Mechatronics 44 (2017) 94–106

Contents lists available at ScienceDirect

Mechatronics

journal homepage: www.elsevier.com/locate/mechatronics

Backlash characterization and position control of a robotic catheter manipulator using experimentally-based kinematic model☆

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ARTICLE INFO

Article history:
Received 4 June 2015
Revised 15 March 2017
Accepted 1 May 2017

Keywords:
Position control
Catheter
Backlash compensation
Inverse kinematics

ABSTRACT

This paper deals with the problem of position control of a robot-assisted catheter manipulator for intracardiac interventions. Kinematic controllers based on the Jacobian inverse are not suitable for the catheter because of multiple singularities in the workspace and significant backlash of the system. To tackle these issues, first, the backlash of the system in axial translation and twist motion due to the interaction of the catheter with the veins through which it passes, are characterized. The effects of variations in clinical settings on the backlash parameters are identified through extensive experiments simulating the clinical procedure. Next, to properly compensate for the backlash behavior of the catheter distal shaft, an inverse kinematic model is proposed based on experimental data. A position controller is developed and implemented using the experimentally-based inverse kinematics and the identified inverse backlash model for the twist and axial motion. The results of experiments performed using a robotic catheter manipulation system show that with a proper choice of controller gains, the proposed scheme is able to guide the catheter tip to the goal with the desired behavior. The tracking performance of the controller has also been evaluated under the dynamic external force simulating the blood drag force. The empirical results demonstrate the improved performance of the proposed approach against the existing kinematic-based and uncompensated control schemes.

1. Introduction

Intracardiac catheterization is an effective procedure for treatment of many cardiac disorders such as arrhythmia. The operation involves advancing several catheters into the patient's cardiac chambers to conduct electrophysiologic (EP) studies and radiofrequency (RF) ablation or cryoablation. It is usually performed manually by axial translation and twisting the proximal body and deflecting the distal shaft of the catheter, using a steering knob at the handle, as shown in Fig. 1(a). For steering of commercially available ablation catheters, tendon mechanism is used. Usually, a knob in the handle of the catheter is used to pull the tendon, which is attached to the tip of the catheter through its body, causing the change in the distal shaft curvature.

Manual navigation of steerable catheters (Fig. 1(b)) is a challenging task and could entail prolonged exposure of the interventionalist and the patient to ionizing x-ray radiation. Moreover, because of the high flexibility and non-smooth behavior of the catheter, accurate positioning of the tip is difficult to realize. Research and development activities have thus focused on facilitating the navigation of the catheter by replacing the interventionalist's hand with an easy-to-operate mechanism [1,2]. Clinical studies imply that the remote catheter navigation systems such as Sensei® robotic catheter system (Hansen Medical®, Mountain View, CA) and Niobe® magnetic navigation system (Stereotaxis, St. Louis, MO), are effective in reducing the radiation exposure of the interventionalist and patient [2]. However, the operations performed by such systems are still manual in nature, i.e., the procedure is not automatically controlled. Another limitation of such technologies is their significant operation cost due to the use of specially designed sheaths instead of the commercially available cardiac catheters. The focus of this paper is, however, on the automatic positioning of the commonly available cardiac catheters inside the heart. We assume that the catheter is manually advanced to the cardiac chamber before the implementation of the automatic controller. In practice, due to the straight shape of the veins and their increasing diameters from the catheter insertion point to the heart, the catheter insertion phase of the procedure does not usually suffer from complication and is performed within a few minutes. The majority of the procedure time and efforts of the clinicians are spent on navi-

☆ This paper was recommended for publication by Associate Editor Prof. M. Steinbuch

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http://dx.doi.org/10.1016/j.mechatronics.2017.05.002
0957-4158/

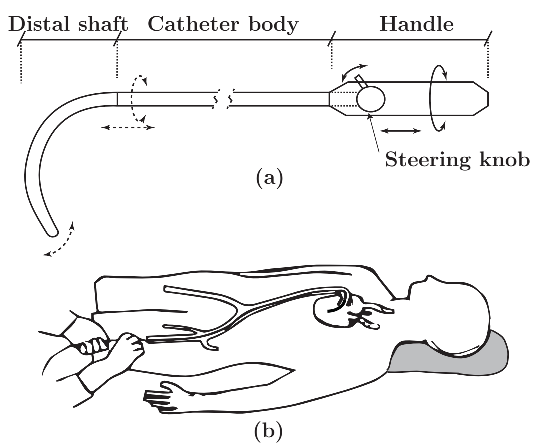

Fig. 1. Schematic view of a steerable catheter (a). Manual catheterization (b).

gating the catheter inside cardiac chambers. Automatic positioning of the catheter can considerably reduce the x-ray exposure time and contribute to the effectiveness of the procedure by accurate positioning of the tip electrode to the desired position of the heart tissue.

