Algorithms for Automated Pointing of Cardiac Imaging Catheters

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Abstract. This paper presents a modified controller and expanded algorithms for automatically positioning cardiac ultrasound imaging catheters within the heart to improve treatment of cardiac arrhythmias such as atrial fibrillation. Presented here are a new method for controlling the position and orientation of a catheter, smoother and more accurate automated catheter motion, and initial results of image processing into clinically use-ful displays. Ultrasound imaging (intracardiac echo, or ICE) catheters are steered by four actuated degrees of freedom (DOF) to produce bi-directional bending in combination with handle rotation and translation. Closed form solutions for forward and inverse kinematics enable position control of the catheter tip. Additional kinematic calculations enable 1-DOF angular control of the imaging plane. The combination of positioning with imager rotation enables a wide range of visualization capabilities, such as recording a sequence of ultrasound images and reconstructing them into 3D or 4D volumes for diagnosis and treatment. The algorithms were validated with a robotic test bed and the resulting images were reconstructed into 3D volumes. This capability may improve the efficiency and effectiveness of intracardiac catheter interventions by allowing visualization of soft tissues or working instruments. The methods described here are applicable to any long thin tendon-driven tool (with single or bi-directional bending) requiring accurate tip position and orientation control.

Keywords: Robot-assisted procedures, Interventional therapy, Image-guided procedures

1 Introduction

Ultrasound (US) imaging catheters with phased-array transducers in the tip are navigated to the patients heart through the vasculature (e.g. femoral vein). These imaging instruments have been used routinely to acquire B-mode images of heart tissues for over a decade [1]. US catheters are advantageous compared with external probes because target views can be captured in the near-field with higher acoustic frequencies. This reduces aberration and attention due to layers of intervening muscle, fat, and other tissues. A downside to US catheter use is the difficulty in manual control while the body of the catheter winds through tortuous blood vessels. Clinicians must maneuver the imaging plane by rotating/advancing the catheter handle and turning control knobs. Extensive time and training is required to aim the imager, align the image plane with a target, and move between targets to obtain adequate views. This has largely limited the use of US catheters to a few critical tasks such as septal puncture [2].

This paper reports the development of a guidance technology that uses robot-driven US catheters to enable high-quality 3D US imaging in the heart. Robot control enables fast acquisition and merging of 2D US image sequences into 3D panoramas showing the tissue structure across a treatment area and beneath the surface. Automated pointing will make US catheters far more useful, effective, and broadly applicable. In electrophysiology (EP) procedures, robotic US catheters will allow the operator to continuously monitor target regions of cardiac tissue without laborious adjustment of the US catheter controls. This will reduce procedure times and potentially increase effectiveness. Continuous monitoring also enables detection of impending complications, such as tenting of the atrial wall prior to perforation. Automatic panoramic US imaging and enhanced displays also promise to decrease the need for fluoroscopy, reducing ionizing radiation exposure to patients and staff.

Robotic techniques are readily applied to overcome the difficulties in manually pointing intracardiac echocardiography (ICE) catheters. A kinematic model can describe the relationship between the catheter controls, tip location, and imaging plane orientation. Electromagnetic (EM) sensors on the catheter tip can determine the image location within the heart in Cartesian coordinates. Actuators can then drive the control knobs and handle position to move the catheter tip to image a region of interest or to track a working catheter. The proposed system provides different functionality than current commercial catheter robots. These systems, such as the Amigo from Catheter Robotics, CorPath from Corindus, Artisan from Hansen Medical, and EPOCH from Stereotaxis [3-8] enable teleoperation of catheter controls to increase operator comfort and reduce exposure to radiation from fluoroscopic imaging. These systems simply replicate manual control knobs, which does not mitigate the difficulties of aiming imaging catheters in joint space. While some systems offer limited Cartesian control, these systems do not feature orientation control which is essential for aiming an imager.

This paper expands upon the system presented by researchers Loschak et al. to demonstrate more accurate position and 1-DOF orientation control [9]. Next, algorithms for visualization strategies are created in conjunction with the bending model. The robot and controller are then described. Experimental results demonstrate that a 4-DOF robotic system is able to achieve accurate positioning and angular control. Finally, image processing techniques are used to combine US data into a panoramic volume useful for diagnosis and treatment. This system will help clinicians to quickly achieve high quality views during procedures while reducing patient and staff exposure to radiation and reducing procedure times.

