An Ultrasonography Assisted Robotic HIFU Ablation Experimental System

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Abstract: In recent years, noninvasive thermal treatment by using High Intensity Focused Ultrasound (HIFU) has high potential in tumor treatment. The goal of this research is to develop an ultrasonography assisted robotic HIFU ablation system for tumor treatment. The system integrates the technologies of ultrasound image assisted guidance, robotic positioning control, and HIFU treatment planning. With the assistance of ultrasound image guidance technology, the tumor size and location can be determined from ultrasound images and the robot can be controlled to position the HIFU probe to focus on the target tumor. An experiment of using mountain-typed template to verify the positioning accuracy of the ultrasonography assisted robotic HIFU ablation system has been done. The results show that the average positioning error is 1.06mm with a standard deviation 0.25, which is feasible for tumor therapy.

1 INTRODUCTION

Liver tumor (cancer) is a common disease. Early diagnosis and treatment of liver disease is very important measures to avoid worsening. Except biochemical tests such as GOT/GOP or α-globulin, ultrasound scanning is usually adopted for first-line screening and diagnosis. If the disease needs further treatment, tissue biopsy, percutaneous ethanol injection, or RF burning will be usually done under ultrasound guidance. For serious cases, open or minimally invasive liver dissection treatment will be necessary. However, all of them are invasive treatments. In recent years, noninvasive High Intensity Focused Ultrasound (HIFU) thermal treatment has demonstrated high potential in tumor treatment (Martinez, et al., 2012). The physical principle of this interventional approach is to apply focused ultrasound waves to the tumor tissue such that the heating of the tissue causes its necrosis (Seo, et al., 2010). Since tumors are typically much larger than the size of HIFU focal point, treatment of the entire volume of tumor is not suitable for hand-held HIFU transducer. Most of the research is conducted with the assistance of robot arm (Masamune, et al., 2013, Chauhan, 2008, Qiu, et al. 2009). Eventually, it is quite difficult to assess the quality of this non-invasive therapy, there is a dire need for a high accuracy system supporting in planning, conduction, and monitoring of such treatments. This research is aimed to study and develop an ultrasound image assisted robotic HIFU ablation system for tumor treatment (Qiu, et al., 2009). With the assistance of ultrasound image guidance technology, ultrasound images are used to determine tumor size and location and the robot is controlled accordingly to position the focus point of a HIFU probe to the target position for thermal ablation of the tumor.

2 THE ULTRASONOGRAPHY ASSISTED ROBOTIC HIFU SYSTEM

As shown in Figure 1, the ultrasonography assisted robotic HIFU system integrates the ultrasound imaging system (ALOKA, Prosound Alpha 6), the HIFU ablation system (Sonic H-106 probe with Instek, GFG-8255 signal generator and AR, 150A100B power amplifier), the robotic arm (YAMAHA, YK400XG), the optic tracker (Northern Digital, Polaris Spectra), and a notebook (Dell, M4500) into a system.
The ultrasound probe scans the tumor phantom to obtain the location of the tumor. The movement of the ultrasound probe is controlled by the motor-driven linear slide and detected by the optic tracker through the DRF (Dynamic Reference Frame, a tool with three IR reflective marker spheres), which is a reference coordinate frame tracked by the optic tracker. Through coordination transformation described below, the position of the tumor phantom relative to the ultrasound image frame can be transferred and represented by the robot frame. The robot is thus able to bring the focus point of the HIFU probe to aim at the tumor phantom. The signal generator and power amplifier are used to enable the HIFU probe to generate high-intensity sound power for thermal therapy.

3 COORDINATE TRANSFORMATION BETWEEN THE OPTIC TRACKER AND THE ULTRASOUND IMAGE FRAMES

Figure 2 illustrates an experimental system for determining the coordinate transformation matrix $T^U_I$ between the ultrasound probe frame ($O_U$) and the ultrasound image frame ($O_I$). A mountain-typed calibration template with three plates is fixed on the bottom of the water tank while a DRF ($O_D$) is also mounted on the upper corner of the water tank. The position ($P_D$) of the target point $P$ (Figure 3) relative to the tank DRF frame ($D$) is calibrated prior to the experiment. A DRF ($O_U$) is also attached on the ultrasound probe for position tracking of the probe. As shown in Figure 3, the middle plate of the calibration template is scanned by the ultrasound probe and the image coordinate ($P_I$) of the target point $P$ is determined from the ultrasound image. The position of the target point $P$ relative to the optic tracker frame can be expressed through either the tank DRF frame or the ultrasound probe frame as shown in equation (1).

$$T^T_D P_D = T^T_U T^T_I P_I$$  \hspace{1cm} (1)

where $I$ represents ultrasound image frame
$U$ represents ultrasound probe frame
$T$ represents optic tracker frame
$D$ represents the tank DRF frame
$T^T_D$, $T^T_U$, $P_D$ and $P_I$ are known.

