Robotic Control of Ultrasound Catheters for Intra-cardiac Visualization

Paul M. Loschak[1], Alperen Degirmenci[1], Laura J. Brattain[1,2],
Cory M. Tschabrunn[3], Elad Anter[3], Robert D. Howe[1]

[1]Harvard Paulson 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

loschak@seas.harvard.edu

INTRODUCTION

Imaging catheters can provide real time imaging from within the heart, but manual navigation is difficult and requires extensive training. This study focuses on the first examples of automatically pointing ultrasound (US) catheters (frequently referred to as intracardiac echocardiography, or ICE) in *in vivo* animal studies. US catheters feature an US transducer at the tip for imaging cardiac structures. US catheters are manually steered to assist in high-resolution, low-distortion visualization during critical steps of minimally invasive cardiac procedures. Our four degree of freedom (DOF) robotic system automatically aims the imager at target anatomical structures and working instruments (Fig. 1), therefore alleviating the difficulty in manual control [1]. Automatically positioning flexible imaging instruments within the body can improve diagnoses and treatments of medical conditions such as cardiac arrhythmias (atrial fibrillation) while reducing the need for burdensome manual manipulation.

MATERIALS AND METHODS

AcuNav US catheters (Biosense Webster, USA) are the most commonly used clinical ICE catheters. They are manipulated by adjusting the two bending knobs (pitch and yaw), rotating the catheter handle (roll), and inserting/retracting the catheter handle (translation) (Fig. 2). A 4-DOF robot (Fig. 3) was designed to actuate the 4-DOF US catheter [2]. All four joints are actuated by DC motors and controllers (EPOS2, Maxon Motors, Switzerland). The tip position and orientation of the catheter are tracked using electromagnetic (EM) trackers (Ascension Technology Corp., USA).

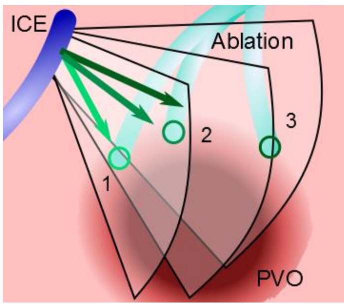

Fig. 1 US imager tracks instrument tooltip.

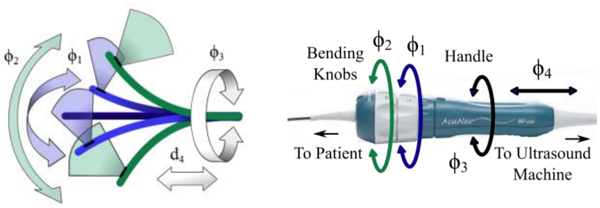

Fig. 2 (*left*) US catheter tip motions resulting from (*right*) US catheter handle joint controls.

The novelty in this work specifically relates to the robust closed-loop control strategy (Fig. 4) [3]. This new strategy rejects disturbances to the body of the catheter. This is important during *in vivo* procedures in which the catheter navigates through tortuous vasculature. Respiratory motion causes disturbances to the catheter body and the base of the bending section, which then disturb the catheter tip pose. The robot must be able to maintain the catheter tip at the desired pose despite these disturbances.

The system measures the catheter bending section tip and base poses to calculate the existing catheter bending section rotation, γ_{curr}. The target pose can be either a relative pose adjustment or based on EM tracking measurements of the angle between the US imaging plane and the target. Achieving the automated motions described in Fig. 1 requires two control goals: (1) maintaining the fixed position, and (2) aligning the US image plane with the target. Inverse kinematic calculations convert the tip space current and target poses, $\boldsymbol{X}_{des}$ and $\boldsymbol{X}_{sensor}$, to configuration space variables,

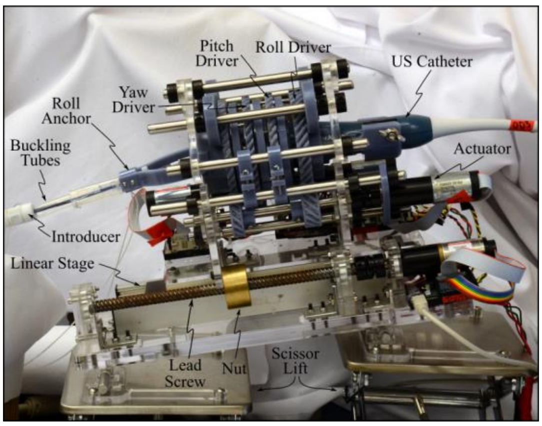

Fig. 3 US catheter mounted in robot.

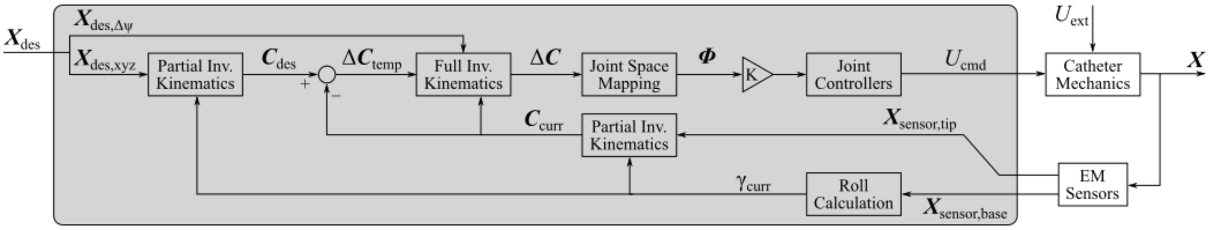

Fig. 4 Position and imager angle control diagram.

