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3-D Ultrasound Guidance of Surgical Robotics Using Catheter Transducers: Feasibility Study

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***Abstract*—The goal of this study was to test the feasibility of using a real-time 3-D (RT3D) ultrasound scanner with matrix array catheter probes to guide a surgical robot. We tested the accuracy of using 3-D catheter transducers with the 3-D measurement software of the scanner to direct automatically a robot arm that touched two needle tips together within a water tank and inside a vascular graft. RMS measurement error ranged from 2.4 to 3.4 mm for two catheter designs.**

I. Introduction

We have previously investigated the feasibility and significance of using real-time 3-D (RT3D) laparoscopic ultrasound to guide a surgical robot [1]. In that study, a 1-cm-diameter probe for RT3D was used laparoscopically for *in vivo* imaging of a canine. The probe, operating at 5 MHz, was used to image the spleen, liver, and gall bladder as well as to guide hand-held surgical instruments. Furthermore, the 3-D measurement system of the volumetric scanner, used with this probe, was tested as an automatic guidance mechanism for a robotic linear motion system to simulate RT3D/robotic surgery integration. Using images acquired with the 3-D laparoscopic ultrasound device, the scanner measured spatial coordinates that were used to direct a robotically controlled needle toward desired *in vitro* targets as well as targets in a post-mortem canine. The rms error for these measurements was 1.34 mm using optical alignment and 0.76 mm using ultrasound alignment.

We have also previously demonstrated that miniaturized catheters incorporating matrix array transducers are capable of delivering and guiding interventional devices during intracardiac and intravascular procedures using a RT3D ultrasound system [2]–[6]. Finally, we note that robotic catheter systems remotely controlled by physicians, such as the Sensei Catheter System (Hansen Medical, Mountain View, CA), have been used for precise intracardiac placement of interventional mapping and ablation catheters in clinical applications [7]–[10]. The goal of this paper is to examine the feasibility of using RT3D ultrasound images from catheter transducer probes to guide such a robotic arm automatically in simulated interventional procedures more suitable for intravascular and intracardiac applications, albeit at reduced spatial resolution compared to our previous robotic study using a larger endoscopic probe. The current study is seen as a prelude to animal experiments.

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II. Materials and Methods

RT3D ultrasound images and distance measurements were obtained using the Model 1 scanner (Volumetrics Medical Imaging, Durham, NC) [11], [12]. Two separate catheter transducer probes, previously described, with 112 matrix array elements operating at 5 MHz were evaluated: the first, a 14 Fr forward scanning catheter appropriate for 3-D intravascular ultrasound (1 Fr = 0.33 mm) with a tool port [2], the second, a 7 Fr side-scanning catheter applicable for intracardiac echo [3]. From different orientations in a water tank, these catheters were used to image an experimental setup consisting of a target needle, and a second probe needle attached to the arm of a Techno-Isel Gantry III Cartesian Robot Linear Motion System and its associated Model H26T55-MAC200SD automated controller (Techno, Inc., New Hyde Park, NY) whose operation and accuracy was previously described in detail [13]. In addition to the water tank setup, the forward-viewing catheter imaged the target and probe needles within a bifurcated surgical aortic graft (12 to 22 mm in diameter and 135 mm long) to simulate a more realistic surgical interventional environment.

For each 3-D catheter transducer, the locations of the tips of the target needle and the probe needle were found within the 3-D image volume, a 65° pyramid with a maximum depth of 4 cm. As previously described for our 3-D ultrasound laparoscope [1], the measurement software in the Model 1 scanner was used manually to acquire rectangular coordinates of the two needle tips with respect to the face of the transducer, and the distance between the two tips was calculated by simply subtracting the coordinates of the probe needle from those of the target needle. From here, the coordinate system of the scanner was translated into that of the robot, and the robot moved its arm holding the probe needle the corresponding distances in each rectangular coordinate. After the arm had completed movement, the error in each coordinate was measured by recording the distance needed to jog the robotic arm manually until the probe needle touched the tip of the target needle. Needle tips were originally separated by several centimeters, and the procedure was repeated five times for each 3-D catheter.