2 Background

2.1 Catheter Steering

ICE catheters are steerable devices that acquire US images of adjacent tissues from the distal tip. They can be guided through the vasculature to the inside of the heart, where they can provide excellent views of fast moving heart structures with resolution that may not be possible with external probes. ICE can also be used for continuous monitoring of radiofrequency energy delivery during cardiac ablation. The catheter consists of a plastic handle that can be rotated about or translated along its axis. Four pull wires (spaced 90 degrees apart in cross section) extend along the length of the catheter body through the bending section to their attachment points at the distal tip. On the proximal end, each pair of opposing pull wires connects to a bending knob. The bending section is designed to be less rigid than the body such that pull wire deflection causes most bending to occur in that region. The distal 2 cm tip of the catheter is rigid and contains the ultrasound transducer. The ICE catheter used for system validation was a 10 Fr (3.30 mm diameter) 110 cm long catheter with a 64-element 2D ultrasound transducer at its distal tip, pictured in Fig. 1 (AcuNav, Biosense Webster, Diamond Bar, CA, USA). AcuNav is the most common ICE catheter in clinical use at present.

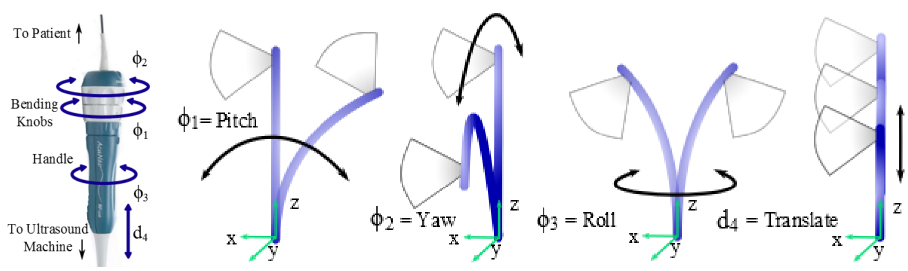


Fig. 1. (*left*) Handle of the AcuNav ultrasound imaging catheter showing control DOFs, (*center and right*) corresponding tip motion directions [9]

The system proposed here is designed to manipulate a commercial ICE catheter with four actuated DOF. The catheter steering robot, capable of manipulating two bending directions, handle rotation, and handle translation, enables clinicians to visualize desired objects or tissue structures in the heart using the same actuated degrees of freedom as in manual manipulation. Cardiac catheters for non-imaging functions such as ablation only require one plane of bending (providing a total of 3 DOF) to reach a desired position without regard to orientation. The ICE catheter is unique in that it features an extra bending direction in order to achieve desired tip orientations for imaging purposes. In the system presented here, the fourth DOF may be utilized differently depending on the task. For instance, a user may wish to reach a desired location (with unspecified orientation) in the heart using 3 DOF and then use the extra DOF to steer the imaging plane towards a region of interest. Another task of interest is to spin the catheter tip about its own axis, thereby sweeping the imaging plane across a desired region, while keeping the catheter tip in the same location. Additionally, the user may image an object from various sides to determine an optimum viewpoint.

Several kinematic strategies focused on catheter positioning have already been developed, and we will use these techniques as the basis of our approach to control the ICE catheter [9-12]. Additionally, researchers have also described the bending characteristics of long deformable objects, sometimes described as remotely actuated continuum robots [13, 14]. However, control of catheter tip orientation has not yet become a focus of investigation even though its development could enable more complicated procedures to be performed in a minimally invasive fashion.

2.2 Robot Design

A robot was built to manipulate the 4-DOF catheter handle knobs as in [9] (Fig. 2). Each DOF was actuated by 6.5 W brushed DC motors driven by digital positioning controllers (EPOS2, Maxon Motor, Switzerland). Two actuators for bending the knobs were mounted to the catheter handle and connected by timing belts. Custom acrylic pieces connected the handle geometry to the timing belts. The US catheter and bending knob actuators were suspended by two ball bearings, allowing rotation about the handle center axis. A third actuator was connected to the catheter handle by a timing belt for handle rotation. The entire system was mounted to a lead screw driven translation stage. For initial testing, a plastic holder was designed to support the distal 7 cm of catheter roughly 1 m away from the handle while still allowing free rotation about the handle axis. The system was designed to move the catheter tip roughly 1 cm/sec.

