Robotic Steering of Cardiac Ultrasound Imaging Catheters

L.J. Brattain[1,2], P.M. Loschak[1], C.M. Tschabrunn[3], E. Anter[3], R.D. Howe[1]

[1]*Harvard School of Engineering and Applied Sciences, Cambridge, MA, USA*

[2]*MIT Lincoln Laboratory, Lexington, MA, USA*

[3]*Harvard-Thorndike Electrophysiology Institute, Beth Israel Deaconess Medical Center, Harvard Medical School, Boston, MA, USA*

brattain@seas.harvard.edu

INTRODUCTION

We have developed a system for steering cardiac imaging catheters to automatically visualize heart structures and instruments. The goal of this system is to improve the efficacy, speed, and safety of imaging during catheter-based arrhythmia treatment procedures. Many cardiac arrhythmias can be effectively treated by radiofrequency (RF) catheter ablation [1], but the primary real time imaging modality is x-ray fluoroscopy, which does not effectively distinguish soft tissues and exposes patients and clinical staff to ionizing radiation. Real time visualization of intracardiac structures is needed to further improve the efficacy of catheter ablation procedures.

Intracardiac echocardiography (ICE) catheters are routinely used during ablation procedures for their high-quality ultrasound soft tissue visualization. A major challenge during catheter ablation is the lack of acute lesion assessment, and ICE visualization of lesion growth has the potential to improve acute procedural outcomes. However, manual use of ICE requires specialized training and maintaining continued alignment of the imaging plane is a significant challenge. Existing robotic catheter systems (e.g. Hansen Medical, http://www.hansenmedical.com, Stereotaxis, http://www.stereotaxis.com, [2]) enable teleoperation of catheter controls and reduce radiation exposure, but they do not solve the problem of steering an ICE imaging plane towards a desired structure.

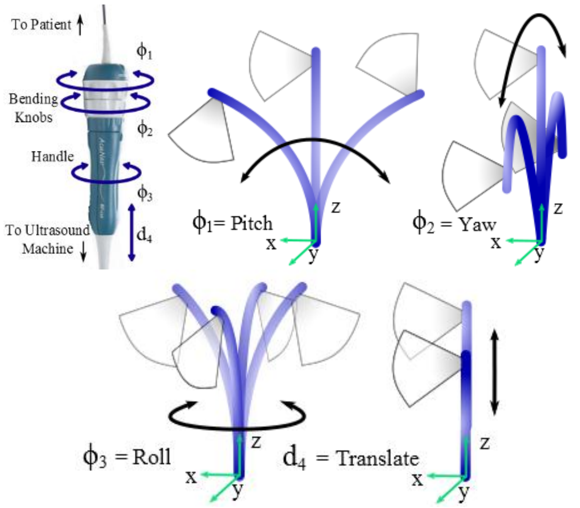

Figure 1: ICE catheter actuated degrees of freedom with corresponding tip and imaging plane motions

In this study our system manipulates an ICE catheter in a water tank to visualize a phantom. Multiple images are stitched together to create a volume of the target structure. This enablement of real time visualization during catheter ablation has potential to facilitate improved long-term treatment of cardiac arrhythmias.

MATERIALS AND METHODS

ICE catheters have an ultrasound array transducer in the tip of a steerable catheter which transmits images to the clinician in real time. The catheter handle has four actuated degrees of freedom (DOF) that create tip motion (Fig. 1). Two bending knobs can be individually actuated to achieve pitch (left-right knob), yaw (posterior-anterior knob), or a combination of both. The catheter handle can be rotated and translated.

The system consists of a catheter manipulator, kinematic and control algorithms, and visualization enhancement. The off-the-shelf catheter is articulated by DC motors connected to belts for rotation and a lead screw for translation. Kinematic algorithms were derived to control catheter motions which are difficult to achieve manually. Specifying a desired position for the ICE catheter tip requires 3 DOF. Since the catheter possesses 4 DOF, the extra DOF can be applied to constrained orientation control. By adjusting both knobs in conjunction with handle rotation, the imaging plane may be rotated about the catheter axis at the tip while the physical location of the catheter remains constant. Fig. 2(a) shows a simulation of a catheter with its imaging plane rotating about the catheter tip axis, where the green lines represent the same vector in each imaging plane. Fig. 2(b) shows the joint actuation required for achieving this motion. A closed form solution for inverse kinematics of the catheter tip based on orientation was used to calculate the knob adjustments [3].

