Towards Automatic Manipulation of Intra-cardiac Echocardiography Catheter

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Intra-cardiac Echocardiography (ICE) has been evolving as a real-time imaging modality of choice for guiding electrophysiology and structural heart interventions. ICE provides real-time imaging of anatomy, catheters, and complications such as pericardial effusion or thrombus formation. However, there now exists a high cognitive demand on physicians with the increased reliance on intraprocedural imaging. In response, we present a robotic manipulator for AcuNav ICE catheters to alleviate the physicians burden and support applied methods for more automated. Herein, we introduce two methods towards these goals: (1) a data-driven method to compensate kinematic model errors due to non-linear elasticity in catheter bending, providing more precise robotic control and (2) an automated image recovery process that allows physicians to bookmark images during intervention and automatically return with the push of a button. To validate our error compensation method, we demonstrate a complex rotation of the ultrasound imaging plane evaluated on benchtop. Automated view recovery is validated by repeated imaging of landmarks on benchtop and in vivo experiments with position- and image-based analysis. Results support that a robotic-assist system for more autonomous ICE can provide a safe and efficient tool, potentially reducing the execution time and allowing more complex procedures to become common place.

Index Terms—Intra-cardiac echocardiography (ICE), Catheter, Continuum manipulator, Tendon-driven flexible robot, Path planning, Automated View Recovery, Non-linear elasticity compensation, Cardiac Imaging

I. INTRODUCTION

Interventional cardiology has expanded its role dramatically in recent years to now encompass treatment of many disease states which were once considered to only have surgical options. This growth has been significantly motivated by the introduction of new treatment devices and advances in intraoperative imaging modalities. Intra-cardiac echocardiography (ICE) has been evolving as a real-time imaging modality for guiding interventional procedures in electrophysiology[1, 2, 3, 4], congenital[5, 6], and structural heart interventions[4], among others. When compared to another more established real-time imaging modality, transesophageal echocardiography (TEE), ICE has improved patient tolerance by not requiring esophageal intubation, requires only local anesthesia with conscious sedation, does not require an additional sonographer operator for imaging, and does not interfere with fluoroscopic imaging[7]. Real-time ICE imaging has an expanding role in providing uninterrupted guidance for valve replacement interventions[8, 9, 10, 11, 12, 13, 14, 15], left atrial appendage closure[16, 17, 18, 19, 20, 21], septal defect closure[22, 23, 24], and catheter-based ablation for cardiac arrhythmia[25, 26, 27, 28]. However, with the increased reliance on imaging to perform these complex procedures, there is a high cognitive demand on physicians, who now must perform both the interventional task and simultaneously acquire the guiding images. Moreover, they are not experts in reading ultrasound and navigating these images, which makes ICE handling even more difficult.

ICE imaging requires substantial training and experience to become comfortable with steering the catheter to desired cardiac anatomical views, which hinders its adoption as standard of care[29, 13, 6]. In practice, the interventionalist is needing to continuously manipulate several catheters throughout the procedure, each having different control mechanisms. For example, a typical ablation treatment for cardiac arrhythmia can require tens to hundreds of individual ablations at very specific locations. ICE imaging can be beneficial for monitoring for developing complications, targeting anatomy, facilitating adequate tissue contact, and monitoring lesion development during ablations[26]. However, this can become an iterative and time-consuming procedure when frequently needing to re-position the therapeutic and imaging catheters. In structural heart procedures, clinicians can manipulate the ICE catheter to localize and measure the area of treatment and then either park (e.g. to watch for complications) or retract the ICE imaging catheter while devices are deployed under fluoroscopic guidance. The ICE catheter is then relocated to visually confirm that devices are sufficiently placed. This manner of repeated manipulation throughout the course of treatment is common for interventions across disciplines but requires intensive coordination, spatial understanding, and manual dexterity that can lead to fatigue in longer or more difficult procedures, imposes a significant learning curve for new users, and does not apply ICE imaging to its potential.

When considering these limitations, it is clear that a robotic-assist system to hold and actively manipulate the ICE catheter,
either through an operator input or semi-autonomy, could ease the workload of the physician during treatment and potentially enable the use of ICE for novel and more complex procedures. Currently, there have been several commercial robotic systems to manipulate catheters on the market, including Amigo RCS (Catheter Precision, Inc., Mount Olive, NJ, USA), CorPath GRX (Corindus Inc., Waltham, MA), Magellan (Hansen Medical Inc., Mountain View, CA, USA), and Sensei X (Hansen Medical Inc., Mountain View, CA, USA). One commercially-available robotic system for ICE catheter manipulation is the Sterotaxis V-Sono system[30], which controls ICE catheter robotically, but limited degree-of-freedoms. The main features available robotic system for ICE catheter manipulation is the Sterotaxis V-Sono system[30], which controls ICE catheter robotically, but limited degree-of-freedoms. The main features are to provide robotic control of devices by human operators at the remote cockpit based on imaging (e.g. fluoroscopic) feedback. Loschak et al. [31] provide a method using electromagnetic (EM) tracking systems to accurately sweep the ultrasound imaging plane about a position, thus creating a way to actively maintain focus within the field of view. In further work [32] they apply a filtering method from EM sensors to compensate for respiratory motion. However, traditional sensors like EM cannot always be mounted at the tip of the catheter to provide required feedback due to practical limitations (e.g. cost, size, sterilization). In practice, ICE catheters of the Siemens AcuNav ICE catheter family are single use with no sensors installed, therefore the controller for such a robotic-assist system requires an open-loop where spatial feedback are not continuously available. In this work, we apply a robotic catheter controller to enable control mechanisms which directly address the previously described challenges to standard use (e.g. repeated manipulation and cycling between views) in an open-loop control system (i.e. no additional sensors required).

In this paper, we introduce new methods to simplify ICE catheter manipulation for the interventionalist—both processes enabled by a robotic controller. Figure 1 shows an overview of the proposed robotic-assisted system. More specifically, (1) We propose a data-driven method to compensate kinematic model errors due to non-linear elasticity fields in the bending planes that result from the catheter structure. With this, we demonstrate a method to spin the ultrasound imaging plane about the catheter axis while maintaining the catheter tip position, which also serves to evaluate the kinematics. (2) In response to limitations in current clinical ICE workflows, we propose an automated image recovery method which can reproduce important views that have been previously saved by the user during the procedure. We implement methods to incrementally generate a topological map, which facilitates to retrace a path to the specific view. We evaluated the proposed methods on benchtop and in a series of animal experiments.

The main contributions of this paper are:

- Data-driven models to compensate catheter kinematics for highly non-linear behaviors caused by the structural composition of the ICE catheter; these methods are evaluated with a practical learning method in the scenario of imaging while rotating about the catheter axis and maintaining a fixed catheter tip (i.e. image spinning) in benchtop studies.
- An automated view recovery method; we introduce a method to incrementally generate a topological map detailing the history of catheter motion during a procedure. When queried, the method provides a path to a specified view that can be reproduced at anytime by the robotic controller.
- The first known systematic evaluation of robotic ultrasound view recovery and image spinning for ICE catheter in in-vivo studies.

