Design and Characterization of a Multiple Needle Insertion MRI-guided Robot for Irreversible Electroporation (IRE) Treatment

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Abstract—Irreversible electroporation (IRE) is a promising tumor treatment that uses an electric field to kill tumor cells. During treatment, 2-6 needles are inserted around the tumor, preferably placed in parallel and located at the same depth. This allows the electric field to be effectively distributed across the cell to destroy tumors. In this paper, we present a body-mounted, four degrees of freedom robot (140 mm × 147 mm × 113 mm), that assists multiple needle placement under Magnetic Resonance Imaging (MRI) guidance. The robot and the actuator can be classified as an MR safe system, where the material composition consists of non-metallic, non-magnetic, and non-conductive material to allow safe operation inside the MRI scanner. The accuracy of the robot was evaluated, and the maximum translation error was 0.72 ± 0.26 mm on the horizontal axis and 1.60 ± 0.75 mm on the vertical axis. The compatibility of the robot with MRI was evaluated and no artifacts or changes to the signal-to-noise ratio were observed in the MRI images. The proposed robot was able to cover the target tumor area and supports the placement of multiple needles for IRE treatment.

I. INTRODUCTION

Several modalities have been developed for the minimally invasive treatment of liver tumors. Cryoablation, microwave ablation, and radiofrequency ablation are popular treatments for larger tumors as an alternative to surgical resection [1]. However, there are some disadvantages to these techniques. For example, vital structures near the liver (vessels and bile ducts) can be damaged [2] and local blood flow can cause heat to dissipate in larger vessels, which may lead to incomplete ablation [3].

Irreversible electroporation (IRE) is a non-thermal ablation technique that has shown promising results in treating liver tumors. IRE applies sufficiently high electric fields to tumor cells, which induces a permanent opening to the cell membrane and leads to cell death [4]. IRE has several advantages over other tumor treatments, including the preservation of vital structures from thermal injury and the avoidance of the heat sink effect [5].

An important part of IRE is the positioning and placing of needles into the tumor [6]. Multiple needles are required and these need to be placed in parallel and at equal depth for effective tumor ablation [7]. In small tumors (<3 cm), two needles are enough for tumor ablation, but for larger tumors (>3 cm), up to six needles may be required [8]. These needles must be accurately placed for complete removal of the tumor [9].

There has been a growing interest in using robots together with magnetic resonance imaging (MRI) to accurately place needles [10]. An advantage of this technique is that the robot can be adjusted inside the MRI bore to achieve accurate needle placement. This may reduce the number of times the patient needs to be in and out of the MRI bore for needle adjustment which expected to significantly reduce the procedure duration. In addition, specific MRI sequences can be used to measure the radius of the electric field during tumor treatment, which may help predict the tissue ablation coverage as a result of IRE [11].

The MRI safety of the robot should be identified clearly
before it can be used in the Magnetic Resonance (MR) environment. According to the ASTM F2503 standard, the safety of medical devices can be labeled into three categories: MR safe, MR conditional, and MR unsafe. Based on this classification, the robot material should be carefully selected in the design process in order to build an MR safe robotic system.

How the robot is fixed and mounted should also be considered. The robot can be fixed to a table, floor, or scanner bed. This provides a rigid platform and allows the robot to be directly registered to the scanner workspace, which improves the accuracy of needle positioning. A commercial computed tomography (CT)-guided robotic system (Maxio, Perfint Healthcare, USA) offers a straightforward solution for needle insertion, increasing needle placement accuracy compared to manual placement of IRE probes [12]. However, movements that may occur during insertion due to organ motion or tissue deformation may need to be corrected manually, increasing the procedure time.

Another option is to mount the robot to the patient’s body, where the robot is fixed directly to the patient’s skin or MRI coil. In this way, the robot moves together with the patient, which is less vulnerable to misregistration of the guidance image due to organ motion.

