Experimental Validation of Autonomous Motion Control with Standard Cardiac Electrophysiology Catheter

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***Abstract*— Cardiac electrophysiology (EP) is an effective treatment to arrhythmias, in which a long and flexible catheter is delivered to a cardiac chamber. Although several control methods have been designed to provide accurate manipulation of the catheter tip, few have been implemented on the standard cardiac EP catheter. In this abstract, we implement a motion control algorithm on our previously developed robotic catheter platform. Experimental validation is conducted by performing autonomous radiofrequency (RF) ablation on *ex vivo* tissue with a standard cardiac EP catheter. Preliminary results demonstrate the potential of the system to perform autonomous EP catheterization.**

***Index Terms*— Cardiac electrophysiology, catheterization, autonomous control, MR safe robot, robot-assisted intervention**

I. Introduction

Cardiac electrophysiology (EP) is an interventional treatment for heart rhythm disorders, where a long flexible catheter ($>$ 1m) is delivered to the heart chamber for radiofrequency (RF) ablation. The ablated non-conductive lesions can isolate abnormal EP signals. However, the slender and flexible body of EP catheters brings challenges for delicate and precise control. Several robotic catheterization systems [1] have aimed to improve performance, with the catheter generally navigated by intra-operative (intra-op) X-ray. By contrast, intra-op magnetic resonance imaging (MRI) can provide improved visualization for soft tissue, and also monitor temperature changes during thermal therapy procedures [2]. Multiple studies have focused on developing tele-operated robotic platforms under intra-operative MRI for various interventions ranging such as biopsy [3-5], thermal therapy for tumor ablation [6], to catheter-based procedures within cardiovascular system [7-8], with improvements to accuracy and overall procedural time.

With the advent of catheterization robots, various control methods were designed for their accurate positional control. Regarding the bendable distal section of a catheter as a continuum robot, kinematic models (e.g. constant curvature (CC) model [9]) have been investigated in previous work. There were also methods that circumvent the modeling procedure by approximating the output-input mapping solely with sensory data [10]. However, current experimental validation of robotic cardiac catheterization systems were mostly performed using non-standard catheters, which typically have different mechanical characteristics, and do not take the RF ablation requirement into consideration [11].

In this project, we aim to implement autonomous control [12] on our robotic platform which is compatible with standard cardiac EP catheters. A kinematic model-based controller was applied as a preliminary test for the motion control. Experimental validation was performed in a left atrium (LA) phantom with *ex vivo* tissue by simulating pulmonary vein isolation (PVI) with RF ablation. The preliminary results demonstrate the feasibility of autonomous control for this robotic system.

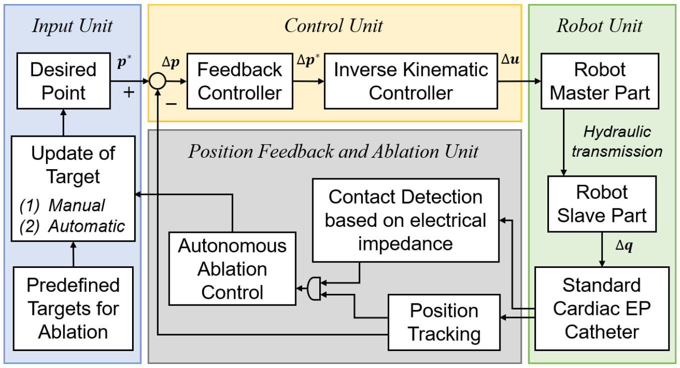

Fig. 1. Block diagram illustrating the autonomous ablation procedure using model-based control algorithm for the catheter robot, with the positional feedback acquiring by a 6-DoF EM tracking marker.

II. Control Method

A. Catheter Robot Control

Current clinically used catheters are typically actuated by two tendons along the catheter body, allowing bi-directional bending of the distal section. Our proposed MRI-compatible robot [13] is designed for teleoperation operation of catheters inside the MRI room. The robot features three degrees of freedom (DoFs) for bending, rotation and insertion of the catheter, which needs to be coordinated by an appropriate controller.