II. BACKGROUND AND RELATED WORKS

A. Kinematics and non-linear elasticity models of steerable catheters

An ICE catheter is a long, thin, and flexible structure, categorized as a continuum device. In which, two pairs of tendon mechanisms in the backbone control the ICE catheter tip, creating an underactuated system. Use of this flexible structure in practical applications requires models of robotic shape and motion, which is more complex than traditional rigid body robots. Several approaches exist to characterize positions, forces, and moments of the tip by actuators and external interactions with the environment. However, due to the complexities of modeling, most methods are solved numerically. As such, many publications have presented a simplified approach. The piecewise constant curvature (CC) approximation models the robot as a series of mutually tangent constant-curvature arcs[33], therefore providing closed-form kinematics and Jacobian formulation. There exist two mapping stages: one is from joint space to configuration parameters that describe constant-curvature arcs and the other mapping is from these configuration parameters to task space, consisting of a space curve which describes position and orientation along the backbone (detailed in Figure 2-3 in Robert J. Webster III [33]). Many continuum manipulators related to medical applications (e.g. endoscopes [34, 35, 36], colonoscopes [37], catheters [31]) are composed of arcs. While imperfect, the constant curvature models are widely applied due to remarkable usefulness of the model approximation. In this work, we apply the constant curvature model as a baseline. However,
the existing ICE catheter is controlled by multiple tendons, which are coupled and have non-linear tensions due to polymer effects (detailed in Section III-A). As a result, the assumptions of the constant curvature model are invalidated; the effects of plastic torsion are neglected. Therefore, additional mapping functions are required to have concise control of the tip. There exist several works [35, 36, 38] related to friction/hysteresis compensation in tendon-driven manipulators. Camarillo et al. [39] studied tendon configuration tracking methods to independently control the multiple sections of a catheter. Kato et al. [34] proposed the forward kinematic mapping method to compensate tension propagation due to hysteresis operation. Similarly, we construct an extended kinematic mapping function; however, focusing on compensation of non-linear elasticity in the bending plane.

B. Ultrasound Imaging and Automation

For some time, physicians have applied ultrasound imaging to observe, detect, and track target anatomies or surgical tools [40, 41] to great effect in a wide variety of procedures. Ultrasound image-based (semi-) autonomous robotic systems have been studied extensively for use in tracking the prostate for brachytherapy [42], to aid in target visualization and tool positioning for liver ablation [43, 44], to detect the tumor boundary in partial nephrectomy [45], and for catheter tracking in multimodal imaging [46].

Robotic catheter systems have been developed to improve maneuverability [31], compensate for the heart motion [32], and mapping for catheter navigation [47]. However, there are still many interventional processes that can benefit from the fast, repeatable, and precise controls that robotic manipulation can provide. Accordingly, we expect that the automated view recovery method presented in this work to be of high value to clinical ICE imaging.

III. MATERIALS AND METHODS

First, we present the ICE catheter mechanism, our robotic system, and we re-visit the existing kinematics models with our proposed compensation method. Then, we introduce our view recovery method.

A. ICE catheter mechanism

The ICE catheter structure has a highly nonlinear behavior due to various slack, elasticity, and hysteresis phenomena in multiple coupled components involved in tendon control. The mechanical composition of the ICE catheter (Figure 2 (a)) is based on two pairs of tendon-sheath pull mechanisms, which consist of a hollow polymer as a sheath and a thread sliding inside the sheath acting as a tendon. Each pair is bound to a common knob, which can pull an individual thread by rotating the knob, allowing one thread to be pulled while the other remains passive. This structure assumes ideally zero-slack transition between threads; however, this is not realistically achievable. Moreover, the ultrasound array is located in the center of the two pairs of tendon mechanisms which are covered by the outer polymer shell for sterilization purposes (Figure 2 (b)). Highly nonlinear behaviors exist due to these structural considerations and lead to the extreme mechanical tolerances presented in Figure 2 (c).

Precise prediction of the catheter tip pose for a specific knob configuration is therefore challenged by these non-linear properties. EM tracking systems have been used to co-localize the tip of the catheter in space. However, this increases the cost of the catheter and is currently only available, or clinically used, for EP procedures. In this paper, we investigate an open-loop control to address these challenges.

B. ICE catheter kinematics

We developed an ICE catheter robotic control system for this study. Our robot manipulator consists of two components as shown in Figure 1: 1) A “Front” component holds the catheter shaft, sits directly outside of the introducer sheath, and contributes linear and rotational motion of the catheter. 2) A “Back” component holds the catheter handle and controls the two knobs for the bending of the catheter tip, and bulk rotation of the catheter. Moreover, this bulk rotation is synchronized with the Front.

The robot has 4 degrees of freedom. Without loss of generality, we follow the same nomenclature from [31]: two DOFs for steering the catheter tip in two planes (anterior-posterior knob angle $\phi_1$ and right-left knob angle $\phi_2$) using two knobs on the catheter handle, bulk rotation $\phi_3$, and translation $d_4$ along the major axis of the catheter. We define the robot’s configuration, $q = (\phi_1, \phi_2, \phi_3, d_4)$ in $\mathbb{R}^4$. The robot can be controlled by manually using an external joystick, which provides a digital input that is directly mapped to the standard knob controls of the catheter or a more intuitive control scheme where the users inputs are directly applied at the catheter tip coordinate frame.

For completeness, we summarize the explicit closed-form kinematics model based on [31]. The overall catheter bending
geometry is described in Figure 3. To use constant curvature models, we set up the base coordinate frame \( T_{base} \) for the bottom of the bending section, and \( T_{tip} \) is the catheter tip coordinate frame where the ultrasound array is installed and the center of the image facing direction is \( \hat{n}_{tip}^x \). The bending section length is defined as \( L \).

**Forward Kinematics (FK) from \( q \) to \( T_{tip} \):**

There exist two configuration parameters in the constant curvature model, \( \theta \) and \( \alpha \); \( \theta \) is the right-handed rotation angle from \( \hat{n}_0^x \) (the \( x \)-axis of \( T_{base} \)) along \( \hat{n}_0^z \) (the \( z \)-axis of \( T_{base} \)); \( \alpha \) is the the angle of the curvature, which is computed from anterior-posterior thread deflection, \( L_{ap} \), and right-left thread deflection, \( L_{rl} \). These thread deflections are normally computed from \( \phi_1 \) and \( \phi_2 \) with a knob radius \( r_{knob} \) as \( L_{ap} = \phi_1 \cdot r_{knob} \) and \( L_{rl} = \phi_2 \cdot r_{knob} \). Then, \( \alpha \) can be computed as \( \sqrt{(L_{ap}/r_{catheter})^2 + (L_{rl}/r_{catheter})^2} \), where \( r_{catheter} \) is a catheter radius.

The remainder parts of kinematics as follows:

\[
\begin{align*}
\theta &= \tan^{-1}(\phi_2/\phi_1), \quad r = \frac{L}{\alpha} \quad (1) \\
\hat{x}_{tip} &= r \left( 1 - \cos \alpha \right) \cos \theta, \\
\hat{y}_{tip} &= r \left( 1 - \cos \alpha \right) \sin \theta, \\
\hat{z}_{tip} &= r \sin \alpha, \quad (2)
\end{align*}
\]

More specifically, \( \theta \) is the angle between the bending plane (due to \( \phi_1 \) and \( \phi_2 \)) and the X-Z plane when \( \phi_3 = 0 \) (Figure 3). \( \phi_3 \) will be added later. \( r \) is the radius of curvature in Equation (1). Then, the catheter tip position \( \hat{P}_{tip} \) is calculated from Equation (2).

The orientation of the tip can be calculated by the Rodrigues’ rotation formula, which is a method for rotating a vector in space, given an axis and angle of rotation. Let \( R(\mu, \beta) \) be the rotation matrix using Rodrigues’ rotation formula from the given axis \( \mu \) and rotating it by an angle \( \beta \) according to the right hand rule. Then, the orientation of the tip is computed by \( R(\hat{n}_{bend}, \alpha) \), where \( \hat{n}_{bend} \) is the vector orthogonal to the bending plane.

