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Path optimization and control of a shape memory alloy actuated catheter for endocardial radiofrequency ablation

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HIGHLIGHTS

- A path optimization and control strategy for shape memory alloy actuated cardiac ablation catheters is presented.
- Catheter tip locations and orientations are optimized using parallel genetic algorithms.
- Closed-loop control of the SMA-actuated catheter along optimized paths is validated experimentally.

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ABSTRACT

This paper introduces a real-time path optimization and control strategy for shape memory alloy (SMA) actuated cardiac ablation catheters, potentially enabling the creation of more precise lesions with reduced procedure times and improved patient outcomes. Catheter tip locations and orientations are optimized using parallel genetic algorithms to produce continuous ablation paths with near normal tissue contact through physician-specified points. A nonlinear multivariable control strategy is presented to compensate for SMA hysteresis, bandwidth limitations, and coupling between system inputs. Simulated and experimental results demonstrate efficient generation of ablation paths and optimal reference trajectories. Closed-loop control of the SMA-actuated catheter along optimized ablation paths is validated experimentally.

1. Introduction

Atrial Fibrillation (AF) is the most common cardiac arrhythmia, affecting over 2.7 million Americans, and is a leading cause of thrombus and stroke [1,2]. AF occurs when the heart's normal electrical impulses are disrupted by random electrical activity, preventing organized contraction of the heart's upper chambers, causing only partial blood evacuation to the lower chambers. Treatment typically requires isolating these abnormal electrical impulses by forming scars in the atrial tissue. Published success rates of open-heart procedures (i.e. Cox Maze [3]) exceed 90%, but the surgeries are highly invasive and complex, encompassing the risks and long recovery associated with open-heart surgery [4]. Alternatively, minimally-invasive catheter ablation can be used to create lesions by burning or freezing the atrial tissue. Current catheter ablation procedures are tedious, time-consuming, and result in significant X-ray exposure to the patient and medical team [5,6]. Success requires highly skilled catheter manipulation in the beating heart, and constant surface contact for transmural and continuous lesions [7,8].

Teleoperated (i.e. robotic) catheters have the potential to enhance catheter maneuverability in the heart, reduce procedure times, and increase the range of motion and contact stability during ablation. Previous work has focused on the design, optimization, and fabrication of shape memory alloy (SMA) actuated robotic catheters for endocardial ablation [9,10]. The SMA-actuated catheter used here (Fig. 1) consists of two bending segments: the distal segment containing the catheter tip, and the adjacent proximal segment. Each segment is actuated by four offset SMA tendons, which produce bending in the catheter. Pulse-width modulation (PWM) is used to regulate electrical power in each tendon based on commands sent from a custom C++ control application. The ability to create continuous, transmural lesions is the fundamental performance objective of this SMA-actuated catheter. This requires not only precise position control of the catheter tip, but also sufficient surface contact, most easily achieved through maintaining the catheter tip perpendicular to the atrial tissue.

Catheter tip position (x_D, y_D, z_D) (Fig. 2) is kinematically dependent on the proximal (P) and distal (D) bending (θ_P, θ_D) and orien-

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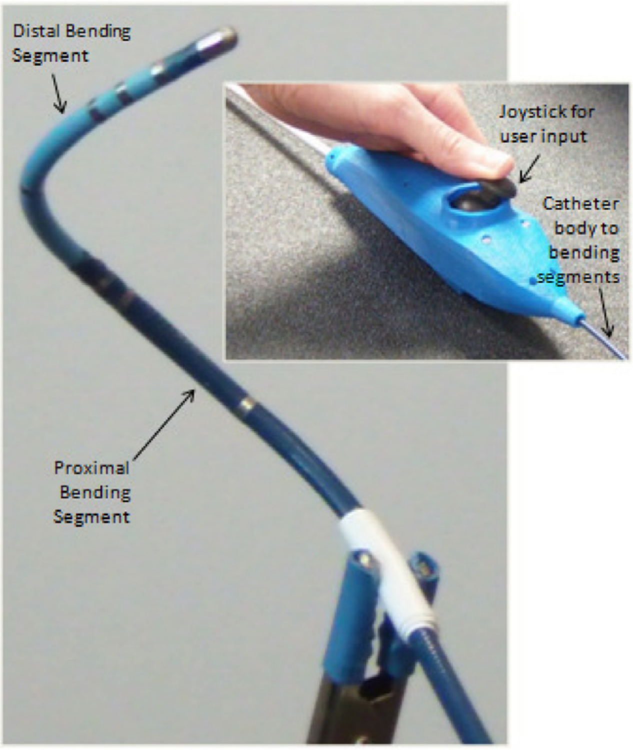

Fig. 1. SMA-actuated catheter showing proximal and distal bending segments and catheter handle with joystick for user input.