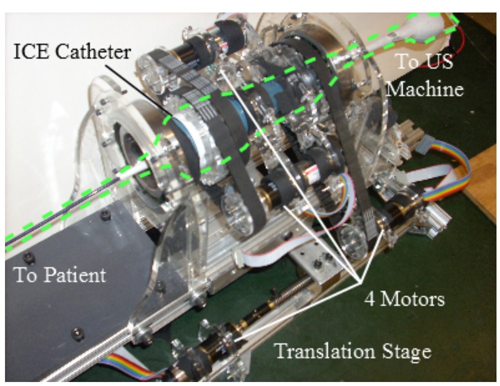


Fig. 2. ICE catheter steering robot with 4 DOF

3 Positioning the Catheter

3.1 Forward and Inverse Kinematics

Depending on the task, kinematic relations are needed for controlling the catheter tip position, tip orientation, or both. Specifically, the kinematics presented by Loschak et al. in [9] model the relationship between the joint space control knobs and the task space US imaging plane positions and orientations. This model, which serves as the basis for our investigation, is based on geometric principles and classic robot kinematics. Closed-form kinematic solutions have been derived for both the forward and inverse cases. The model calculates both the position and orientation of the catheter tip for catheters with two bending directions. With orientation information, it is then possible to determine the location and direction of the ICE image. A primary assumption of the model assumes that catheter bending occurs in the bending plane (neglecting the effects of plastic torsion). It also assumes a constant radius of curvature in bending, which has been examined by [11], and that dynamic effects of catheter motion are negligible due to low-speed actuation.

An additional assumption for deriving the kinematic solution to the system involves positional joint coupling in bi-directional bending. Solving for the tip orientation of a traditional serial manipulator would normally require multiplying the origin orientation by transformation matrices corresponding to each joints orientation change in the proper order (depending on the manipulator). However, the bi-directional bending catheter is a manipulator in which pitch and yaw can occur simultaneously. It is assumed that the effects of coupling between bending directions are negligible. It is assumed that applying pitch then yaw will yield the same kinematic results as applying yaw then pitch. These claims were validated in [9].

3.2 Position Control

The systems control strategy is a function of the distance between the catheter tip and the desired tip position. For large motion changes above a specified distance threshold the inverse kinematics calculations use the desired task space position, X_D, to calculate the joint space solution, Q_D. A low-level control loop drives each actuator to reach the commanded joint angles, Q. An EM sensor on the tip of the catheter measures its position, X_{EM}. Due to uncertainties with polymer effects in continuum robots and inaccuracies in the system, this large motion change typically positions the catheter tip a small distance from the desired position. Smaller position adjustment are then calculated as the desired change in task space coordinates, ΔX, which is used in an inverse Jacobian calculation to obtain ΔQ. The Jacobian is obtained by differentiating (5)-(7). The cycle of measurement and adjustment continues as in Fig. 3 until the catheter has reached the desired position within a specified threshold.

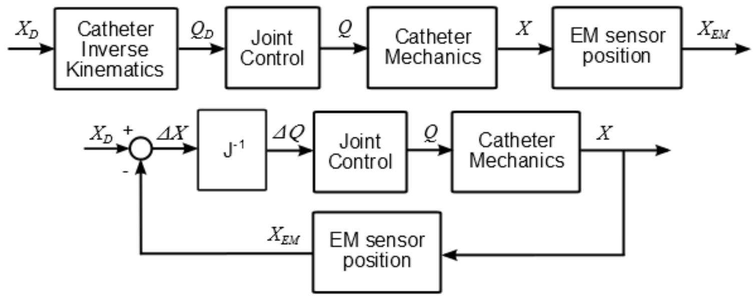


Fig. 3. Position controller: (*top*) inverse kinematics loop for large motions, (*bottom*) Jacobian loop for small corrections

3.3 Experimental Results

The kinematic and control methods in Sections 3.1-3.2 were used to move the catheter tip to a sequence of specific locations along a path across the workspace. These experiments focused solely on position control, without regard to the imaging plane directionality. Therefore only three DOF required for positioning (chosen to be pitch, yaw, and translation) were used. Square paths were chosen because this shape requires the robot to adjust all three DOF in navigating to every point. The robot was commanded to move to the first point and the controller moved the catheter tip until it reached the desired point (within a tolerance of 2 mm). Then the robot was commanded to move to the second point, and so on. Shapes in various planes were tested and typical results are shown in Fig. 4 *(left)*. The catheter tip successfully navigated to each position to within the threshold distance, 2 mm, resulting in positioning error 1.9 mm RMS. The joint space adjustments required for creating this trajectory are shown in Fig. 4 *(right)*, illustrating the difficulty in achieving tip control through simultaneous manual adjustment of three control inputs.