Let \( T_{tilt} \) be the 4x4 transformation matrix from \( \hat{P}_{tip} \) and \( R(\hat{n}_{bend}, \alpha) \) without the body rotation \( \phi_3 \) and translation \( d_4 \). The rotation of \( \phi_3 \) is \( T_{roll}(\phi_3) \). The translation of \( d_4 \) is \( T_{trans}(d_4) \). Then, the overall transformation matrix \( T_{tip} \) is given as \( T_{trans}(d_4) \cdot T_{roll}(\phi_3) \cdot T_{tilt} \).

**Inverse Kinematics (IK) from \( T_{tip} \) to \( q \):**

Similarly, a closed-form solution of the inverse kinematics is as follows based on [31]:

\[
\begin{align*}
\alpha &= \cos^{-1}(\hat{n}_0^z \cdot \hat{n}_{tip}^x), \\
\theta' &= \arctan2(\hat{n}_{tip}^y, \hat{n}_{tip}^x), \\
\phi_3 &= \theta' - \arctan2(\hat{n}_{tip}^y \times R(\hat{n}_0^z, \alpha) \cdot \hat{n}_{tip}^x \cdot R(\hat{n}_0^z, \alpha),) \\
\hat{\phi}_1 &= \alpha \cdot r_{catheter} \cdot \cos(\theta) \\
\hat{\phi}_2 &= \alpha \cdot r_{catheter} \cdot \sin(\theta), \\
\hat{d}_4 &= z_{tip} - r \sin \alpha, \quad (8)
\end{align*}
\]

\( \alpha \) is the dot product of \( \hat{n}_0^z \) (the \( z \)-axis of \( T_{base} \)) and \( \hat{n}_{tip}^x \) (the \( z \)-axis of catheter tip) in Equation (3). The \( \theta' \) is computed from the catheter tip position \( \hat{P}_{tip} \) in Equation (4). \( \phi_3 \) is computed from the angle between \( R(\hat{n}_0^z, \alpha) \) (\( x \)-axis of \( T_{base} \) rotated by \( \alpha \)) and the dot product of \( \hat{n}_{tip}^x \) (\( x \)-axis of \( T_{tip} \)) and \( R(\hat{n}_0^z, \alpha) \). The computed \( \hat{\phi}_1 \) and \( \hat{\phi}_2 \) represent the estimated joint states. We will compensate these for updated real values \( \hat{\phi}_1' \) and \( \hat{\phi}_2' \). Other estimated joint states \( (\phi_3 \text{ and } d_4) \) are not effected by the non-linearity.

**C. Non-linear elasticity compensation**

Let \( \hat{P}_{tip} \in \mathbb{R}^3 \) be the real position \( (x_{tip}, y_{tip}, z_{tip}) \) of the catheter tip. When \( \phi_1 \) and \( \phi_2 \) are input to the kinematics model, the model predicted position \( \hat{P}_{tip} \) can present large discrepancies with the actual position \( \hat{P}_{tip} \) due to the effects of non-linear elasticity of the bending space. We assume
that the bending length of the catheter remains constant due to the arc constraints, and then the two control knobs (i.e., anterior-posterior and right-left) cover the full working space. Accordingly, only $\hat{P}_{\text{tip}}$ and $P_{\text{tip}}$ are misaligned as shown in Figure 4 (a).

To increase the accuracy of the kinematics model, we propose to map the model input ($\phi_1$ and $\phi_2$ for $P_{\text{tip}}$) with the real joint states ($\phi'_1$ and $\phi'_2$ for $P_{\text{tip}}$). This mapping function is applied to both forward/inverse kinematics. We define the mapping function $F$ as follows:

$$\phi'_1, \phi'_2 = F(\phi_1, \phi_2)$$ (9)

The function $F: \phi_1, \phi_2 \rightarrow \phi'_1, \phi'_2$ is the mapping function based on correcting the estimated position, $\hat{P}_{\text{tip}}$ to the real position values, $P_{\text{tip}}$. Each catheter has an individual model of elasticity behaviors within the catheter tolerance map as shown in Figure 2 (c).

The non-linear elasticity field learning method is addressed as follows:

First, we need to learn the model. We collect the ground-truth data by manipulating the catheter by robot control and sampling the joint state ($\phi_1, \phi_2$) and the real position $P_{\text{tip}}$. Then, we have $S$ number of samples, which gives the real positions $P_{\text{tip}}$ related to ($\phi_1, \phi_2$). Figure 4 (a) shows an example of the sampled ground-truth, $P_{\text{tip}}$, as purple dots while $\hat{P}_{\text{tip}}$ is shown as the black dots.

Second, let $P^*_j = (x'_j, y'_j, z'_j)$ be the unobserved values based on the whole workspace ($[-d, d] \in \phi_1$ and $\phi_2$), where $d$ is the maximum degree of knobs, and $j \in U$, $U$ is the number of unobserved values in the whole workspace. Then, we use a 2D interpolator with collected data to estimate $P^*_j$.

We have three interpolators: ($\phi'_1, \phi'_2$) $\rightarrow$ $x'_j$, ($\phi'_1, \phi'_2$) $\rightarrow$ $y'_j$, and ($\phi'_1, \phi'_2$) $\rightarrow$ $z'_j$. Figure 4 (b) shows an example of interpolated $P^*$. We used the linear interpolator, which interpolated the value at a query point based on linear interpolation of the values at neighboring points in two dimensions. Several methods for interpolation exist (e.g., barycentric, polynomial, spline, etc).

Third, we applied the whole workspace inputs ($\phi'_1, \phi'_2$), $k \in S + U$ into the forward kinematics model. Then, we get $\hat{P}_{\text{tip}}$, which is shown in Figure 4 (c) as examples.

Lastly, we pick the query position $\hat{P}_{\text{tip}}$, and find the nearest position in $P^* + P_{\text{tip}}$. Then ($\phi'_1, \phi'_2$) $\rightarrow$ $\hat{P}_{\text{tip}}^k$ and $\hat{P}_{\text{tip}}^k$ $\rightarrow$ $P^* + P_{\text{tip}}$, thus $P^* + P_{\text{tip}}$ give the corrected values ($\phi'_1, \phi'_2$) corresponding to ($\phi'_1, \phi'_2$). As examples, we show the overall values in Figure 4 (d).

We demonstrate non-linear elasticity compensation in the application of rotating the ultrasound image about the catheter axis, $\hat{u}_{\text{tip}}^z$ (z-axis of the ICE catheter), while maintaining a constant tip position. This trajectory computation is possible using inverse kinematics. One example is that: (1) Initially, we start from ($\phi_1, \phi_2$) = ($60^\circ, 0^\circ$), and rotate $360^\circ$ along $\phi_3$. Then, the trajectory is one cosine function of $\phi_1$, one sine function of $\phi_2$, and one negative linear function of $\phi_3$. An example result is shown in Figure 5 (a). These combined controls are challenging by hands, but robotic controls can provide easily.