Several patient-mounted robots have been developed for percutaneous intervention. A shoulder-mounted robot with four degrees of freedom (DOF) [13], had two identical stages that implemented a scissor mechanism to achieve a large workspace within a compact model. Hungr et al. developed light puncture patient-mounted robot with a workspace of 135 mm × 120 mm [14]. This five DOF robot inserted needles into thoracic and abdominopelvic regions under CT and MRI guidance. Li et al. developed a fully actuated six DOF robot with needle alignment and a needle driver module that assisted injection into the lower back with a workspace of (♂80 mm) [15].

Although various patient-mounted robots with a large workspace have been developed, most of these systems do not support multiple needle insertion. Wu et al. developed a compact patient-mounted robot that supported the insertion of multiple needles [16], but only through a single entry point. Using this system for the case of multiple needle entry points would require an adjustment step for each insertion. He et al. developed small patient-mounted robots that could treat multiple tumors in different locations [10]. However, this system was not suitable for treating larger tumors where multiple needles have to be inserted close together. The minimum distance between the needles is limited by the robot dimension, since the insertion of multiple needles was accomplished by using several robots.

In our study, a patient-mounted robot has been developed that can support multiple needle insertion for IRE treatment of tumors in the liver, pancreas, and abdomen area. The proposed system can position multiple needles using a single device with a large workspace (♂119 mm), and offers a solution to the multiple entry points and the electrode minimum distance problem seen in previous robot designs. The robot and actuators were made using MRI compatible materials, enabling the robot to operate under the MRI scanner. We validated the performance of the proposed robot and the compatibility of the robot material with MRI.

II. METHODOLOGY

A. Robot Design Requirements

The main goal of the proposed robot is to help clinicians position electrodes under MRI guidance. To achieve this goal, the following points were considered when designing the robot:

1) Robot components made using nonmetallic, nonmagnetic, and non-conductive materials
2) Actuators can operate safely inside the MRI
3) The robot is not too heavy, especially for the patient-mounted model
4) The robot is compact enough to meet the dimensional constraints of the MRI bore
5) The robot has enough space to accommodate insertion of multiple needles

The robot was designed to operate within a Magnetom Aera 1.5T MRI scanner (Siemens AG, Munich, Germany) with an open-bore design and a 700 mm diameter. The robot was secured directly to the patient’s body using belts that were connected to the table and the strap slots in the base of the robot. The robot was mounted on the abdominal area, so needed to be less than 350 mm high. A robot width of less than 200 mm was chosen based on the median abdominal diameter of men and women [17].

Moir et al. [18] showed that IRE can treat a tumor size of 1-7 cm. To cover the minimum tumor size, the robot must be able to position the needle with an error of less than ±5 mm. To achieve complete tumor ablation, a safety margin of 5-10 mm should be considered during IRE treatment [19]. Therefore, the robot workspace should cover the maximum tumor size as well as an additional safety margin (♂90 mm). The electrodes should be placed parallel to each other, although small deviations may be required to place all electrodes in the desired position. IRE protocol allowed for a maximum angulation of 10° to ensure a homogeneous distribution of the electric field [20].

B. Overview of Robot Structure

The robot components were 3D printed with Makerpoint Ultimaker Tough PLA material (Makerpoint Holding, Wageningen, The Netherlands) and were fixed together using nylon screws and bolts. These materials were chosen because they are lightweight and MRI compatible. After all components were assembled, the robot had a total weight of 240 g and dimensions of 140 mm × 147 mm × 113 mm. The DOFs and dimensions of the robot prototype are shown in Fig. 1.

The robot was designed to guide the simultaneous insertion of two electrodes at a fixed distance of 10-25 mm. A multiple needle holder in the robot ensured parallel placement of the electrodes (Fig. 1). The distance between the electrodes must be at least 10 mm and not exceed 20-25 mm.
for optimal treatment [21], [22]. If more than two electrodes are required, they can be inserted in sequence, following a planned path to avoid collision of the electrodes with the robot frame.