B. Model-based Control Algorithm

We apply kinematic control based on the CC model for our catheter robot. This model assumes constant circular curvature and zero torsion along the distal bending section. The movement of the catheter tip is controlled by the manipulation on the catheter handle, where d, α and ϕ represent the insertion distance, the twisting angle of the knob and the rotation angle of the handle, respectively. The variable $\boldsymbol{q} = \begin{bmatrix} d & \alpha & \phi \end{bmatrix}^{\mathrm{T}}$ represents the catheter handle state. The 3D tip position $\boldsymbol{p}_c = \begin{bmatrix} x_c & y_c & z_c \end{bmatrix}^{\mathrm{T}}$ in the frame of the CC model $\{\boldsymbol{C}\}$ can be derived based on geometric relationships. The Jacobian matrix $\boldsymbol{J}$ could be then calculated by differentiating the catheter tip position $\boldsymbol{p}_c$ with respect to the input variable $\boldsymbol{q}$. We establish its inverse kinematic function, which can be discretized to $\Delta\boldsymbol{q} = \boldsymbol{J}^{-1}\Delta\boldsymbol{p}_c$. The inverse Jacobian matrix $\boldsymbol{J}^{-1}$ could be calculated using the positional values in the last time step. The input command generated in the master part of the catheter robot can be represented as $\boldsymbol{u}$, which is linearly correlated to $\boldsymbol{q}$.

C. Autonomous Motion and Ablation

A series of targets in $\{\boldsymbol{C}\}$ for ablation are predefined around the pulmonary vein ostium in the phantom. Positional tracking devices record the real-time tip position $\boldsymbol{p}_w$ in the world coordinates $\{\boldsymbol{W}\}$. $\boldsymbol{p}_c$ and $\boldsymbol{p}_w$ are transformed using the rotation matrix $\boldsymbol{R}_w^c$ and translation vector calculated by registration approach.

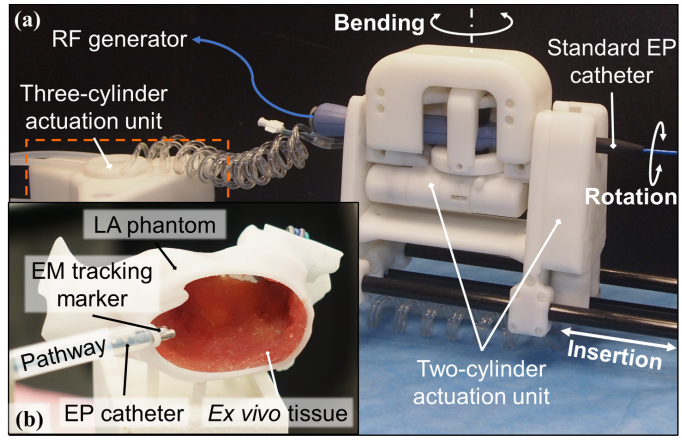

Fig. 2. **(a)** MR safe robotic catheter platform providing the 3-DoF manipulation (bending, rotation and insertion) of a clinical EP catheter; **(b)** EP ablation catheter manipulated to perform catheterization in a left atrial (LA) phantom model. EM tracking marker was attached on the catheter tip.

During each targeting cycle, the target could be appointed either automatically in clockwise (/counterclockwise) order or selected by the operator. Once a target is defined, the robot would approach it by a uniform speed. The error between current tip position $\boldsymbol{p}_c$ and desired position $\boldsymbol{p}^*$ would be calculated and normalized with a constant step size as $\Delta\boldsymbol{p}_c$, then multiplied by the inverse Jacobian matrix. When the error satisfies the tolerance distance, the robot would keep still for ablation or reset for another target. The control block diagram in **Fig. 1** shows the key processing components including the kinematic control and autonomous ablation.

III. Experimental Setup

A. MR Safe Robotic Catheter Platform

The control algorithm is implemented on an MR safe catheter robot [13] (**Fig. 2a**), which is capable of operating under intra-op MRI. The robot features a master-slave hydraulic transmission which can manipulate a clinical catheter in three degrees of freedom (DoFs) for bending, rotation and insertion. The master unit is actuated by electric motors located in the control room and the power can be transmitted to the slave part through 10-meter long hydraulic pipelines. The robot was designed to incorporate a standard cardiac EP catheter (Thermocool® Bi-Directional Catheter, Biosense Webster Inc.).