D. Automated View Recovery: a topological map construction and path planning

During the procedure, we continuously construct a topological graph (“a roadmap”) and a library of views (i.e., important locations on the roadmap) based on the user’s trace and inputs when manipulating the catheter by joystick input to the robotic manipulator. Queries by the user to return to a specific view will be given to the controller to search a path. More specifically, let $G(V,E)$ represent a graph in which $V$ denotes the set of configurations $q_i$ and $E$ is the set of paths ($q_i, q_j$). Our path planning is divided into two phases of computation:

Construction phase: The library of views and roadmap generation phase: as the robot moves, the current configuration $q_n$ is updated. If $q_n$ is not the same as the previous configuration $q_{\text{before}}$, then the algorithm inserts $q_n$ as new vertex of $G$, and connect pairs of $q_n$ and existing vertices if the distance is less than a density parameter $\epsilon$ (lines 10-12 of Algorithm 1). We apply $\epsilon$ based on Euclidean distance (assuming $1 \text{mm} = 1^\circ$). If a larger $\epsilon$ (default = 1) were applied, then the search would be faster, however a safety of the path would not be guaranteed, as larger steps along the path could result in collision with anatomy. Concurrent with roadmap generation, the algorithm constructs a library of views $\mathcal{V}$ when the user saves the view anytime, where $\mathcal{V} = \{q_{t_1}, ..., q_{t_m}\}$. $q'$ is the user saved configuration. $m$ is the number of the user saved views. This step is shown in line 16 of Algorithm 1.

Algorithm 1 BUILD_ROADMAP_VIEWS ($q_n, G, V, \epsilon$)

1: INPUT: the current configuration $q_n$, the current roadmap $G$, the current library of views $\mathcal{V}$, the density parameter $\epsilon$

2: OUTPUT: $G$, $\mathcal{V}$

3: Initialize: $q_{\text{before}} = [], \mathcal{G} = [], \mathcal{V} = []$

4: while ROBOT is OPERATIONAL do

5: $q_n$ is updated from the current configuration

6: if $q_{\text{before}} \neq q_n$ then

7: for each $q_i \in \text{NEIGHBORHOOD}(q_n, G)$ do

8: if dist($q_i, q_n$) $\leq \epsilon$ then

9: if $q_0 \notin G$ then

10: $G.add\_vertex(q_n)$

11: end if

12: $G.add\_edge(q_i, q_n)$

13: end if

14: end for

15: if VIEW SAVING_FLAG then

16: $\mathcal{V}.pushback(q_n)$

17: end if

18: $q_{\text{before}} = q_n$

19: end if

20: end while

Query phase: Given a start configuration $q_s$ (the current $q_n$) and a goal configuration $q_G \in \mathcal{V}$, is given during the procedures. Since each configuration is already in $G$, we use a discrete $A^*$ search algorithm to obtain a sequence of edges
that forms a path from $q_S$ to $q_G$. The more detailed roadmap construction and search algorithms in the graph are in [48].

The overall illustration of automated view recovery is shown in Figure 1: The roadmap to view the library of image views are constructed in (construction phase); the blue dot shows the entire path of the user’s trace during joystick manipulation of the catheter; the red dot represents the bookmarked or saved state of the robot when viewing a desired image (i.e. corresponding to the library of views). When applied during a procedure, the user can specifies the desired view (red dot). The controller then identifies a path from the current configuration to the target configuration along the edges connecting the blue dots.

IV. EXPERIMENTS AND RESULTS

A. Experimental Design

1) Data-driven compensation model

Evaluation of the proposed compensation model was performed on benchtop. In this setup, we assume that the catheter is straight. This allowed us to locate the front component of the robotic manipulator near the bottom of the bending section of the catheter to hold catheter properly. For modeling and testing, we used three ICE different AcuNav Volume catheters. We collected the real position $P_{\text{tip}}$ corresponding to $(\phi_1, \phi_2)$ to create the interpolated non-linear field $P_{\text{tip}}^\ast$. We used $\pm 90^\circ$ for extent of $\phi_1$ and $\phi_2$. To consider realistic scenarios, we compared with the baseline, and two learning conditions: (1) The baseline uses the pure $\phi_1$ and $\phi_2$ to then produce trajectories based on $P$. (2) The brute-force condition uses the densely collected data for each catheter consisting of 360 samples at $(10^\circ$ intervals along $\pm 90^\circ$) for each knob to interpolate $P_{\text{tip}}^\ast$. Then, we generated trajectories based on $P_{\text{tip}}^\ast$ corresponding to $(\phi_1^*, \phi_2^*)$. (3) The practical condition uses a sparse sampling of the workspace. We evaluate this condition because the dense ground-truth information would be time consuming to acquire intraoperatively. Thus, we propose the simple training condition based on the tolerance map in Figure 2 (c). From our observation, the critical point is the boundary of the arc, which is the $90^\circ$ from $T_{\text{base}}$ for each bending side. Therefore, we pick five points experimentally that are easy to verify visually. The idea is that we manipulate two knobs using the joystick and try to achieve the desired position. The desired position is determined by $(x_{\text{tip}}, y_{\text{tip}})$ (c.f. $z_{\text{tip}}$ is ignored due to arc constraints.). We propose five points: two $90^\circ$ bending shape of the right-left planes when $x_{\text{tip}} = 0$, two $90^\circ$ bending shape of the anterior-posterior planes when $y_{\text{tip}} = 0$, the last one is the initial position by $(x_{\text{tip}}, y_{\text{tip}}) = (0, 0)$. After generating the motion trajectories, we applied the Savitzky-Golay filtering method to produce a smooth path. The chosen filter smooths according to a quadratic polynomial that is fit over each windowed trajectory. Three exemplary trajectories of the testing conditions are shown in Figure 5.

2) In vitro Study Design

Initial validation of robotic catheter control was performed on benchtop. An electromagnetic (EM) sensor (Model 800 sensor, 3D Guidance, Northern Digital Inc.) was attached to the catheter tip to provide real-time localization as the catheter was manipulated by robotic control for baseline evaluation of automated view recovery and image spinning methods.

3) In vivo Study Design

Three in vivo validation experiments were performed at the Houston Methodist Institute for Technology, Innovation & Education (MITIE, Houston Methodist Hospital) with the in vivo study protocol approved by the Institutional Animal Care and Use Committee (IACUC). All testing of the robotic catheter controller was performed under general anesthesia. Vascular access was achieved bilaterally to allow for manipulation of ICE and other device catheters. In vivo experimental setup is pictured in Figure 1. In each experiment, the AcuNav Volume ICE catheter, with robotic controller pre-attached, was introduced to the venous system through a 20F introducer sheath with balloon seal (DrySeal Flex Introducer Sheath, Gore) before being manually inserted to the junction of the inferior vena cava (IVC) and right atrium (RA) under fluoroscopic guidance. When viewing anatomy, ultrasound image data were recorded as DICOM format on an Acuson SC2000 (Siemens Healthineers). Dynamic computed tomography (DCT) images were acquired throughout experimentation on an Artis Zeego (Siemens Healthineers) to provide volumetric ground-truth catheter localization relative to anatomy (200° total rotation, 5 second acquisition, 60 frames-per-second).

4) Validation metrics

For this study, we compare catheter tip location across multiple robotic positioning events to an image target as the primary spatial validation approach. For any catheter positioning to an image target, the robotic motors will theoretically return to an identical final state, assuming no slippage and consistent backlash. As we have created an open-loop system, when the robot executes movement along a path it is unaware of any external influences which may affect its final positioning. As such, any error in the positioning of the catheter tip are due to those external influences (e.g. catheter-robot mechanics, intravascular catheter interactions, cardiac motion, etc). These measurements, when taken relative to a reference catheter position, represent the distribution of uncertainty in robotic catheter positioning resulting from these external sources of error. Because of this, each experimental robotic positioning of the catheter to an image target can be considered a sampling of that uncertainty (Figure 6). Therefore, we have elected to use the geometric median catheter (i.e. the test catheter nearest the centroid of the test distribution) as the reference catheter.
for each imaging target when evaluating the automated view recovery method.