The robot had four pneumatic motors, each of which provides actuation to four separate joint states $q_1$, $q_2$, $q_3$, and $q_4$, as shown in Fig. 2. Motor $q_1$ provides translation along the $x$ axis (1st DOF). Motor $q_2$ and $q_3$ are mounted in parallel to provide translation along the $y$ axis when moved together (2nd DOF) and rotation around the $x$ axis when moved differentially (3rd DOF). Finally, motor $q_4$ provides rotation around the $z$ axis (4th DOF).

Joint movement in the robot was actuated using pneumatic stepper motors [23] that were produced at the University of Twente. The motor was 3D printed with Stratasys Objet Eden260 (Stratasys Ltd., Eden Prairie, MN, USA) using FullCure720 material. The motor was moved using a double-acting cylinder that was controlled by four pneumatic tubes made of a polyurethane. In this prototype, two types of motors were used: a linear motor and a rotational stepper motor. The resolution of the motor depends on the size made of a polyurethane. In this prototype, two types of motor. The orientation change $\theta$ used to derive the forward kinematics.

C. Forward Kinematics

Two intermediary variables $\theta$ and $d_{\text{target}}$, (Fig. 3), were used to derive the forward kinematics. $\theta$ represents the change in orientation around the $x$ axis due to $q_2$ and $q_3$, while $d_{\text{target}}$ is the needle translation movement along the $y$ axis at $z = 0$. Other variables, such as the horizontal distance between the center of the top motor and the needle position ($d_{\text{needle}} = 26$ mm), the vertical distance of $q_2$ and $q_3$ ($l_{\text{motor}} = 40$ mm), and the vertical distance between the target at $z = 0$ and $q_3$ ($l_{\text{target}} = 51.9$ mm), were derived from the dimensions of the robot prototype.

The orientation change $\theta$ can be written in terms of $q_2$ and $q_3$ by:

$$\theta = \arctan2 \frac{q_3 - q_2}{l_{\text{motor}}}.$$  (1)

Furthermore, $d_{\text{target}}$ can be calculated by extrapolating the line made by two points ($\bullet$, $q_2$, $l_{\text{motor}} + l_{\text{target}}$) and ($\bullet$, $q_3$, $l_{\text{target}}$) to the reference target plane at $z = 0$.

$$d_{\text{target}} = \frac{l_{\text{target}}}{l_{\text{motor}}} (q_3 - q_2) + q_3.$$  (2)

Finally, the mapping from the actuator space to the end effector space is given by the transformation matrix $T_{ee}$. This transformation matrix can be derived by compounding the transformation for each degree of freedom, including the insertion motion:

$$T_{ee} = T_{q_4} T_{d_{\text{target}}} T_{\theta} T_{q_2} T_{q_3} T_{\text{insert}}.$$  (3)

where $I$ is a $3 \times 3$ identity matrix, $T_{\text{insert}}$ is the needle insertion degree of freedom (manually performed), and the rotation matrices are given by:

$$R_{q_4} = \begin{bmatrix} \cos q_4 & -\sin q_4 & 0 \\ \sin q_4 & \cos q_4 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad R_{\theta} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \theta & -\sin \theta \\ 0 & \sin \theta & \cos \theta \end{bmatrix}.$$

D. Workspace Analysis

The robot workspace is limited during operation by the motion of the pneumatic stepper motor and collision of the needle with the robot frame at the target plane ($z = 0$). Using...
forward kinematics, the boundary of the workspace can be calculated by substituting \( q_1, q_2, q_3 \) and \( q_4 \), which gives a cone-shaped boundary.

The cone-shaped robot workspace has a top diameter of 119.18 mm for electrode insertion on the skin and becomes larger depending on the depth of the electrode. The robot can also support a large insertion angle normal to the skin surface, with a maximum tilt of 32.3°. With proper placement on the patient’s body, the robot workspace is large enough to cover the maximum tumor size, including the safety margin for IRE treatment (>90 mm), and the maximum angulation for the electrode (>10°) as discussed in Section II-A.