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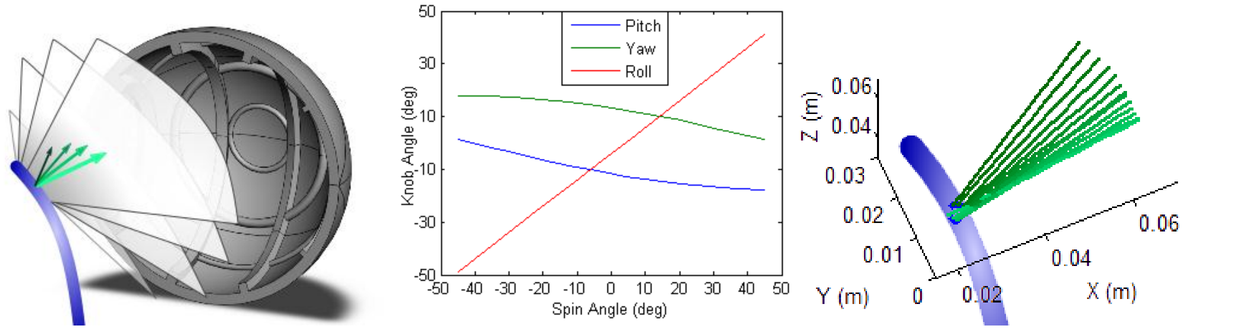

Figure 2: (a) Schematic of imaging plane rotation while visualizing CAD model of phantom, (b) example handle inputs for large image plane rotation, (c) data for 23° total imaging plane rotation

A series of images obtained during plane rotation across a region may be spatially registered into the Cartesian coordinate frame and interpolated into a reconstructed 3D volume model of the cardiac cycle. Electromagnetic (EM) trackers with RMS position errors on the order of 1.4 mm (trakSTAR, Ascension Technology) were mounted to the catheter tip for reconstruction. EM tracking is typically used for electroanatomic mapping in many interventional catheter labs. For testing purposes, this technique was applied to image an object of known dimensions that was fabricated on a high-resolution 3D printer. The phantom was designed with distinctive 3D features that would visualize well under ultrasound and be useful for catheter tip localization during calibration.

RESULTS

Robotic steering data for an ICE catheter is shown in Fig. 2(c), where the green lines represent the same vector in each imaging plane and the color intensity represents the order in which rotations occurred. The imaging plane rotated in 13 steps averaging 1.8° per step for a total of 23°. During rotation the total tip motions were constrained to within ±2.0 mm in every direction, which is an acceptable error tolerance given the accuracy of the EM tracker system and sufficient for safe procedural use. Fig. 3 shows 13 image slices reconstructed to visualize a region of the phantom.

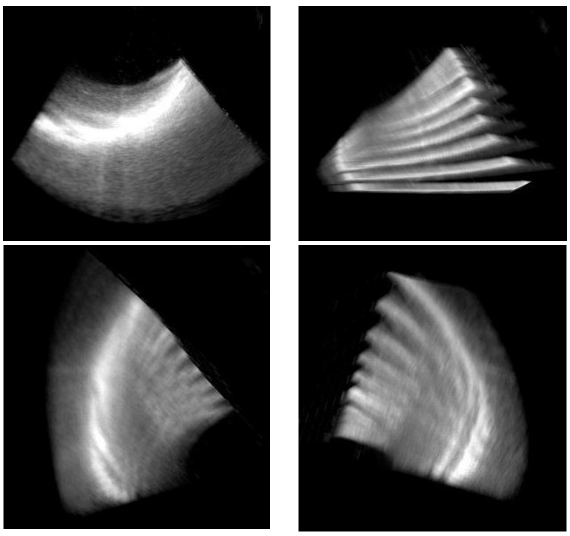

Figure 3: Ultrasound image slices stitched into a volume

DISCUSSION

The tests described in this study signify the first use known to the authors of applying ICE catheter position and orientation kinematics to robotically enhance clinicians' visualization abilities. Fig. 2(c) showed that the system was able to rotate the imaging plane using the kinematic algorithms without significantly displacing the location of the catheter. This could enable clinicians to move the ICE catheter to a safe location and image structures that are difficult to focus on by manual manipulation. Reconstructed volumes can be useful in performing diagnoses or lesion assessment during ablation.

This approach can enable other visualization techniques, such as allowing a user to choose an angle from which to image a target object from a set of possible viewing angles, and then automatically steering the imaging device to the proper position and orientation for monitoring catheter-tissue interactions.

The capabilities demonstrated in this study are meant to be a proof of concept for the use of a robotic system to control ICE imaging. Future work will correct for system inaccuracies (such as friction, backlash, imperfect curvature, etc.), apply safety boundaries based on the known locations of surrounding heart structures, and use image processing to assist in navigation. Kinematic algorithms for imaging can be applied to many catheter-based procedures involving visualization of various organ systems via long, thin, flexible imaging tools. This robotic system, specifically, has the potential to greatly increase clinicians' visualization capabilities while reducing procedure times and training times related to mastering the use of ICE.

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