To measure in vivo, 3D models of the ground-truth observation of each ICE catheter were generated following an intensity-based threshold segmentation of intra-procedural DCT images (voxel spacing 0.498 mm) using ITK-SNAP [49]. Co-registration between DCT images were not necessary as no bulk patient motion was observed between scans. Next, the ICE catheter tip was manually labeled within each model and the centroid taken to define the discrete tip location for a given robotic positioning event. A curve was then fit to each catheter, constrained to terminate at the predefined catheter tip, by automatically fitting a low-order polynomial. This process provided a discrete spatial representation of the catheter tip and body. Catheter tip localization error was calculated as the Euclidean distance between test and reference catheter tip locations for a given imaging target.

Robotic catheter positioning was further validated by measuring the similarity of acquired ultrasound images between test and reference acquisitions. Ultrasound image clips encompassing multiple heart cycles were acquired following each robotic positioning event. Image sequences were manually synchronized in time based on visible anatomy (e.g. valve leaflet position; from the first frame of the target valve being open to the last frame before re-opening in the next cycle) and trimmed to encompass exactly one heartbeat. As before, image sequences from the geometric median catheter were selected as the reference images for comparison. Test images for each series of target imaging events were then compared, in corresponding frames based on the heart cycle, to the reference images by computing the image cross-correlation. In-image regions of interest (ROI) were also manually labeled for each image series. Test image ROI centroids were measured to corresponding reference image ROI centroids by Euclidean distance.

B. Results

1) In vitro Evaluation of Image Spinning

The robotic controller was tasked with revolving the ultrasound imaging plane 360° about the catheter axis while maintaining a constant catheter tip position. This was performed from three initial conditions: a 20° anterior-posterior bend, a 40° anterior-posterior bend, and a 60° anterior-posterior bend (i.e. bending in φz). Under these conditions, the RMSE catheter tip positional error from comparing the observed (EM tracking) and modelled (Ptip) positions for the three model conditions and each model variance are addressed in Table I. The baseline shows catheter tip error of 12.8 mm for 20°, 10.1 mm for 40°, and 16.0 mm for 60°. Rotational RMSE were 19.3°, 16.0°, and 44.8° respectively. Also, the variance of model is 7.7 mm for 20°, 6.6 mm for 40°, and 11.0 mm for 60°. The brute-force model shows catheter tip error of 4.1 mm for 20°, 5.6 mm for 40°, and 6.5 mm for 60°. Rotational RMSE were 19.4°, 20.8°, and 24.8° respectively. Also, the variance of model is 4.2 mm for 20°, 4.8 mm for 40°, and 5.2 mm for 60°. The practical model shows catheter tip error of 6.5 mm for 20°, 7.99 mm for 40°, and 10.0 mm for 60°. Rotational RMSE were 20.3°, 24.4°, and 27.0° respectively. Also, the variance of model is 4.3 mm for 20°, 5.2 mm for 40°, and 7.2 mm for 60°.

Based on the results, the baseline gives high bias and variance. The brute-force condition shows low bias and low variance. However, the practical condition also shows reasonably lower bias and low variance than baseline.

2) In vitro Evaluation of Automated View Recovery

The robotic controller was tasked with cycling the ICE catheter tip through four target positions 18 times each to quantify the accuracy of robotic catheter control. Catheter tip positions requiring manipulation of all 4 DOF were established within the benchtop testing environment. These positions encompassed motion of up to 1.8 cm of translation, 51° whole body rotation, ±51° anterior-posterior bending, and ±50° left-right bending. Under these conditions, the RMSE catheter tip positional error was 0.49 mm and rotational error was 0.75°.

3) In vivo Evaluation of Automated View Recovery, Positional Analysis

Initial ultrasound views of the Aortic, Mitral, and Tricuspid valve imaging targets were manipulated by the physician using joystick input to the robotic controller (i.e. the joystick input maps to the standard catheter control knobs, these digital inputs are then translated to the robotic motors to result in catheter manipulation). For each target, the robotic control state was then added to the library of views for later automatic return via topological path planning. Views were then automatically returned to in series several times by automated robotic control (e.g. consecutively cycling through return to Aortic, return to Mitral, return to Tricuspid). The ultrasound image was recorded for several heart cycles and a DCT image was acquired for each viewing of an anatomical target.
These data were then compared to measure the reproducibility of robotically controlled catheter motions. In total, three independent in vivo experiments evaluating automated view recovery were performed with four, six, and seven imaging events respectively per image target, resulting in 51 total view recoveries.

In animal catheter tip localization error from DCT is presented in Table II for each imaging target. Average and maximum catheter tip localization error was $1.39 \pm 1.14$ (2.63) mm, $1.59 \pm 0.92$ (3.31) mm, and $1.39 \pm 0.76$ (2.43) mm for the Aortic, Mitral, and Tricuspid valves respectively. Across all image-targets, average catheter tip localization error was 1.46 ± 0.92 mm.

4) In vivo Evaluation of Automated View Recovery, Image Analysis

Example images from independent robotic re-acquisitions of the Tricuspid valve (i.e. unique imaging events) are presented in Figure 7 alongside the corresponding ground-truth catheter segmentations from DCT. Further examples of the Aortic and Mitral valves are presented in Figure 8. Image similarity as measured by image cross-correlation is presented in Table II for each image target. Average and maximum image similarity was $81.35 \pm 5.63$ (90.67) %, $80.91 \pm 5.58$ (88.56) %, and 80.96 ± 9.33 (89.87) % for the Aortic, Mitral, and Tricuspid valves respectively. Average image similarity across all image-targets and experiments was $81.07 \pm 6.92$ %. For comparison and to establish an accuracy ceiling, average image similarity when comparing images from immediately consecutive heart cycles (i.e. without moving the catheter) was 89.80%.

Finally, in-image ROI were designated for each image target based on anatomy (Figure 7(A) and 8(A,C)) and compared in corresponding test and reference image sequences. Average and maximum in-image ROI localization error was $2.82 \pm 1.37$ (6.07) mm, $1.79 \pm 0.80$ (4.22) mm, and $3.96 \pm 3.02$ (13.60) mm for the Aortic, Mitral, and Tricuspid valves respectively. Average in-image ROI localization error across all image-targets was $2.85 \pm 2.15$. Again for comparison and to establish an accuracy ceiling, average ROI localization error when comparing ROI from immediately consecutive heart cycles (i.e. without moving the catheter) was 1.98 mm.

V. DISCUSSION

The methods presented in this study represent the first work to demonstrate automated image recovery through robotic ICE catheter control. While there are several commercially available robotic catheter control systems on the market, there is only one commercial system, Vdrive (Stereotaxis Inc., St. Louis, MO, USA), which can provide limited manipulation of ICE catheters and one research prototype with a fully articulated 4 DOF [50]. In Brattain et al. [51], robotic methods were introduced for stitching together volumetric images of an ROI from 2D ICE images and tracking of a device catheter within images. Similarly, our work further advances ICE catheter robotics by augmenting the robotic control scheme with a spatially aware process to achieve more autonomous imaging; therefore, streamlining the user experience and allowing the interventionalist to not divide focus throughout the procedure in order to image.