III. EXPERIMENTS AND RESULTS

The robot was controlled using Robot Operating System (ROS) Melodic in Ubuntu 18.04 operating system. The needle trajectory was calculated using the ROS MoveIT package. By providing the position of the target, MoveIT calculated the inverse kinematics of the robot while preventing collision of the joint position. After obtaining the joint position, Arduino Mega 2560 was used to activate the pneumatic valve and actuate the pneumatic motor into the desired position. Open-loop control was used to move the pneumatic motor based on the motor step.

A. Needle Accuracy Test

Accuracy of the robot in free air was tested by inserting a needle into the target points as depicted in Fig. 4. We opted to use only a single needle in this accuracy test, as the additional needles will move together due to the rigid connection to the needle holder. The positioning error of one needle should not differ compared to multiple needles, since the motion between the needles are relative to each other. Error is mainly introduced by the fabrication accuracy of the multiple needle holder which is 3D printed with submillimeter accuracy.

The robot was set to start at position T4 (the center of the robot coordinate) before moving to the other target points, from T1 to T8. The needle was inserted 15 times for each target and a variety of needle insertion orientations were also evaluated. In the first experiment, the needle was inserted parallel to the \( z \) axis. In the next experiment, the needle angle was increased incrementally by 5° until a maximum angle of 25° in the \( x \) direction.

Accuracy values of the robot are presented in Table I. In a parallel position, the robot accuracies were 0.21 ± 0.14 mm for the \( x \) axis and 0.70 ± 0.50 mm for the \( y \) axis. We also found that the error increased in the direction of needle orientation. For instance, the position error in the \( y \) axis increased as the needle angle increased. This can be explained by the number of motors that were used to achieve the target position. On the axis where the orientation is given, two stepper motors were needed to control the needle tip, while on the other axis, only one motor was needed.

The accuracy in the \( z \) direction was not reported because the needle was inserted manually. This was intended to mimic the clinical procedure. Robot actuation is used to guide the needle to the desired position, and the clinician should be the one who has full responsibility and control over the insertion process due to regulation and safety concerns.

B. MRI Accuracy Test

We tested the ability of the robot to target several tumors in a triple modality 3D abdominal phantom (Model 057A; CIRS Inc., Norfolk, VA, USA) under MRI guidance. The robot was placed on top of the phantom, which left enough space inside the MRI bore. Fish oil capsules were used as fiducial markers on the phantom (four capsules) and robot (three capsules). The T2 sequence was used to obtain MRI images. The initial scan was performed with an image dimensions of 768 × 768 × 192 pixels and image spacing of 0.49 mm × 0.49 mm × 1 mm. From this scan, several important objects were segmented from the phantom, including: phantom shell, liver, tumors, and fish oil markers, using 3D Slicer software [24].
In Slicer, these objects were manually segmented using pixel intensity information as a guidance for object region and boundaries. Segmentation quality was improved using the painting tool to refine the object selection. These segmentations were exported to STL files and used for robot registration. Fiducial registration wizards from the SlicerIGT module [25] were used to register the segmentation files from MRI images to the robot coordinates.

Four tumors were selected as targets from the phantom. The accuracy of needle insertion in the axial and coronal planes was assessed. Robot inverse kinematics was used to calculate the required joint positions, using the center of the tumor as the target point. The needles were manually inserted, and the MRI images of the phantom were taken to evaluate the result.

Insertion results are shown in Fig. 5. The distance between the needle tip and the tumor center was measured using 3D Slicer. In the coronal plane, the insertion error was 2.53 ± 2.56 mm. In the axial plane, the accuracy was lower with an error of 8.73 ± 1.95 mm.

