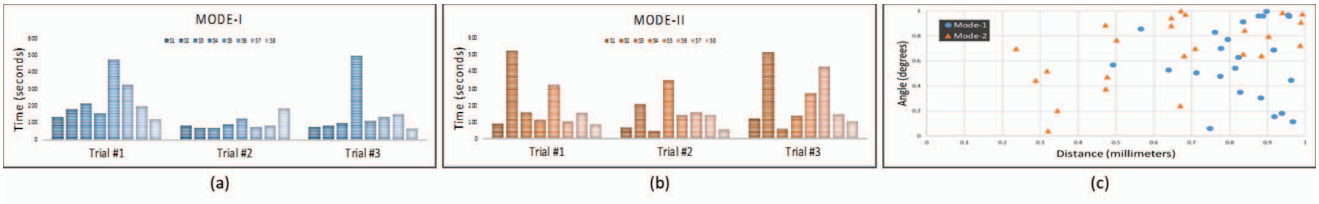

Fig. 8. Results of experimental studies conducted with eight subjects: (a) and (b) Time required by the subject to reach an accuracy within the threshold for Mode-I and Mode-II, respectively. (c) Measured accuracy between the angle (in degrees) against the distance (in millimeters) for both modes.

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