The transformation matrix $T^U_I$ can be determined by bringing the tracker and image coordinates of the target point $P$ at three or more positions, $P_i (P_{Di} \cdot P_{Pi})$, $i=1, 2, \ldots, N$, $N \geq 3$ into equation (1) and solved by optimization method such as the least square algorithm. After the transformation matrix $T^U_I$ has been determined, the coordinates of any target tumor detected by ultrasound scan (Figure 5) can be transferred and expressed relative to the optic tracker frame as described by equation (2).

$$P_T = T^T_U T^U_I P_I$$  \hspace{1cm} (2)
4 COORDINATE TRANSFORMATION BETWEEN THE ROBOT AND THE ULTRASOUND SYSTEM

Figure 4 shows the coordinate transformation relationship between the optic tracker and the robot. A tracking device mounted with a DRF (coordinate frame E) and a pin of 10cm in length (tip point P represents the focus point of the HIFU transducer) is designed and mounted at the end effector of the robot. A DRF is fixed on the robot base and used to define the world coordinate frame W in case the optic tracker is moved during the experiment. The robot coordinate frame is defined as frame R. The transformation matrix $T_W^R$ and $T_E^R$ can be determined directly by the optic tracker. The transformation matrix $T_W^E$ is to be solved so that the coordinates relative to the optic tracker frame can be transformed relative to the robot frame. In other words, the coordinates of any target point determined by the ultrasound scan can be transformed to those relative to the robot frame through the optic tracker.

The position of the origin of the coordinate frame $E$, $O_E$, can be described relative to the coordinate frame W as below.

$$O_W = \left(T_W^T\right)^{-1}T_E^TO_E$$  \hspace{1cm} (3)

If the robot is manipulated to move around, the coordinates of point $O_R$ relative to the coordinate frames R and W are calculated by the robot controller and equation (3) respectively. Therefore, the transformation matrix $T_W^R$ between the robot and optic tracker can be determined by equation (4).

$$O_R = T_W^RO_W$$  \hspace{1cm} (4)

Because both $O_W$ and $O_R$ are not square matrices (4x1), we use least mean square algorithm to solve $T_W^R$.

$$T_W^R = O_RO_W^T\left(O_WO_W^T\right)^{-1}$$  \hspace{1cm} (5)

After completion of the registrations between the ultrasound image and the optic tracker and between the optic tracker and the robot, the coordinates of the target tumor scanned and detected by the ultrasound system can be transformed and represented by the robot frame. The transformation is defined by Eq. (6) and illustrated by Figure 5.

$$P_R = T_W^R T_W^U T_U^R T_U^E P_I$$  \hspace{1cm} (6)

where $P_I$: Image coordinate of the target tumor.

Figure 4: The coordinate transformation between the optic tracker and the robot.

Figure 5 also shows that the HIFU transducer has been mounted to the end effector of the robot for HIFU thermal treatment.

Figure 5: The coordinate transformation between the tumor PI and the robot.
The procedures of the HIFU thermal ablation of the ultrasonography assisted robotic HIFU system is described in the flow chart of Figure 6.

![Flow chart of the procedures of the HIFU thermal ablation of the ultrasonography assisted robotic HIFU system.]

Figure 6: The procedure of thermal ablation of the robotic HIFU system.

5 EXPERIMENT AND DISCUSSION

5.1 Position Measure of the Target

An experiment has been conducted to verify the position measure error through the coordinate transformation between the ultrasound image and the optic tracker frames. The mountain-type template was seated in depth of 3cm, 7cm and 12cm. The template in each depth was scanned three times by the ultrasound probe. The positioning error is defined as the difference between the image coordinate of the target point after coordinate transformation and the coordinate measured directly by the optic tracker. The average positioning error of the three peak points of the template in depth of 3cm, 7cm and 12cm are 1.49mm, 1.46mm and 2.15mm respectively. Table 1 listed the experiment data of the case in 7cm depth.

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<tr>
<th>No. of point</th>
<th>Coordinate of the target point</th>
<th>No. of Image</th>
<th>Coordinates of the guided pinpoint</th>
<th>Distance error</th>
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<td>z</td>
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<td>Average error</td>
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<td>Standard deviation</td>
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5.2 Positioning of the Robot Arm

The robot was commanded to move around to ten positions to calculate the transformation matrix $T_{rb}$ by Eq. (5). After that, the calibration template of Figure 3 seated in depth 7cm was scanned by the ultrasound. Then the robot was command to move the pinpoint P (Figure 4) of the rod to the three peak points of the template as shown in Figure 7. The distance errors between the peak points and the pinpoint P are listed in Table 2. The positioning error is 1.06±0.25mm.

![Figure 7: The pinpoint of the rod positions to the peak point of the calibration template.]

Table 1: Distance error of the phantom in 7cm depth.
Table 2: Positioning error of the robot arm.

<table>
<thead>
<tr>
<th>No. of point</th>
<th>Coordinate of the target point</th>
<th>No. of Image</th>
<th>Coordinate of the guided pinpoint</th>
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<td>Max error</td>
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Table 3: Positioning error of HIFU thermal ablation.

<table>
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<tr>
<th>No. of points</th>
<th>Position of the target (mm)</th>
<th>Position of the ablation (mm)</th>
<th>Distance error</th>
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<td>81.24</td>
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5.3 Positioning of HIFU Ablation

The ultrasonography assisted robotic HIFU treatment experiment was conducted by commanding the robot to move HIFU focus point to ablate the four corner points of a phantom, which was detected by ultrasound images. Figure 8 shows the HIFU focus point can be positioned to the target (corner) points for thermal ablation. The average positioning error is $1.3 \pm 0.8$mm and the distance error of each corner point is listed in Table 3.

Figure: 8: Positioning experiment of the HIFU thermal ablation.

6 CONCLUSIONS

This study proposes an ultrasonography assisted robotic HIFU system for thermal ablation of tumor. The position coordinates of targets determined by the ultrasound image are transformed to the robot coordinate frames so that the robot can move the HIFU probe to focus on the targets. The experiment results show that positioning errors of the robotic HIFU system is accurate enough for thermal ablation treatment of tumor tissue. Since robots have great dynamic response in motion, it is highly possible to apply the robotic HIFU system to treat live tumors in the future, which requires the compensation of movement due to respiration.

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