$\boldsymbol{C_{des}}$ and $\boldsymbol{C_{curr}}$, which describe the bending section curvature and orientation. The difference between the current and target configurations, $\boldsymbol{\Delta C}$, is converted to joint space, $\boldsymbol{\Phi}$. The robot actuates each joint by sending commands to the motor controllers, which run onboard servo loops at 1 kHz. The controller navigates the catheter to the target pose. US images are collected when the tip pose converges to allowable error thresholds.

RESULTS

The robotic catheter navigation system was tested through *in vivo* porcine experiments to demonstrate tip positioning, US imager orientation, and disturbance rejection. The clinician manually introduced the US catheter through the femoral vein to a safe location within the right atrium of the heart. The US catheter handle was then attached to the robot and switched to autonomous motion mode. The US imager was rotated about the catheter axis while maintaining the same safe position in the right atrium. This required active manipulation of all four DOF. During 4D volume reconstruction tests a sequence of 80 2° US imager adjustments was given as target step inputs. The resulting motions had mean absolute errors 2.0 mm (σ = 1.1 mm) and 0.65° (σ = 0.51°). Ramp disturbances (Fig. 5) due to respiratory motion on breath-hold were

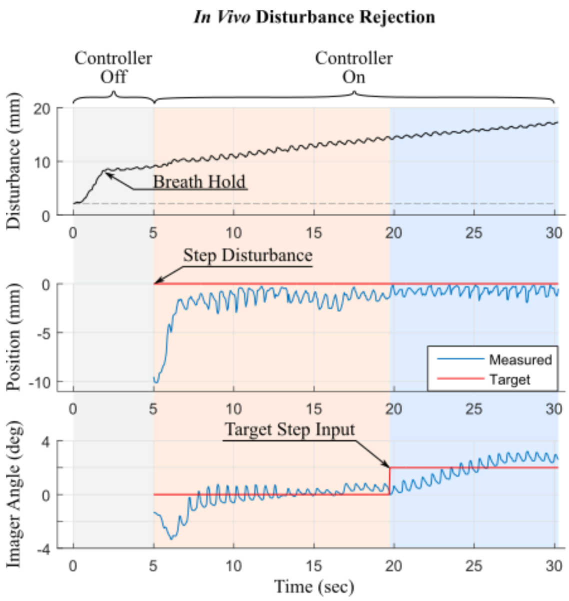

Fig. 5 *In vivo* tests: (*Top*) Ramp input disturbances to the catheter body are rejected. (*Middle*) The catheter tip remains at the fixed point. (*Bottom*) Step input angles command the US imager to rotate towards the target.

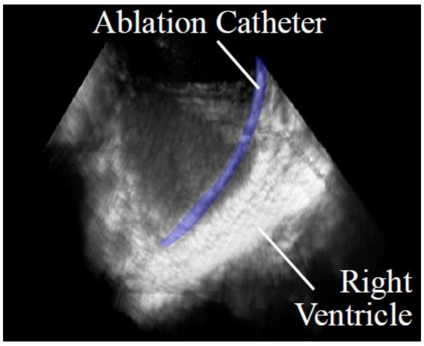

Fig. 6 *In vivo* instrument tracking (false color applied).

rejected by the controller. The system was able to maintain its pose with mean absolute errors 1.1 mm (σ = 0.7 mm) and 0.44° (σ = 0.31°). An ablation catheter (Fig. 6, highlighted in blue false color) in the right ventricle was imaged by the US catheter system. The sequence of 2D US images was reconstructed into 3D and 4D volumes using the method described in [4].

DISCUSSION

Experimental results from *in vivo* studies demonstrate a system for automatically steering US imaging catheters to provide better clinical visualization during procedures. Future work includes actively steering to compensate for respiratory motion disturbance. The robot system for controlling US imaging catheters has the potential to improve workflow, enhance situational awareness, and improve outcomes in a range of minimally invasive procedures.

REFERENCES

[1] Loschak PM, Brattain LJ, Howe RD. Automated pointing of cardiac imaging catheters. ICRA 2013; 5774-5779.

[2] Loschak PM, Degirmenci A, Tenzer Y, Tschabrunn CM, Anter E, Howe RD. A 4-DOF robot for positioning ultrasound imaging catheters. JMR 2015.

[3] Degirmenci A, Loschak PM, Tschabrunn CM, Anter E, Howe RD. Compensation for unconstrained catheter shaft motion in cardiac catheters. ICRA 2016.

[4] Brattain LJ, Loschak PM, Tschabrunn CM, Anter E, Howe RD. Instrument tracking and visualization for ultrasound catheter guided procedures. MICCAI workshop AECAI 2014.

This work was supported by the Harvard John A. Paulson School of Engineering and Applied Sciences, American Heart Association Grant #15PRE22710043, the National Institutes of Health Grant #1R21EB018938, the NVIDIA Academic Hardware Grant Program, and the Assistant Secretary of Defense for Research and Engineering under Air Force Contract No. FA8721-05-C-0002 and/or FA8702-15-D-0001. Any opinions, findings, conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the Assistant Secretary of Defense for Research and Engineering.