MR-Compatible Robot for Needle-Based Prostate Interventions

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INTRODUCTION

Prostate cancer is the most common type of cancer worldwide and the second leading cause of death from cancer in men [1]. Early detection and treatment are of significant importance in reducing mortality rate. The common clinical practice for prostate cancer diagnosis is the transrectal ultrasound (TRUS)-guided biopsy. However, an early stage prostate cancer usually cannot be visualized in ultrasound images. On the other hand, an enhanced visualization of an early stage prostate lesion is possible using Magnetic Resonance (MR) imaging. However, MR-guided prostate interventions face several challenges, such as space constraints and electromagnetic compatibility requirement of clinical tools. MR-compatible robotic systems have been proposed to facilitate MR-guided prostate biopsy. These systems can be divided in two groups based on whether the needle is inserted manually [2] or autonomously [3]. In the first group, the robot controls the position of the needle guide and the clinician manually inserts the needle. Whereas in the latter, the guide is robotically positioned and the needle is autonomously inserted. Previous studies using robotic systems for MR-guided prostate interventions were performed in open-loop and needle deflection was not considered.

This work presents a novel robotic system for transperineal prostate biopsy under MRI guidance. The device has 9 degrees-of-freedom (DoF), allowing needle insertions in various directions and a fully autonomous operation (Fig. 1), integrated with a new pre-operative path planning, a steering controller and a needle tracking system.

MATERIALS AND METHODS

The requirements for a robot-assisted transperineal prostate biopsy are defined based on clinical inputs. The workspace is defined by the anthropometric data of a patient in semi-lithotomy position. The robot must be capable of inserting, rotating and firing a biopsy needle (MR-Clear Bio-Cut, Sterylab, Milan, Italy) clinically-approved to be used in the MR scanner. The maximum allowed targeting error is set to be 2.5mm, which is determined based on the smallest clinically significant tumor in pathology (diameter of 5mm) [4].

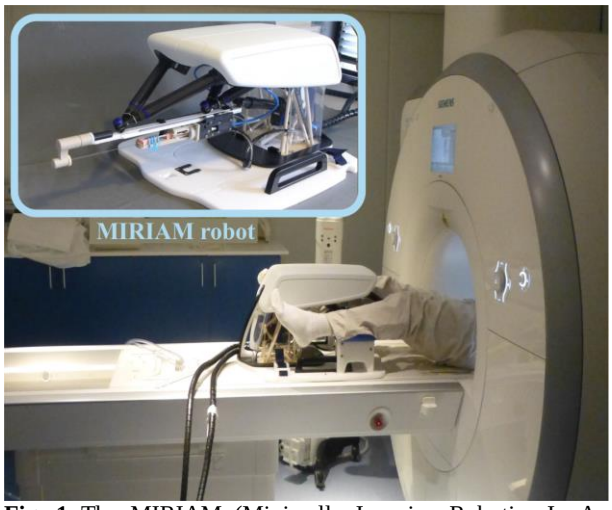

Fig. 1 The MIRIAM (Minimally Invasive Robotics In An MRI environment) robot is a 9 degrees-of-freedom magnetic resonance (MR)-compatible system designed for transperineal prostate biopsy. The system is capable of inserting, rotating and firing a biopsy needle to collect tissue samples.

The MIRIAM (Minimally Invasive Robotics In An MRI environment) system consists of a 5 DoF parallel robot to position and orientate the biopsy needle (Fig. 2) and a 4 DoF needle driver to insert, rotate and fire the biopsy needle. The needle driver inserts and rotates the needle using piezoelectric motors and fires the biopsy needle using pneumatic actuation. The needle driver is primarily designed for prostate biopsy, but it can be modified for other clinical applications, such as brachytherapy or cryotherapy. The 5 DoF parallel robot contains 5 adjustable length rods, which allow for the translation of the needle guided in all three Cartesian axes and also two rotations. Each rod is actuated by a piezoelectric motor (HR2, Nanomotion, Yokneam, Israel). The robot provides maximum translational motion for the needle guide of 24 mm, 70 mm and 130 mm in *x*, *y* and *z* direction, respectively (Fig. 2). The robot also allows rotations of ±15° around the *y*-axis and rotations between 5° and -15° around the *x*-axis. This workspace guarantees that the robot is able to place the needle guide along the perineum and the needle can reach any point within the prostate even considering the variation in its size and location among individuals.