The error we observed during registration of the robot and MRI images may have contributed to the higher error observed in this experiment compared to the accuracy test result. Our finding that deeper tumors have a higher error than tumors located closer to the skin surface indicates that error in needle orientation increases as the target deepens. Needle deviation might also occur because of tissue compression deformation, and may contribute to the error.

C. Image Quality Testing

The image quality test evaluated the effect of the robot on the quality of the MRI images. In this test, the robot was operated inside a Magnetom Aera 1.5T MRI scanner. A standard Siemens 1900 ml phantom plastic bottle (model# 8624186; 3.75 g NiSO₄ × 6H₂O + 5g NaCl) next to the robot was used to check the homogeneity of the MRI images. Three operating conditions were set for the experiment. Scans were performed in three ways: (1) with a phantom only as a control image, (2) with a phantom and robot in the OFF state, and (3) with a phantom and robot in the ON state.

Two image sequences, T1 and T2, were used during the test. The images for both sequences had a field of view of 320 × 320 × 20 with a voxel size of 0.625 mm × 0.625 mm and a slice thickness of 3.5 mm. The image quality was evaluated by measuring the signal-to-noise ratio (SNR) of the phantom MR images using the NEMA standard [26]:

\[
SNR = \frac{\overline{S}_{signal}}{\sigma_{noise}}
\]  

where \(\overline{S}_{signal}\) is the mean pixel value in the region of interest (ROI) of the signal and \(\sigma_{noise}\) is the standard deviation of all pixels in the ROI of the noise.

Fig. 6 shows the ROI for both signal and noise, including the normalized SNR results. A maximum of 10% SNR loss is acceptable when demonstrating the MRI compatibility of the robot [27]. The maximum decrease in SNR due to the robot presence was less than 1.08\% for the T1 sequence and 1.03\% for the T2 sequence. No significant differences were observed in the SNR when the robot was in the ON and OFF states and no artifacts were observed in the MRI images. This showed that our robot prototype can be used in an MRI scanner bore.

IV. CONCLUSION

We have presented the design, fabrication, and validation of the four-DOF robotic system that supports multiple needle insertion using MRI guidance.

Robot and actuator were fabricated using non-metallic, non-magnetic, and non-conductive materials (PLA and Full-Cure720) so that the robot could be operated safely inside the MRI scanner. The robotic system can be classified as MR safe robot based on the material composition. Robot performance was evaluated with a needle accuracy test in free air and needle insertion to target tumors on a phantom inside the MRI scanner. Additionally, image quality test was

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TABLE I
ROBOT POSITIONING ACCURACY (IN mm)

<table>
<thead>
<tr>
<th>Needle angle</th>
<th>0 degree</th>
<th>5 degrees</th>
<th>10 degrees</th>
<th>15 degrees</th>
<th>20 degrees</th>
<th>25 degrees</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(T_x)</td>
<td>(T_y)</td>
<td>(T_x)</td>
<td>(T_y)</td>
<td>(T_x)</td>
<td>(T_y)</td>
</tr>
<tr>
<td>Mean error [mm]</td>
<td>0.21</td>
<td>0.70</td>
<td>0.62</td>
<td>0.81</td>
<td>1.72</td>
<td>1.10</td>
</tr>
<tr>
<td>Std. deviation [mm]</td>
<td>0.14</td>
<td>0.50</td>
<td>0.18</td>
<td>0.53</td>
<td>0.26</td>
<td>0.66</td>
</tr>
</tbody>
</table>
performed to assess the effect of the robot presence on the quality of MRI images.

The main limitation of this system is the absence of sensor feedback to determine the real-time position of the motor. Although the accuracy of the stepper motor in this robot prototype is quite high, untracked motor errors can accumulate over time, which can affect robot performance. In the future, we plan to embed sensors into the robot to track the position of the motor in real time. We also plan to reduce the rack size on the motor to fine-tune the position and the orientation of the needle [28]. Finally, an interface needs to be developed to help clinicians insert needles using the robotic system.

REFERENCES