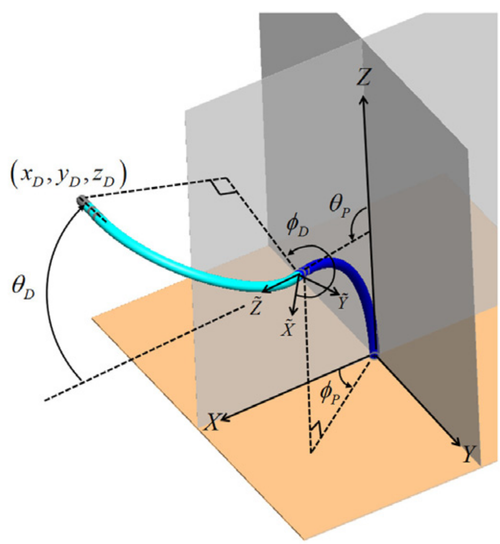

Fig. 2. Coordinate systems of the SMA-actuated catheter: proximal segment bending and orientation angles (θ_P, ϕ_P) and catheter tip location (x_D, y_D, z_D) relative to the global *XYZ* coordinate system, and distal segment bending and orientation angles (θ_D, ϕ_D) relative to the local $\tilde{X}\tilde{Y}\tilde{Z}$ coordinate system.

tation (ϕ_P, ϕ_D) angles. Multiple combinations of these angles can achieve a given tip position (Fig. 3); this redundancy enables limited control of catheter tip orientation. Optimization can be used to determine the most advantageous tip position and orientation to create transmural lesions in minimal time.

Widespread clinical adoption of this robotic catheter ablation technology requires robust, real-time control of the bending segments, which is complicated by the highly nonlinear, hysteretic behavior of the thermally-activated SMA tendons. Hysteresis compensation of SMA actuators has been investigated extensively [11–14]. Additionally, the literature is replete with control

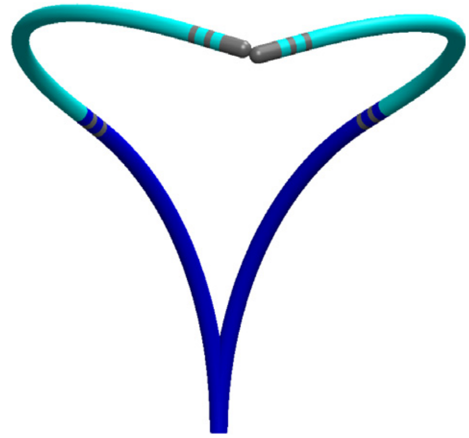

Fig. 3. Kinematic redundancy of the two segment catheter showing identical tip position achieved with different catheter orientations.

algorithms developed to address SMA bandwidth limitations [15–21]. However, the multivariable control problem presented here introduces additional challenges: axial compression, coupling between tendons, tendon slack, and redundancy in catheter tip positioning.

This paper presents a trajectory optimization and control strategy for the dual segment SMA-actuated catheter, with emphasis on the efficient creation of continuous, transmural lesions in atrial tissue during endocardial radiofrequency ablation. The proposed clinical procedure for creating lesions is as follows:

I. Using the catheter's joystick, the physician navigates the catheter tip and specifies three critical locations on the endoatrial surface.
II. An algorithm computes an ablation path through these physician-specified locations.
III. Optimal bending and orientation angles are generated for several locations along the path.
IV. Real-time control algorithms ensure adequate tracking of the reference trajectory during ablation.

Steps I and II are discussed in Section 2.1. For Step III, the optimization problem is presented in Section 2.3 and the solution method is detailed in Section 2.4. The controller for Step IV is described in Section 2.5. Simulated and experimental results are presented in Section 3, with concluding remarks presented in Section 4.

The method presented here serves as a first step toward developing an optimization and control strategy for this sophisticated clinical procedure. Two key assumptions are made in the derivations and analyses presented here. First, the desired ablation paths are assumed to be planar. While this assumption might be valid for short lesions along the atrial wall, its validity is questionable for longer lesions along concave surfaces of the heart. In such cases, step II can be modified to account for the more complex ablation path; all other steps will remain valid. The second assumption is that the optimal bending and orientation angles are obtainable within the confined spaces of the heart. A special term was included in the cost function derived in Section 2.3 to address this, however future work must focus on refining this term and possibly adding tissue contact constraints to the optimization.

2. Methods

2.1. Ablation path

The methods described here begin with three physician-specified points on the atrial wall (A, B, and C), expressed in global *XYZ* coordinates (the global coordinate system is located at the