In robotics literature, cardiac catheters can be classified under continuum manipulators, which can be defined as continuously bending infinite degrees of freedom (DoF) robots with smooth curve shapes. Cardiac catheters are distinguished by their axial translation whereas continuum robots usually have fixed bases. Current trends in continuum robot modeling and position control involve the development of forward and inverse kinematic relationships, based on constant curvature or “semi-rigid structure” assumption [3–5]. This assumption leads to a closed-form kinematic model of the flexible robot that allows the use of traditional position control algorithms developed for rigid robot manipulators. The performance of this approach has been studied for navigation control of the intracardiac catheter in [6]. One drawback of the inverse kinematic control based on constant curvature model is the existence of singularities of the catheter in multiple points within the workspace which degrades the stability of the motion in the vicinity of the singular points. Additionally, the kinematic-based controller relies on a simplified model of the catheter which does not account for the backlash behavior of the distal shaft. Recently, the non-smooth behavior of the catheter due to the tendon actuation mechanism, without considering its interaction with the surrounding environment, has been experimentally obtained for a cardiac catheter [7] and modeled for a specially designed catheter [8]. A simple inverse backlash model has also been adopted in [9] to compensate the inherent dead-zone of the tendon actuation mechanism of intracardiac echocardiography catheters. As opposed to the experimentally-based approach presented in the current paper, the compensation approach in [9] still relies on the kinematic model of the catheter which might significantly deviate from its real behavior.

In addition to the nonlinearities associated with the tendon mechanism, interaction of the catheter with the environment in which it navigates contributes to the non-smooth behavior of the catheter. Nevertheless, there are not many studies on quantification and compensation of the interaction between catheters and their surroundings. Modeling and compensation of the backlash behavior of the catheter as a result of its friction and buckling inside a guiding sheath has been performed in [10,11]. However, in these studies only one DoF of the system has been considered, i.e., it is assumed that the catheter can only move in the axial direction. As opposed to the existing literature, the current paper characterizes the catheter-vein interaction for not only the axial translation but also the twist motion of the catheter. Additionally, because for the case of the catheter ablation procedure, the catheter passes through veins with the geometry that may vary significantly from one patient to another, in-depth experimental analyses have been performed to evaluate the effect of variations in the vasculature anatomy on the backlash characteristics of the catheter.

Beside the kinematic-based approach, another approach for position control of continuum robots that has been proposed and implemented for concentric tubes is to use the static Jacobian instead of the kinematic one [12,13]. This approach requires the solution of the static model of the catheter which is not practical for the fast moving environment of the heart where the control frequency required is more than 10 Hz.

In this paper, we propose a position control scheme for robot-assisted catheter manipulation systems, using experimentally obtained inverse kinematics. The uniqueness of the proposed controller is that, since it is based on the experimental data, it can intrinsically compensate for the non-smooth dynamics of the distal shaft due to the tendon actuation. The controller is computationally efficient and singularity-free. Compensation of the backlash behavior of the catheter due to its interaction with the surrounding veins, for both axial translation and rotation, is also incorporated in the control scheme. That makes this work, to the best knowledge of the authours’, the first study that characterizes the backlash behavior of intracardiac catheters for all 3 DoFs of the system. The proposed backlash compensation along with the experimentally obtained inverse kinematics form an integrated control structure for 3D navigation of commercially-available cardiac catheters.

The rest of this paper is organized as follows. In Section 2, characteristics of the robotic catheter manipulation system are identified for each DoF of the system. Section 3 proposes the experimentally-based inverse kinematics for the cardiac catheter. Section 4 introduces the structure and components of the position controller. Results of the experiments performed under conditions simulating the heart environment are presented in Section 5. The paper concludes by discussing the results and suggesting directions for further research.

2. Characterization of the catheter backlash behavior

At the beginning of the ablation procedure, when the catheter enters the cardiac chamber through veins, the catheter tip is required to be guided to the target tissue using axial translation, twist and bending of its distal portion. However, the vein interaction forces applied along the long body of the catheter cause the backlash behavior of the catheter in its axial translation and rotation. The rest of this section characterizes this backlash for different parameters of the vascular system. It is worth noting that the effect of the beating heart on the catheter motion will be later included in the experimental evaluation by an oscillating external force applied at the distal shaft.

2.1. Experimental setup

The setup consists of a 3 DoF robotic catheter manipulator developed in the laboratory as shown in Fig. 2, to perform the catheter manipulations similar to the interventionalist’s hand in the interventional procedure. Axial translation of the catheter is performed by a motorized linear stage (Velmex, Bloomfield, NY) which pulls/pushes two rotary stages and the catheter handle. The first rotary gear system is responsible for the axial rotation (twist) of the catheter. Bending of the distal portion of the catheter is performed by the rotation of the steering knob using a second rotary stage. All three stages are driven by stepper motors coupled with shaft encoders.