B. LA Phantom with Ex Vivo Tissue

To perform a simulated PVI task, a LA phantom model was designed and 3D-printed based on a patient-specific imaging data (**Fig. 2b**). A semi-rigid sheath was fixed near the transseptal puncture to the LA phantom. To simulate the cardiac tissue of the LA, a slice of swine tissue with a thickness around 3 mm was attached on the inner surface of the phantom. To allow RF ablation with the EP catheter, electric wires are fixed under the tissue and connected to the electrode pad of the RF generator.

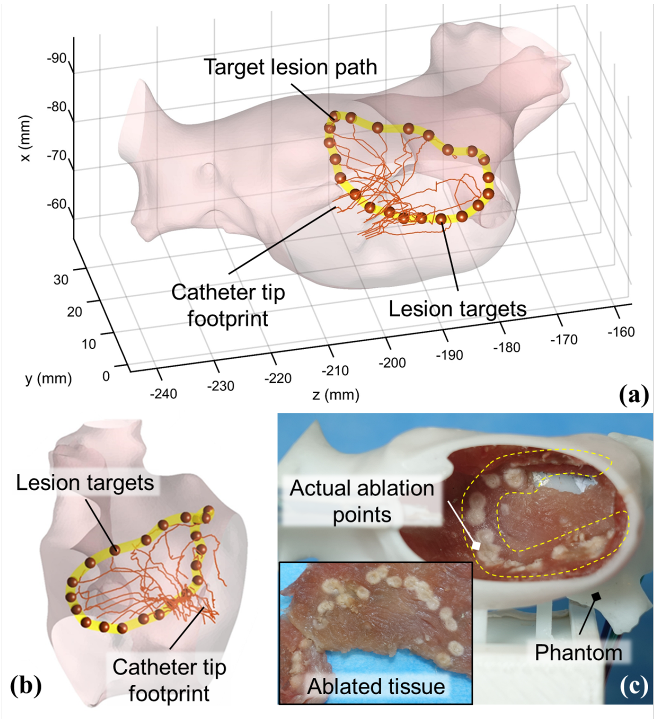

Fig. 3. Results of the PVI task conducted in LA phantom model. A standard EP ablation catheter was tele-manipulated to reach a series of targets around the pulmonary vein ostium. **(a)** Front view showing the catheter tip footprint, the 22 targeted ablation points, and also the desired lesion path (yellow). The footprint (red line) indicates the tip motions towards the targets; **(b)** Side view showing the catheter footprint covers along most of the path; **(c)** Tissue with ablated points (white) showing a nearly-closed lesion path.

IV. Performance Evaluation

To evaluate the performance of the controller incorporated with the catheter robot and standard cardiac EP catheter, a simulated PVI task with *ex vivo* tissue is performed inside the LA phantom model. To obtain the position and orientation (pose) of the catheter, a 6-DoF EM positional sensor (Ø0.8× 9 mm, NDI Medical Aurora) is attached near the catheter tip (**Fig. 2b**). During the task, the catheter is manipulated by the robot to reach the predefined ablation targets on the phantom (**Fig. 3a**). A tolerance of 2 mm is set for each target. RF ablation will be automatically triggered by an RF generator when the catheter tip reaches the target range and contacts the tissue. After conducting ablation at each target point, the robot will retreat for a distance of 20 mm and move towards next target.

As shown in **Fig. 3a-b**, the red dots, with a total number of 22, represent the predefined ablation targets, which then form a yellow line corresponding to the circumferential lesion targeted path nearby the pulmonary vein ostia. The footprint (red line) indicates the targeting motions towards the lesions. 18 out of the 22 (81.8%) lesion targets were successfully reached by the catheter tip and conducted RF ablation, leaving a set of scars (**Fig. 3c**). The actual lesion points on the *ex vivo* tissue (**Fig. 3c**) formed a nearly-closed ablation path, which matches the shape of the predefined lesion path. The average time taken to complete the targeting motion was 10.3s. The results demonstrate the capability of the control algorithm combined with the robotic catheter system to enable dexterous control for autonomous RF ablation.