Each catheter transducer imaged the target and probe from a different orientation. As shown in Fig. 1, the forward-scanning catheter transducer incorporated a tool port [2], which was used to deliver the target needle into the 3-D field of view, with the tip being approximately

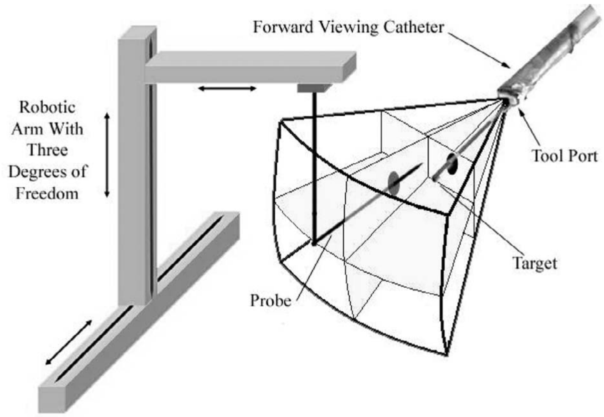

Fig. 1. Schematic of the forward-scanning 3-D catheter experiment. The target needle was inserted via the tool port while the needle probe was attached to the robotic arm.

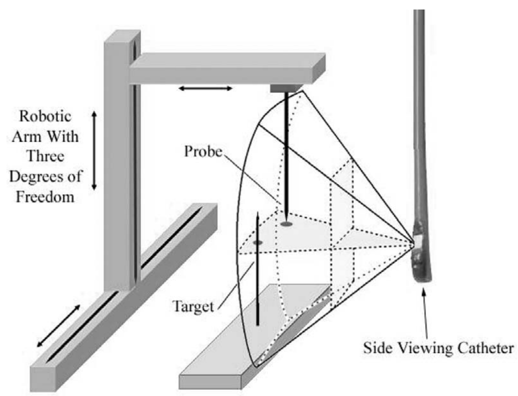

Fig. 2. Schematic of the side-viewing 3-D catheter transducer experiment. The target probe was fixed within a piece of rubber while the needle probe was attached to the robotic arm.

1.5 cm in front of the face of the transducer. This created the risky situation where the probe needle tip was guided directly toward the face of the transducer.

In the second setup (Fig. 2), the side-scanning 3-D catheter hung vertically into a water tank and imaged the target needle and probe needle from a distance of approximately 3 cm. This time the target needle protruded vertically from a sheet of sound-absorbing rubber, and the probe needle approached it from the top.

In addition to measuring accuracy, we wanted to demonstrate the catheter's use in a more realistic situation. We used a bifurcated abdominal aortic graft to simulate the closed environment that the catheter would actually encounter in a clinical trial. The catheter entered the graft from one of the smaller branches as if it were ascending from the femoral artery, and the needle probe entered the graft from the larger opening on the superior end, as seen in Fig. 3. No error measurements were recorded during this setup, because it was not possible to confirm target-probe contact visually. However, the error data of Table I is applicable to this experiment.

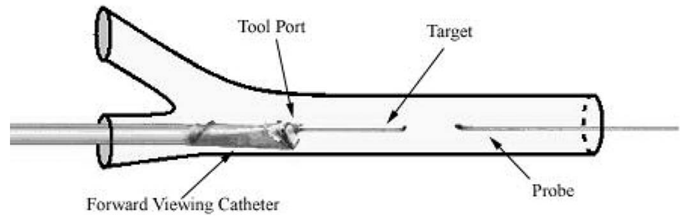

Fig. 3. The forward-viewing catheter in a bifurcated aortic graft. The goal of this setup was to simulate a more realistic setting for the catheter to guide the robot and needle probe.

TABLE I
RMS Errors in 3-D Scanner Measurement.