4 Imaging Plane Kinematics

4.1 Sweeping Kinematics

ICE catheters with bi-directional steering knobs can be used to spin the imaging plane about the axis of the catheter while in bending as in Fig. 5 *(left)*. During manual manipulation, a clinician may wish to position the ICE catheter in a desired region of the heart and sweep the imaging plane to get a comprehensive view of the region. While in bending, it is extremely difficult to intuitively and manually spin the catheter about its own axis while keeping the tip in place. Here the catheter robot has the opportunity to use its fourth DOF to accomplish this task. The user may input the desired range of angles to sweep with a specified angular resolution. Rotations about the z-axis by angle ψ are applied to the tips mobile coordinate frame

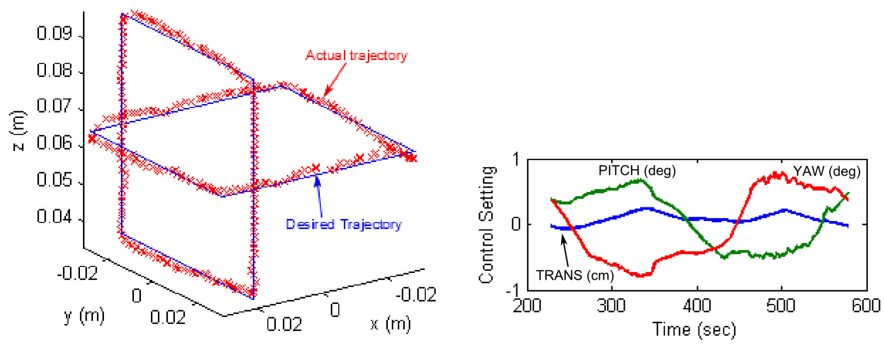


Fig. 4. (*left*) Catheter position control experimental results. Lines are commanded positions, symbols are measured positions. (*right*) Normalized control knob adjustments required to navigate through the square in the YZ plane

$$T_{SWEEP} = \begin{bmatrix} \cos\psi & -\sin\psi & 0 & 0 \\ \sin\psi & \cos\psi & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

$$T_{NEW} = T_{TIP} T_{SWEEP} \tag{2}$$

which calculates the new catheter pose. Due to the physical configuration of the catheter, in order to physically reach a pose in which the imager has swept by angle ψ, the catheter handle must be rolled from 0 to ψ. However, this would cause the position of the tip to move away from the desired position. The position controller above can then be used to adjust the pitch and yaw in order to converge on the desired position, reducing the imager angle change to a value between 0 and ψ. By using the position control and roll control simultaneously and continuously, the imager can be rotated to ψ while the catheter tip is continuously position-controlled to remain at the fixed point.

4.2 Controller

The control strategy used for imager sweeping and motion around targets is based on the positioning controller described in Section 3.2. In short, a proportional controller adjusts roll in series with the position controller maintaining the desired position. Although both the imager angle and the catheter position are dependent on roll and pitch/yaw/translation, it will be shown that alternately controlling roll and position leads to accurate results. Fig. 5 (*right*) shows a diagram of this strategy. First, the catheter is navigated by position control (Fig. 3) to the desired position, X_D. The low-level control, catheter mechanics, and EM sensing steps are summarized as 'Robot.'Next, the orientation of the catheter tip (contained in X_{EM}) is used to calculate the angle between the image plane