In this work, we apply a robotic ICE controller to implement a method for constructing a case-specific library of desired views and achieve automated recovery of those views during the procedure. In practice, standardized anatomical imaging views are emerging as indications for ICE continue to expand across disciplines. Enriquez et al. [52] detail standard imaging

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**TABLE I**

| Initial condition ($\phi_1$) | 20° | 40° | 60° |
|-------------------------------|-----|-----|-----|
| Baseline                      | (12.8 mm, 19.3°), 7.7 mm | (10.1 mm, 16.0°), 6.6 mm | (16.0 mm, 44.8°), 11.0 mm |
| Brute-force                   | (4.1 mm, 19.4°), 4.2 mm | (5.6 mm, 20.8°), 4.8 mm | (6.5 mm, 24.8°), 5.2 mm |
| Practical                     | (6.5 mm, 20.3°), 4.3 mm | (7.99 mm, 24.44°), 5.2 mm | (10.0 mm, 27.0°), 7.2 mm |

**TABLE II**

| Image Target   | Catheter Localization [mm] | Image Similarity [%] | ROI Localization [mm] |
|----------------|---------------------------|----------------------|-----------------------|
|                | $\mu$ | $\sigma$ | $\mu$ | $\sigma$ | $\mu$ | $\sigma$ |
| Aortic Valve   | 1.4   | 1.1     | 81.4  | 5.6     | 2.8   | 1.4   |
| Mitral Valve   | 1.6   | 0.9     | 80.9  | 5.6     | 1.8   | 0.8   |
| Tricuspid Valve| 1.4   | 0.8     | 81.0  | 9.3     | 4.0   | 3.0   |

![Fig. 7. Example results from in vivo validation experiments. (A) the initial view of the Tricuspid Valve from joystick control by the interventionalist. (B-D) reacquisitions by semi-autonomous robotic control of the ICE catheter. (E) presents the ground-truth catheter position of (A) in green and (B-D) in magenta, cyan, and yellow respectively. Manually labeled in-image ROI are also shown in (A).](image-url)
views for a variety of structural and electrophysiology procedures. Similarly, early identification and unobstructed monitoring of potentially life-threatening complications is one of the most valuable functions that ICE provides [22, 28, 53, 54] and is leading to its adoption as a primary imaging modality for certain procedures, especially those involving transseptal puncture for left heart catheterization [7, 55]. In response, we have developed the method presented in this paper to enable fast and precise cycling through selected views to both observe therapeutic delivery and monitor for procedural complications. If implemented in practice, these methods provide the interventionalist a means to initialize desired views covering the treatment area and then automatically return to those views at any point during a procedure. We have validated the accuracy of this approach in a series of animal experiments by a combination of spatial analysis (Figure 6) and image similarity measures (Figures 7 - 8).

The level of error observed in the automated view recovery results is quite acceptable. However, we must note that the measurements taken in vitro are below the maximum accuracy of the EM measurement sensor (i.e. 1.4 mm) and should be considered as such. In contrast, the in vivo validation measurements are well within the resolution of the DCT imaging. These in vivo results further represent a compounding of error due to multiple factors including mechanical coupling of the robot and catheter, interactions between the catheter and vascular anatomy, and physiological sources such as cardiac motion. Whereas the in vitro data are only impacted by the mechanical coupling of robot and catheter. Therefore, we believe the EM measurements are likely accurate in magnitude. When considering the multiple sources of error and how they manifest in the catheter repositioning, it highlights a further limitation of our study. Error accumulation affects not only the catheter tip position but also the orientation, or heading, of the ultrasound imaging plane. While we report high accuracy in tip positioning, we were unable to discretely measure misalignment of the imaging plane in vivo. As a surrogate measurement, we present the image-based validation approach. Figures 7 and 8 along with the similarity and ROI results in Table II represent a high degree of spatial and content similarity in the produced images following robotic catheter manipulation. Altogether, these results support our conclusion that the robotic controller and automated view recovery method introduced in this study are accurate and reproducible in real-world application.

Safety is a major concern when considering any degree of robotic autonomy in human interfacing applications. As described, our automated view recovery method is not autonomously seeing views in an active manner, but rather rely- ing on the user’s initialization of each view and their tracing of possible paths (i.e. roadmap $G$). As the user controls the ICE catheter during the procedure, they may cause the catheter to contact critical anatomies (e.g. septal wall, valves). However, the ICE catheter’s end portion and tip are designed to be yielding so that the catheter will not puncture or damage tissue. With our presented semi-autonomous functionality, we rely on the user’s previous navigation which we assume to conform with standard clinical practices. Furthermore, our spatial- and image-based results support that the robotic controller can maintain accurate and safe accordance with the expert user’s trace.

As we mentioned in section III-A, there exist slack, elasticity, hysteresis in the two pairs of tendons which mechanically drive the catheter. However, our study is limited we are unable to separate and independently compensate these components. For example, as we collect benchtop data, hysteresis may exist when one tendon control knob is rotated, but slack may be present when the knob is near its zero or neutral position. Errors exist in the system because these phenomena are difficult to model and highly variable between different catheters. We can observe on interesting compensation in Figure 5(c). This represents an example of a trajectory from
the brute-force condition. Here a relatively rough trajectory was observed even after filtering is applied. Specifically, rather steep slopes exist near the zero position, which may be able to compensate for slack. As expected, this is not visible in the practical condition due to the sparsely sampled data. For the hysteresis, in our work, we did not separately collect the direction of the movement for $\phi_1$ and $\phi_2$. In other words, if we make more interpolators considering directionality of data, it might be able to compensate hysteresis. However, this may require more densely sampled data, which means the practical condition might not be applicable due to real-world constraints. From our results in Table I, the elasticity compensation method substantially reduces model errors, and shows reduced model variance. However, there still exist errors even in the densely sampled, brute-force method. We believe this is because slack and hysteresis are not fully accounted by the model. Thus, in future works, we might be able to integrate hysteresis models (e.g., [36, 38]) with our proposed compensation method.

VI. Conclusion

While ICE has many benefits when compared to other intraprocedural imaging modalities, it has limitations for clinical use which are largely due to difficulties associated with learning to control the imaging plane and interpret the resulting image. It is clear from these limitations that a robotic-assist system to oversee significant portions of procedural ICE usage could ease the workload and burden of the interventionalist, enable complex procedures that are currently impractical for vascular intervention, and reduce the overall resource burden of procedures by easing the transition from TEE to ICE imaging. We suggest that the field can be further advanced, and the driving clinical need better addressed, by augmenting the robotic controller with spatial- and image-based applications that provide direct input to the motor control loop and achieve more autonomous ICE imaging. Moreover, in our review of clinical literature, we have identified several natural use cases in standard ICE imaging that are synergistic with the application of advanced robotic control.

This work represents a significant advancement in the application of robotics for the challenging environment of intracardiac imaging. Herein, we present and validate in animal what we believe to be the first semi-autonomous ultrasound image recovery method for automating clinical ICE imaging in a natural use case. This work demonstrates that robotic control can be applied to accurately and reproducibly image. While further investigation is required to fully characterize and compensate the effects of various sources of error on both catheter kinematics modeling and in vivo catheter control, the methods presented here are already quite promising. Based on this work, we would suggest consideration of a paradigm shift in the field of intracardiac imaging towards procedural automation by robotic assistance. We believe these data are supportive that robotic control can be reliably applied to automate standard processes within the clinical workflow.

DISCLAIMER

The concepts and information presented in this paper are based on research results that are not commercially available. The proposed system is currently under development. Due to regulatory reasons there future availability cannot be guaranteed. The scientists giving this presentation have a contractual relationship with Siemens Healthineers and have received financial compensation.