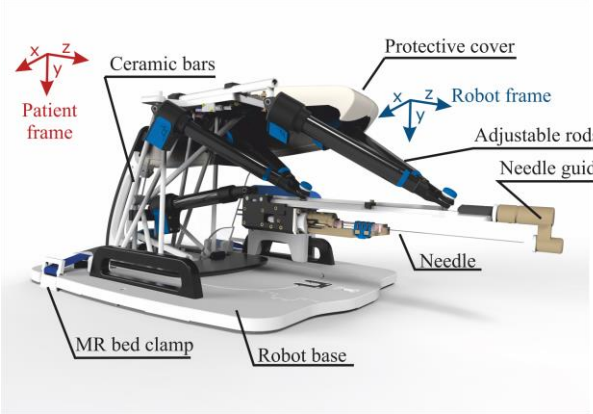

Fig. 2 Magnetic Resonance (MR)-compatible robot for prostate biopsy and its principal components. The x-, y- and z-axis correspond to the Axial, Coronal and Sagittal planes, respectively.

The location of the suspected prostate tumor (target) is selected by the clinician in the pre-operative MR images of the prostate. The pre-operative planner defines the best entry point using a needle deflection model and the information about the insertion environment, such as obstacles and target locations. The pre-planned path is used by the steering controller during the insertion.
The system divides the insertion in iterative steps of fixed insertion depths (typically 10mm). An MR scan is performed at the end of each step. Our tracking system processes MR images and estimates the needle tip position and orientation. A needle steering controller computes thousands of paths from the current needle tip until the target location. The sequence of needle rotations that minimizes targeting error and needle rotations is chosen. This process is repeated until the target is reached. The clinician can also tele-operate the needle insertion depth using a haptic interface located within the control room, while the system autonomously controls the needle rotation.

RESULTS

An MR compatibility analysis is performed by calculating the signal-to-noise (SNR) ratio in different conditions (baseline, robot off, robot on and motors running) [3] and calculating a deterioration factor as defined by Stoianovici [5]. The analysis is performed in an MRI Scanner MAGNETOM Aera (Siemens AG, Erlangen, Germany) using T2 Turbo Spin Echo (TSE) imaging protocol. The SNR drops 16% when the robot is placed inside the scanner and drops 25% when the robot power is turned on. In the last configuration, the SNR reduces 27% when the insertion and rotation motors are running. For the deterioration analysis, the deterioration factors are always lower than the limit of 1%, which means that our system does not induce any interference perceivable by radiologists. The targeting accuracy is evaluated in six needle insertions performed in the same MRI scanner. A clinically-approved 18-gauge is inserted towards physical targets with a radius of 2mm, embedded in a gelatin soft-tissue phantom.

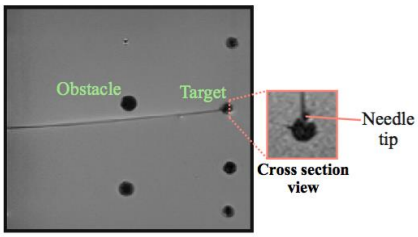

Fig. 3 A coronal magnetic resonance image of one representative insertion. The inset figure shows the cross-sectional view of the final needle tip position.

The targeting error is defined as the Euclidean distance between the final needle tip position and the center of the target. The average targeting error is 1.86mm with a standard deviation of 0.48mm. A representative insertion is presented in Fig. 3.

DISCUSSION

In this study, we present an MR-compatible robotic system for needle-based interventions in the prostate. The image distortion analysis indicates that the robot does not induce any visible deterioration in the image. The needle steering experiments show an average targeting error of 1.86mm, which is 0.64mm less than the desired accuracy defined in the system requirements. Different issues can impact the targeting accuracy, such as target motion and variations of the amount of needle deflection. However, real-time target tracking and online curvature estimation can mitigate these factors and reduce even more the targeting error. Future work will focus on implementing a real-time MR imaging protocol. Additionally, it is planned to perform experiments in biological tissues and cadavers.

ACKNOWLEDGEMENT

This research was supported by funds from the Dutch Ministry of Economic Affairs and the Provinces of Overijssel and Gelderland, within the Pieken in de Delta (PIDON) Initiative, Project MIRIAM.

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