	ε_X (mm)	ε_Y (mm)	ε_Z (mm)	$\varepsilon_{\text{Total}}$ (mm)	% Error
Forward Viewer	3.22	1.10	0	3.41	10.6
Side Viewer	1.30	1.53	1.22	2.36	9.12

III. Results

The data from the forward-viewing catheter showed an rms error of 3.41 mm yielding an error of 10.6% relative to the measurement distance. The side-scanning catheter yielded an error of 2.36 mm, and relative error of 9.12%. This error was due to the limited spatial resolution of the 3-D catheters coupled with the difficulty of aligning the coordinate axes of the transducer face with the robot's three-axis coordinate system. Tilt between the two coordinate systems leads to error in any nonparallel axes.

Finally, we tested the forward-viewing catheter inside the bifurcated aortic graft. The probe needle started about 3 cm away from the tip of the target needle and was moved in only one dimension due to the space restrictions inside the graft. Fig. 4(a) shows a photograph of the experimental setup including the 3-D catheter with target needle, vascular graft, and robot arm with probe needle. Fig. 4 also shows images from the 3-D ultrasound scans, including two simultaneous perpendicular planes of the vascular graft with the two needles separated by 3 cm— before, Fig. 4(c)—and with the needle tips touching after the robot moves the probe needle—after, Fig. 4(c).

IV. Conclusion

We have shown the ability to direct needle probes to target needles using a surgical robot guided by 3-D ultrasound catheter transducer probes. Our water tank experiments showed accuracy results similar to our previous results using a laparoscopic probe with a higher channel count [1]. Our ability to guide a probe toward a target within a vascular graft is a first step toward using the system for intravascular procedures in an animal model.

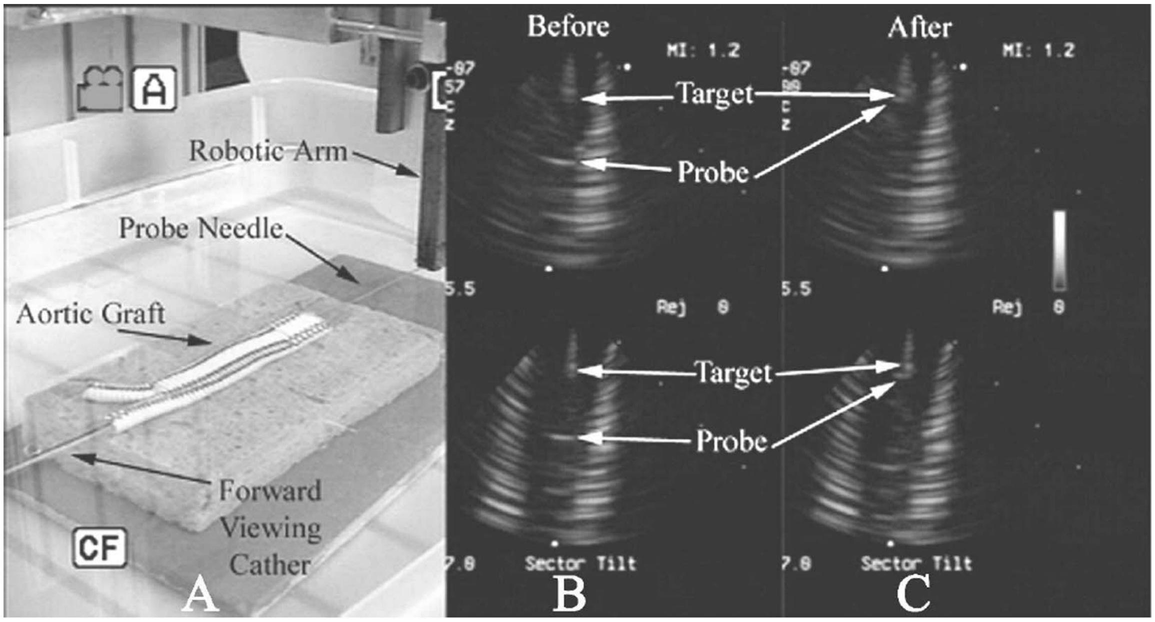

Fig. 4. (a) Experimental setup, (b) before, and (c) after images of the arterial graft. Notice the walls of the arterial grafts running vertically along either side of the target and needle probe.

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