REFERENCES

[1] L. Epstein, T. Smith, and H. TenHoff, “Nonfluoroscopic transseptal catheterization: safety and efficacy of intracardiac echocardiographic guidance,” Journal of Cardiovascular Electrophysiology, vol. 9, no. 6, pp. 625–630, 1998.
[2] E. Daoud, S. Kalbflieisch, and J. Hummel, “Intracardiac echocardiography to guide transseptal left heart catheterization for radiofrequency catheter ablation,” Journal of Cardiovascular Electrophysiology, vol. 10, no. 3, pp. 358–363, 1999.
[3] L. Calo, F. Lamberti, M. Loricchio, M. D’Alto, A. Castro, A. Boggi, and et al., “Intracardiac echocardiography: from electroanatomic correlation to clinical application in interventional electrophysiology,” Italian Heart Journal, vol. 3, no. 7, pp. 387–398, 2002.
[4] C. Basman, Y. Parmar, and I. Kronzon, “Intracardiac echocardiography for structural heart and electrophysiological interventions,” Current Cardiology Reports, vol. 19, no. 10, p. 102, 2017.
[5] G. Rigatelli, “Expanding the use of intracardiac echocardiography in congenital heart disease catheter-based interventions,” Journal of the American Society of Echocardiography, vol. 18, pp. 1230–1231, 2005.
[6] W. Tan and J. Aboulhosn, “Echocardiographic guidance of interventions in adults with congenital heart defects,” Cardiovascular Diagnosis and Therapy, vol. 9, no. 2, pp. S346–S359, 2019.
[7] F. Silvestry, R. Kerber, M. Brook, J. Carroll, K. Eberman, S. Goldstein, and et al., “Echocardiography-guided interventions,” Journal of the American Society of Echocardiography, vol. 22, no. 3, pp. 213–231, 2009.
[8] N. Green, A. Hansgen, and J. Carroll, “Initial clinical experience with intracardiac echocardiography in guiding balloon mitral valvuloplasty: technique, safety, utility, and limitations,” Catheterization and Cardiovascular Interventions, vol. 63, no. 3, pp. 385–394, 2004.
[9] T. Bartel, N. Bonaros, L. Muller, G. Friedrich, M. Grimm, C. Velik-Salchner, and et al., “Intracardiac echocardiography: a new guiding tool for transcatheter aortic valve replacement,” Journal of the American Society of Echocardiography, vol. 24, pp. 966–975, 2011.
[10] S. Ahmari, A. Amro, M. Otabi, M. Abdullah, S. Kasab, and H. Amri, “Initial experience of using intracardiac echocardiography (ice) for guiding balloon mitral valvuloplasty (bmv),” Journal of the Saudi Heart Association, vol. 24, no. 1, pp. 23–27, 2012.
[11] K. Marmagkiolis and M. Cilingiroglu, “Intracardiac echocardiography guided percutaneous mitral balloon valvuloplasty,” *Revista Portuguesa de Cardiologia*, vol. 32, pp. 337–339, 2013.

[12] A. Henning, I. Mueller, K. Mueller, C. Zuern, T. Walker, M. Gawaz, and et al., “Percutaneous edge-to-edge mitral valve repair escorted by left atrial intracardiac echocardiography (ice),” *Circulation*, vol. 130, no. 20, pp. e173–e174, 2014.

[13] T. Bartel, A. Edris, C. Velik-Salchner, and S. Muller, “Intracardiac echocardiography for guidance of transcatheter aortic valve implantation under monitored sedation: a solution to a dilemma?” *European Heart Journal of Cardiovascular Imaging*, vol. 17, no. 1, pp. 1–8, 2016.

[14] M. Saji, A. Rossi, G. Ailawadi, J. Dent, M. Ragosta, and D. Lim, “Adjunctive intracardiac echocardiography imaging from the left ventricle to guide percutaneous mitral valve repair with the mitraclep in patients with failed prior surgical rings,” *Catheterization and Cardiovascular Interventions*, vol. 87, no. 2, pp. e75–e82, 2016.

[15] J. Patzelt, J. Schreieck, E. Camus, and et al., “Percutaneous mitral valve edge-to-edge repair using volume intracardiac echocardiography first in human experience,” vol. 1, no. 1, pp. 41–43, 2017.

[16] H. Rao, S. Saksema, and R. Mitraka, “Intra-cardiac echocardiography guided cardioversion to help interventional procedures (ice-chip) study: Study design and methods,” *Journal of Interventional Cardiac Electrophysiology*, vol. 13, pp. 31–36, 2005.

[17] S. Shah, D. Bardo, L. Sugeng, L. Weinert, J. Lodato, B. Knight, and et al., “Real-time three-dimensional transesophageal echocardiography of the left atrial appendage: initial experience in the clinical setting,” *Journal of the American Society of Echocardiography*, vol. 21, no. 12, pp. 1362–1368, 2008.

[18] I. Ren, F. Marchlingsy, G. Supple, M. Hutchinson, F. Garcia, M. Riley, and et al., “Intracardiac echocardiographic diagnosis of thrombus formation in the left atrial appendage: a complementary role to transesophageal echocardiography,” *Echocardiography*, vol. 30, pp. 72–80, 2013.

[19] E. Anter, J. Silverstein, C. Tschabrunn, A. Schvilkin, C. Haffajee, P. Zimethbaum, and et al., “Comparison of intracardiac echocardiography and transesophageal echocardiography for imaging of the right and left atrial appendages,” *Heart Rhythm*, vol. 11, no. 11, pp. 1890–1897, 2014.

[20] S. Bertü, U. Paradossi, F. Meucci, G. Trianni, A. Tzikas, M. Rezzagh, and et al., “Periprocedural intracardiac echocardiography for left atrial appendage closure: a dual-center experience,” *JACC Cardiovascular Interventions*, vol. 7, pp. 1036–1044, 2014.

[21] Y. Matsuo, P. Neuzil, J. Petru, M. Chovanec, M. Janotka, S. Choudry, and et al., “Left atrial appendage closure under intracardiac echocardiographic guidance: feasibility and comparison with transesophageal echocardiography,” *Journal of the American Heart Association*, vol. 5, no. 10, p. 4, 2016.

[22] Z. Hijazi, Z. Wang, Q. Cao, P. Koenig, D. Waight, and R. Lang, “Transcatheter closure of atrial septal defects and patent foramen ovale under intracardiac echocardiographic guidance: feasibility and comparison with transesophageal echocardiography,” *Catheterization and Cardiovascular Interventions*, vol. 52, no. 2, pp. 194–199, 2001.

[23] M. Mullen, B. Dias, F. Walker, S. Sui, L. Benson, and P. McLaughlin, “Intracardiac echocardiography guided device closure of atrial septal defects,” *Journal of the American College of Cardiology*, vol. 41, pp. 285–292, 2003.

[24] B. Medford, N. Taggart, A. Cabalka, F. Cetta, G. Reeder, D. Hagler, and et al., “Intracardiac echocardiography during atrial septal defect and patent foramen ovale device closure in pediatric and adolescent patients,” *Journal of the American Society of Echocardiography*, vol. 27, no. 9, pp. 984–990, 2014.

[25] J. Kalman, A. Fitzpatrick, J. Olgin, and et al., “Biophysical characteristics of radiofrequency lesion formation in vivo: dynamics of catheter tip tissue contact evaluated by intracardiac echocardiography,” *American Heart Journal*, vol. 133, pp. 8–18, 1997.

[26] W. Saliba and J. Thomas, “Intracardiac echocardiography during catheter ablation of atrial fibrillation,” *Europace*, vol. 10, no. 3, pp. 42–47, 2008.

[27] N. Bhatia, J. Humphries, K. Chandrasekaran, and K. Sripavathsan, “Atrial fibrillation ablation in cor triatriatum: value of intracardiac echocardiography,” *Journal of Interventional Cardiac Electrophysiology*, vol. 28, no. 2, pp. 153–155, 2010.

