

Automatic Steering of Cardiac Imaging Catheters

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Abstract—A robotic system for automatically steering cardiac imaging catheters enables enhanced visualization of anatomical structures and working instruments during catheter-based procedures. This system is comprised of several components for manipulating imaging catheters, sensing and control, user interface, and image collection and processing. Developments in each of these components have enabled the system to move towards *in vivo* studies in porcine models. The physical implementation of the robot can manipulate the four input degrees of freedom of the catheter with sub-degree and sub-millimeter accuracy. The sensing and control enables the inputs to maneuver the catheter tip with millimeter-level accuracy. The image collection and processing methods (in conjunction with the user interface) provide useful visualizations of simulated cardiac anatomy. Altogether, these components can potentially improve workflow, accuracy, and patient outcomes during minimally invasive interventional procedures.

Keywords—*Medical robotics, flexible robots, image-guided interventions*

I. INTRODUCTION

Cardiac ultrasound imaging catheters, also called intracardiac echocardiography (ICE) catheters, are commercially available steerable catheters featuring miniaturized phased-array ultrasound (US) transducers at the distal catheter tip [1]. US catheters are useful for imaging structures and instruments from within the heart. This is advantageous compared with external probes because targets can be imaged in the near-field with higher acoustic frequencies. A key disadvantage to the use of US catheters is the difficulty in manually controlling the alignment of the imaging plane. Properly aligning the US imager with the target through tortuous vasculature requires extensive time and training. This limits the use of US catheters to critical tasks, such as septal puncture [2].

We propose improving the utility of US catheters through robotic steering. Our system functions differently from existing commercially available or research-level prototype catheter robots, which replicate manual joint space actuation with remote control or feature Cartesian control [3]. In addition to controlling the position of the US imager at the catheter tip, the system presented here can automatically adjust the angle of the imager, providing panoramic images of cardiac anatomy or

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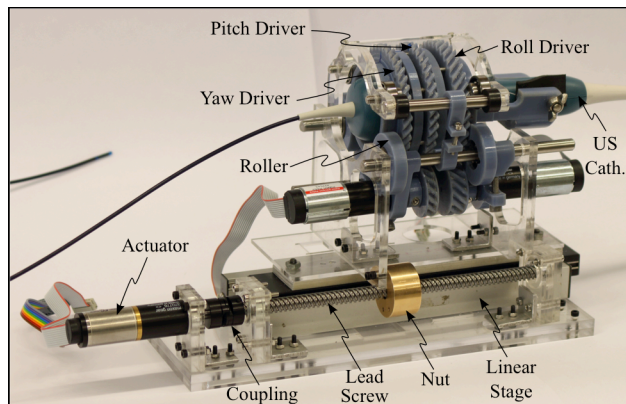


Fig. 1. 4-DOF US catheter robot.

tracking instruments [3-6]. The following sections describe the robot design, the controller, the user interface, and enhanced US image processing.

II. ROBOT DESIGN

The physical implementation of the robot (Fig. 1) was designed with two primary goals in mind: (a) accurate 4-DOF actuation, and (b) quick installation and removal of US catheters [6]. The four degrees of freedom (DOF) actuate catheter pitch, yaw, roll, and translation. The rotational transmission combines pitch, yaw, and roll actuation in a set of concentrically rotating helical gears. The rotational transmission is then translated on a linear stage by a lead screw. An optical tracker with position accuracy 0.25 mm RMS was used to characterize the accuracy of the robot actuation. The joint positioning accuracies of the three rotational DOF were measured to be 0.28-0.38° with average measured backlash error 0.44°. Translational movement and backlash errors were less than the reported accuracy of the optical tracker. Catheter insertion and removal times were measured to be 5-10 seconds, which is sufficiently fast for use in an operating room setting.

