Kinematic-Model-Free Positional Control for Robot-Assisted Cardiac Catheterization

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INTRODUCTION

Cardiac electrophysiology (EP) [1] is a typical example of catheter interventions for cardiovascular diseases, in which a catheter is delivered from the femoral vein to perform ablation in the heart chamber. It requires precise targeting of the catheter tip at a small region for radio-frequency (RF) ablation of tissues in order to isolate the abnormal electrophysiological signals causing the arrhythmia. This procedure is considered as an effective treatment for heart rhythm disorder (arrhythmia). However, maneuvering of such a long and flexible catheter inside the cardiac chamber is still a challenging task even for the latest advances in the robotic-assisted platforms. The continuum structure of catheter, as well as the rapid cardiac motion, make it very difficult to predict the catheter motion during an intervention.

Previous research attempts [2] aim to control the catheter motion by deriving its explicit kinematic model; however, a number of assumptions, such as that the catheter shape bends as a series of connected arcs without torsion [3], are required. In the real practice, the number and length of these arcs can be changed rapidly due to numerous contacts along the vascular tissue.

To avoid dependency on model based kinematic control for catheter navigation, we developed a model-free control interface capable of providing effective teleoperated control of a clinically used catheter, with the incorporation of visual-motor alignment. A sequential sampling method, particle filtering [4], is used to update the mapping from actuation input to our proposed virtual camera coordinate smoothly in order to realign the visual-motor coordinates time-by-time. It aims to provide the operator with a consistent motion reference to maneuver the catheter tip aiming at the desired target in unknown or unstructured constrained environments. Subject tests have been conducted to demonstrate how the proposed approach enhances the navigation effectiveness.

MATERIALS AND METHODS

As shown in **Fig. 1**, a 2D virtual camera view is defined and attached at the catheter tip, of which the *z*-axis is aligned along the tip normal. The standard catheter is driven by 3 DoFs, namely advancement, rolling and steering $[l, q_r, q_s]$. The incremental tip displacement $\Delta \boldsymbol{x} = \left[x_C(k+1)-x_C(k) \quad y_C(k+1)-y_C(k)\right]^T$ is modelled as a linear function of the incremental change of the latter two DoFs $\Delta \boldsymbol{q}_C = [q_r(k+1)-q_r(k) \quad q_s(k+1)-q_s(k)]^T$ such that:

$$\Delta \boldsymbol{x} = \boldsymbol{J} \Delta \boldsymbol{q}_C \qquad (1)$$

where $\boldsymbol{J} \in \mathbb{R}^{2\times 2}$ is the Jacobian matrix **(Fig. 2)**.

A sequential sampling method, Particle Filtering [5], is implemented to update the Jacobian matrix $\boldsymbol{J}$ online from the measurement of $\Delta \boldsymbol{x}$ and $\Delta \boldsymbol{q}_C$.

The operator teleoperates the catheter with a motion input device specifying the desired change of tip position $\Delta \boldsymbol{x}^* = \left[x_C^*(k+1)-x_C(k) \quad y_C^*(k+1)-y_C(k)\right]^T$ in the virtual camera coordinate. The control input

$$\Delta \boldsymbol{q}_C = \boldsymbol{J}^{-1} \Delta \boldsymbol{x}^* \qquad (2)$$

accomplishes the visual-motor alignment where the catheter moves with the desired change $\Delta \boldsymbol{x}^*$ in the virtual camera coordinate.

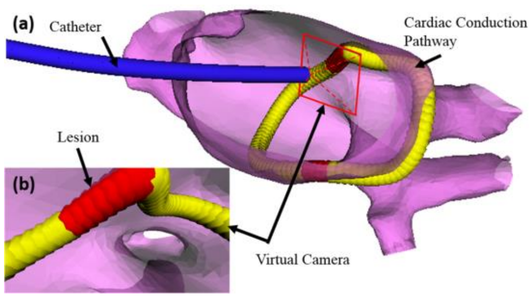

Fig. 1(a) 3-D cardiac roadmap (purple) with lesion targets (yellow) indicated on the pulmonary vein ostium. The targets in red depict the completion of RF ablation. **(b)** Virtual camera view is augmented from the catheter tip's point of view.

RESULTS

To evaluate the proposed catheter control approach, a teleoperated 3-DOF catheter robotic platform has been developed to perform simulated EP procedures on an atrium phantom. The catheter robot (**Fig. 3**(a)) is actuated by 3 stepper motors. Novint Falcon® Haptics

Controller is used for reading motion input command. An electromagnetic tracking system (NDI Aurora) keeps track of the position of catheter tip in the world coordinate. An atrium phantom model (**Fig. 3**(b)) has been fabricated based on a 3D model obtained from patient MR image. Such 3D printed phantom model aims to mimic the constraints characteristics in a clinical scenario.