[28] D. Filgueiras-Rama, F. de Torres-Alba, S. Castrejon-Castrejon, A. Estrada, J. Figueroa, O. Salvador-Montanes, and et al., “Utility of intracardiac echocardiography for catheter ablation of complex cardiac arrhythmias in a medium-volume training center,” *Echocardiography*, vol. 32, no. 4, pp. 660–670, 2015.

[29] N. Vitulano, V. Pazzano, G. Pelargonio, and et al., “Technology update: intracardiac echocardiography - a review of the literature,” *Medical Devices (Auckland, NZ)*, vol. 8, pp. 231–239, 2015.

[30] Stereotaxis, “Stereotaxis v-drive robotic navigation system,” 2020, http://www.stereotaxis.com/products/vdrive.

[31] P. M. Loschak, L. J. Brattain, and R. D. Howe, “Algorithms for automatically pointing ultrasound imaging catheters,” *IEEE Transactions on Robotics*, vol. 33, no. 1, pp. 81–91, Feb 2017.

[32] P. M. Loschak, A. Degirmenci, and R. D. Howe, “Predictive Filtering in Motion Compensation with Steerable Cardiac Catheters,” in *Proceedings of the International Conference on Robotics and Automation, Singapore, Singapore*, May 2017.

[33] B. A. J. Robert J. Webster III, “Design and kinematic modeling of constant curvature continuum robots: A review,” *International Journal of Robotics Research*, vol. 29, no. 13, pp. 1661–1683, 2000.
continuum Robot for Neuroendoscopy,” in Proceedings of the International Conference on Intelligent Robots and Systems, Chicago, USA, Sep. 2014.

[35] T. Do, T. Tjahjowidodo, M. Lau, T. Yamamoto, and S. Phee, “Hysteresis modeling and position control of tendon-sheath mechanism in flexible endoscopic systems,” Mechatronics, vol. 24, no. 1, pp. 12 – 22, 2014.

[36] W. Xu, C. C. Y. Poon, Y. Yam, and P. W. Y. Chiu, “Motion compensated controller for a tendon-sheath-driven flexible endoscopic robot,” The International Journal of Medical Robotics and Computer Assisted Surgery, vol. 13, no. 1, p. e1747, 2017.

[37] G. Chen, M. T. Redarce, and T. Redarce, “Development and kinematic analysis of a silicone-rubber bending tip for colonoscopy,” in Proceedings of the International Conference on Intelligent Robots and Systems, Beijing, China, Oct. 2006.

[38] X. Wang, D. Bie, J. Han, and Y. Fang, “Active modeling and compensation for the hysteresis of a robotic flexible ureteroscope,” IEEE Access, vol. 8, pp. 100 620–100 630, 2020.

[39] D. B. Camarillo, C. R. Carlson, and J. K. Salisbury, “Configuration tracking for continuum manipulators with coupled tendon drive,” IEEE Transactions on Robotics, vol. 25, no. 4, pp. 798–808, 2009.

[40] A. M. Priester, S. Natarajan, and M. O. Culjat, “Robotic ultrasound systems in medicine,” IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, vol. 60, no. 3, pp. 507–523, 2013.

[41] M. Antico, F. Sasazawa, L. Wu, A. Jaiprakash, J. Roberts, R. Crawford, A. K. Pandey, and D. Fontanarosa, “Ultrasound guidance in minimally invasive robotic procedures,” Medical Image Analysis, vol. 54, pp. 149 – 167, 2019. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1361841519300027

[42] J.-A. Long, N. Hungr, M. Baumann, J.-L. Descotes, M. Bolla, J.-Y. Giraud, J.-J. Rambeaud, and J. Troccaz, “Development of a Novel Robot for Transperineal Needle Based Interventions: Focal Therapy, Brachytherapy and Prostate Biopsies.” Journal of Urology, vol. 188, pp. 1369–1374, Aug. 2012. [Online]. Available: https://hal.archives-ouvertes.fr/hal-00724924

[43] E. Boctor, M. Choti, E. Burdette, and R. Webster, “Three-dimensional ultrasound-guided robotic needle placement: An experimental evaluation,” International Journal of Medical Robotics and Computer Assisted Surgery, vol. 4, no. 2, pp. 180–191, Jun. 2008.

[44] J. Xu, Z.-z. Jia, Z.-j. Song, X.-d. Yang, K. Chen, and P. Liang, “Three-dimensional ultrasound image-guided robotic system for accurate microwave coagulation of malignant liver tumours,” The International Journal of Medical Robotics and Computer Assisted Surgery, vol. 6, no. 3, pp. 256–268, 2010.

[45] R. Papalia, G. Simone, M. Ferriero, M. Costantini, S. Guaglianone, E. Forastiere, and M. Gallucci, “Laparoscopic and robotic partial nephrectomy with controlled hypotensive anesthesia to avoid hilar clamping: Feasibility, safety and perioperative functional outcomes,” Journal of Urology, vol. 187, no. 4, pp. 1190–1194, 2012.

[46] X. Wu, J. Housden, Y. Ma, B. Razavi, K. Rhode, and D. Rueckert, “Fast catheter segmentation from echocardiographic sequences based on segmentation from corresponding x-ray fluoroscopy for cardiac catheterization interventions,” IEEE Transactions on Medical Imaging, vol. 34, no. 4, pp. 861–876, 2015.

[47] Z. F. Issa, J. M. Miller, and D. P. Zipes, “6 - advanced mapping and navigation modalities,” in Clinical Arrhythmology and Electrophysiology (Third Edition), third edition ed., Z. F. Issa, J. M. Miller, and D. P. Zipes, Eds. Philadelphia: Content Repository Only!, 2019, pp. 155 – 205.

[48] S. M. LaValle, Planning Algorithms. New York, NY, USA: Cambridge University Press, 2006.

[49] P. A. Yushkevich, J. Piven, H. Cody Hazlett, R. Gimpel Smith, S. Ho, J. C. Gee, and G. Gerig, “User-guided 3D active contour segmentation of anatomical structures: Significantly improved efficiency and reliability,” Neuroimage, vol. 31, no. 3, pp. 1116–1128, 2006.

[50] P. M. Loschak, A. Degirmenci, Y. Tenzer, C. M. Tschabrunn, E. Anter, and R. D. Howe, “A four degree of freedom robot for positioning ultrasound imaging catheters,” Journal of mechanisms and robotics, vol. 8, no. 5, 2016.

[51] L. J. Brattain, P. M. Loschak, C. M. Tschabrunn, E. Anter, and R. D. Howe, “Instrument tracking and visualization for ultrasound catheter guided procedures,” in Workshop on Augmented Environments for Computer-Assisted Interventions. Springer, 2014, pp. 41–50.

[52] A. Enríquez, L. C. Saenz, R. Rosso, F. E. Silvestry, D. Callans, F. E. Marchlinski, and F. Garcia, “Use of intracardiac echocardiography in interventional cardiology: working with the anatomy rather than fighting it,” Circulation, vol. 137, no. 21, pp. 2278–2294, 2018.

[53] S. S. Kim, Z. M. Hijazi, R. M. Lang, and B. P. Knight, “The use of intracardiac echocardiography and other intracardiac imaging tools to guide noncoronary cardiac interventions,” Journal of the American College of Cardiology, vol. 53, no. 23, pp. 2117–2128, 2009.

[54] J. E. Banchs, P. Patel, G. V. Naccarelli, and M. D. Gonzalez, “Intracardiac echocardiography in complex cardiac catheter ablation procedures,” Journal of interventional cardiology, vol. 28, no. 3, pp. 167–184, 2010.

[55] R. Bazaz and D. Schwartzman, “Site-selective atrial septal puncture,” Journal of cardiovascular electrophysiology, vol. 14, no. 2, pp. 196–199, 2003.