III. CONTROL

Catheter pose sensing at the catheter tip is done with one 6-DOF electromagnetic (EM) tracker mounted just proximal to the bending section and another EM tracker just distal to the bending section. An earlier version of the controller decoupled position and orientation control using one EM sensor at the tip [5]. The angle of the imager was adjusted by the roll DOF in series with the position controller. Position control motor adjustments were calculated by an inverse Jacobian matrix (calculated using knowledge of the joint angles) multiplied by the desired change in Cartesian coordinates. A new approach uses two EM sensors to measure the amount of bending experienced at the tip and then calculates the inverse Jacobian

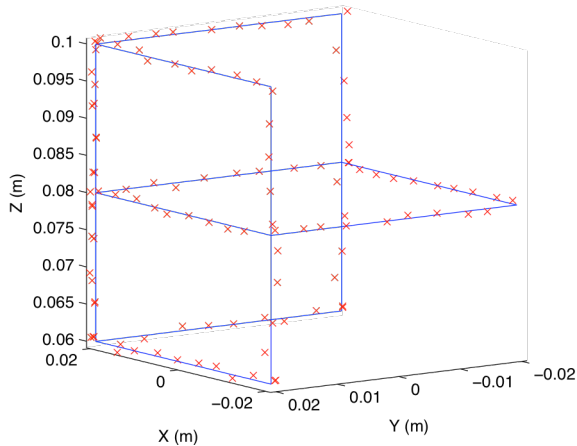


Fig. 2. Results of catheter tip position control tests while tracing squares.

matrix. New results of position control tests tracing the outlines of squares are shown in Fig. 2. The blue line represents the desired trajectory and the red symbols mark the actual catheter tip position. The system positions the catheter tip to the correct position with mean error 0.96 mm (standard deviation 0.37 mm).

IV. USER INTERFACE

The robotic catheter steering system is controlled via a graphical user interface (GUI) that is programmed in C++ using the Windows MFC libraries. The GUI communicates with the robot hardware (e.g. Maxon motors) through API calls to the respective dynamically linked libraries (DLL). The user interface allows the control of the catheter in tip space. The user can adjust the level of accuracy through the GUI. The UI also enables more advanced control features, such as automatic panorama generation. In this control mode, the user can input a starting and end angle for the US imager, the number of steps to take, and the number of images to be acquired at each step.

V. IMAGE PROCESSING

Our robotic catheter system provides a unique capability in acquiring a set of 2D US images using an US catheter and reconstructing these slices into a high-resolution 3D US volume. To enable the use of this feature, we integrated a frame grabber (DVI2USB 3.0, Epiphan Systems Inc., Ottawa, Ontario, Canada) that acquires images from the ultrasound machine (ACUSON Cypress Cardiovascular System, Siemens Healthcare GmbH, Germany). Using the information from the EM tracker at the tip of the catheter our algorithms register these 2D image slices together in 3D space.

Once the image slices are registered to a common coordinate frame, we perform interpolation to fill in the gaps between the slices. The visualization of the interpolated volume is enabled through raycasting, where the image on the user's screen is formed by shooting 'rays' through the

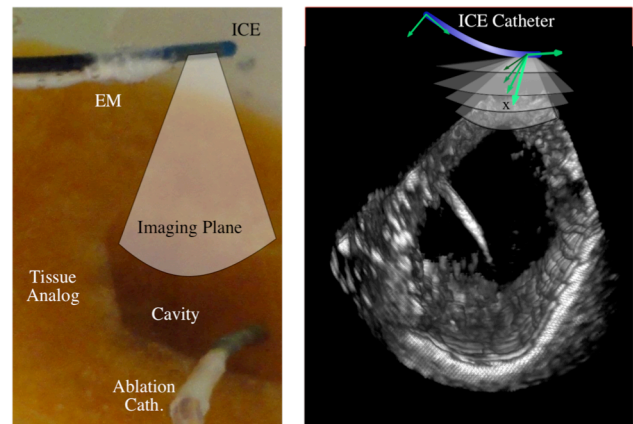


Fig. 3. (left) The water tank imaging setup, with an ablation catheter introduced into the cavity in a tissue analog. (right) The reconstructed 3D US volume shows the 'tissue' walls and the ablation catheter body. The cartoon of an ICE catheter on the top shows the relative orientation of the ICE catheter and the US images.

volumetric field and integrating the density of 'matter' (intensity) that the ray passes through [7]. This is a computationally expensive but highly parallelizable operation; therefore we use graphics hardware in order to accelerate it. This interpolated volume is transferred to the graphics processor unit (GPU) for real-time volume rendering (GeForce GTX TITAN, NVIDIA).

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