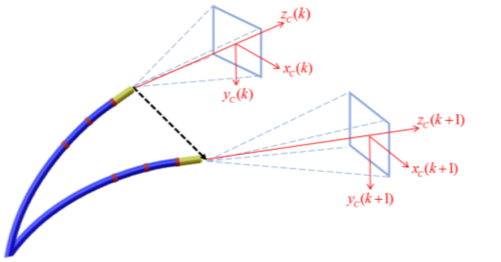

Fig. 2. Illustration of virtual camera coordinates aligned with catheter tip.

Subject tests (N=10, age ranging from 20-35) were carried out for evaluation, where the pulmonary vein isolation ablation tasks were simulated using the robotic experimental setup. Each subject performed the same task under two different conditions: 1) Only the fly-through view (**Fig. 1a)** was provided without the proposed control approach. 2) Fly-through view and the virtual camera view (**Fig. 1b**) were provided, where the proposed visual-motor alignment was employed. Each had to perform RF ablation on pre-defined lesions within 5 minutes. The RF ablation at the catheter tipwas activated by a foot pedal.

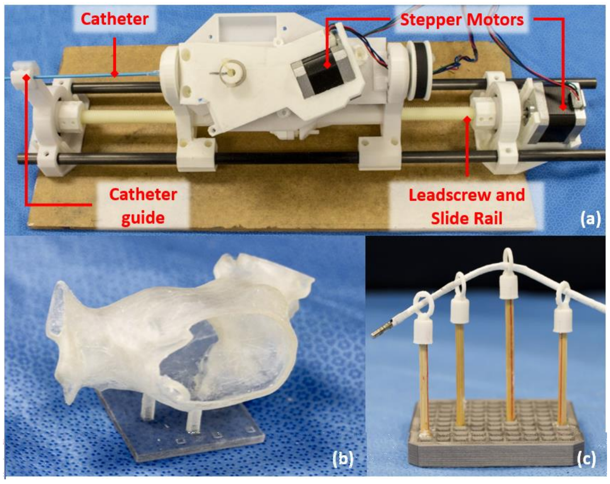

Fig. 3. (a) Tele-operative robotic catheter platform actuated by stepper motors. (b) An atrial phantom model. (c) The catheter is telemanipulated to pass through a series of ring checkpoints.

The performance in terms of: 1) Task accuracy, and 2) Task efficiency are shown in Table I. The total distance traveled and the ablation missed percentage were both measured and evaluated as task efficiency. A maximum of 41% improvement in missed target reduction could be found among the subjects and the average travel distance was reduced by 27%. For task efficiency, subjects were observed that they could successfully ablate a certain target with less attempts using our proposed control method which offers better awareness of distance between the catheter tip and lesion target.

TABLE I. PERFORMANCE INDICES AVERAGED ACROSS THE 10 SUBJECTS IN PERFORMING THE SIMULATED ROBOTIC CATHETERIZATION

	Without alignment		With alignment		Improve ment.
Task Efficiency	Mean	SD	Mean	SD	% *p-val.
Aver. Trav. Dist. (mm)	207	30.9	167	35.4	28.8% *0.13
No. of missed target (%)	80.0	1.7	76	6.4	9.3% *0.28
Task Accuracy	Mean	SD	Mean	SD	% *p-val.
No. of times ablation has turn on	12	7.9	8.8	5.0	9.5% *0.54
Average ablation time (sec)	3.41	0.37	3.64	1.26	-6% *0.72
Average tip to lesion target distance (mm)	3.98	0.36	2.48	0.2	37.7% *0.009

DISCUSSION

To avoid dependency on analytical kinematics model, we propose a model-free kinematics control framework for cardiac catheterization, by means of a time series forecasting method called Particle Filtering. To the best of our knowledge, it is the first successful attempt to exploit such time-series forecasting concept in surgical catheterization applications. Promising improvements in both effectiveness and accuracy were found in subject tests, where the proposed method achieved a more accurate control of the catheter in reaching the target ablation point and shorter time for repositioning the catheter tip than without the visual-motor alignment provided. The future work will focus on the extension of the proposed method into dynamic environments, such as navigation under the rapid deformation of cardiovascular tissues due to cardiac motion.

ACKNOWLEDGMENT

This work is supported in parts by the Croucher Foundation and the Research Grants Council (RGC) of Hong Kong. We sincerely thank to the team in the Division of Cardiology, the Prince of Wales Hospital, The Chinese University of Hong Kong (CUHK) for the access to their equipment.

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