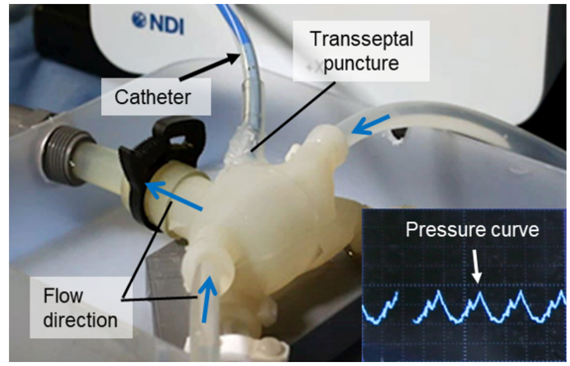

Fig. 4. LA phantom filled with liquid, of which the pulsatile flow is generated by a hydraulic pump. Such a liquid flow/pressure can be measured and indicated during the experiments.

V. Towards Realization of Robot-assisted Cardiac EP under Intra-operative MRI

In real practice, the pulsatile blood flow will impact the flexible catheter distal section, thus inevitably increasing the control difficulty. However, the implemented CC model-based controller is not able to compensate for these motions. Therefore, we will explore other controllers for the proposed setup to handle the influence of rapidly changing circumstance. An online-updated compensator based on Gaussian process regression (GPR) is considered to improve the targeting accuracy. In addition to modelling uncertainties, the external disturbances resulting from pulsatile flow would induces a dynamic position error. The compensator updated by GPR could adapt to the real-time environmental state by adding newly-collected sensing data into the trained GPR model. The combination of kinematic model-based control and an online compensator would have the potential to improve the controlling accuracy.

Real-time MR-based positional tracking of the catheter is the key component to close the robot control loop, instead of EM tracking system in the experiment. MR-*active* tracking can enable precise, fast and continuous 3D locations of the catheter tip in the MR image coordinates. Wireless tracking coil units can be integrated along the catheter body or close to its tip. Such coil units can resonate with Larmor frequencies (1.5T: 63.8 MHz or 3T: 123.5 MHz) by means of wireless inductive coupling with the MRI system [14]. Such wireless setting can avoid generating any RF interference to imaging, also any heating hazards along the cables.

In the upcoming work, we aim at testing the control algorithm of robotic catheterization using a phantom heart chamber with pulsatile liquid flow (**Fig. 4**). The flow and resultant motion of such a heart chamber, such as left atrium, could be gated with ECG signal, even the patient-specific one. Pre-clinical animal trials are also fell into our list of future work. RF ablation will be conducted on a live porcine prepared with arrhythmia. The proposed catheter will be made ready to operate with commercial MR conditional systems of 12-lead ECG acquisition and RF ablation (e.g. ClearTrace$^{\text{TM}}$, MRI Interventions, Inc. or Imricor Medical System). The necrosis created by RF ablation, and its efficacy, will also be examined with the post-mortem histology.

VI. Conclusion

In this abstract, we implement a control algorithm on a robotic catheter platform for autonomous control of a standard cardiac EP catheter. Experimental validation has been conducted by performing RF ablation in a LA phantom with *ex vivo* tissue. This preliminary result demonstrates the performance of the CC model-based controller applied to our robotic catheter platform in a static environment. In our future work, we intend to enhance the preclinical validation in the following aspects:

1) Conduct experiments with the phantom heart chamber simulated with the pulsatile liquid flow. The standard EP catheter will be controlled to perform RF ablation inside the dynamic environment;
2) Improve the controller by supplementing the current modelling approach with an online-updated compensator to handle the complex and rapidly changing disturbances inside the LA;
3) Validate the system under MRI by incorporating real-time MR-based positional tracking coils and commercial MR conditional RF ablation systems.

Acknowledgments

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