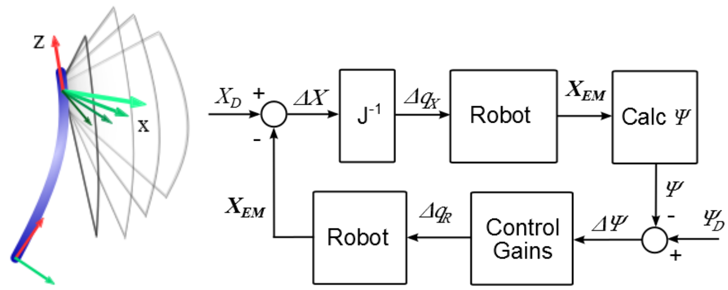


Fig. 5. (*left*) Simulation of imaging plane sweeping [9], (*right*) control diagram for position and imaging angle

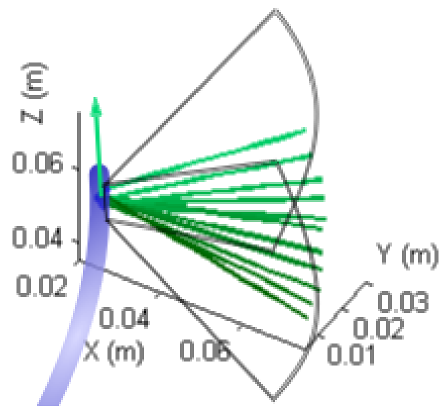
and the target, ψ. This angular difference is multiplied by a proportional gain ($K_P < 1$) and the roll actuator rotates the catheter handle by ΔQ_R. Then the position controller is activated again to ensure that the catheter tip remains in the correct position. Position changes affect ψ (unless the robot performs translation only), which is recalculated and the roll axis is adjusted again. This loop of position adjustment, angle measurement, roll adjustment, and position measurement continues until both the imager angle and the catheter tip position have reached their targets within specified tolerances.

4.3 Experimental Results

The sweeping algorithm described in Section 4.1 was used to adjust the angle of the imaging plane 11 times in increments of 5° per adjustment. The results of one trial are shown in Fig. 6 *(left)*. The green lines represent the same vector in each imaging plane and the color intensity represents the order in which rotations occurred. The lightest green arrow represents the starting angle of the imager and the darkest green represents the final angle. The control inputs which led to accurate positioning and angular adjustments are shown in Fig. 6 *(right)*. This sweeping test was repeated ten times in varying regions of the workspace in different directions. The angular adjustment 5° per step resulted in 0.25° RMS error and unwanted catheter tip displacement 1.0 mm RMS error.

5 Image Processing

After validating the motion algorithms for positioning and angular control, the ICE catheter was connected to a Siemens Acuson X300 US imaging system. The bending section of the robotically controlled ICE catheter was manually introduced through the side of a water tank containing phantom objects. The phantom objects were gelatin-based with suspended fiber supplement, closely mimicking animal tissue features [15]. Fig. 7(a) is the phantom shaped into a left atrium form with four openings that simulate the pulmonary veins (PV). PV



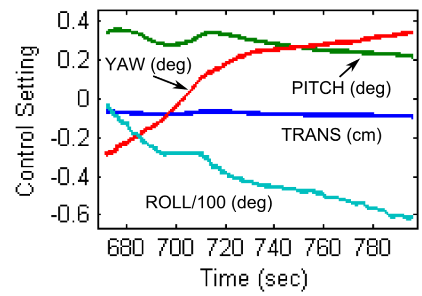


Fig. 6. (*left*) Results of sweeping tests, (*right*) control adjustments

openings are critical areas for imaging and tracking during an atrial fibrillation ablation procedure. The atrium area is roughly 40 mm x 40 mm. The ICE catheter tip imaging region was directly in front of the phantom. The images were acquired at depth 90 mm and frequency 6.7 MHz.

The system swept across the phantom in one-degree increments over 40° while the ICE position remained stationary. This enabled acquisition of closely-spaced 2D images across a user-specified region of the treatment area. Since US images are inherently noisy, the images were filtered first to reduce the speckle noise. Images were then spatially registered into a common Cartesian coordinate frame using the tip EM tracker locations and interpolated and compounded into a gridded 3D volume. This process is discussed in greater detail in [16].

6 Conclusions

Clinicians using ICE catheters currently express frustration at the need to frequently adjust imaging catheters to track the non-imaging catheters and monitor interactions with surrounding tissue. Therefore, controlling the position and orientation of the catheter tip and the imaging plane is essential for improving current catheter-based procedures and enabling additional procedures to be performed using minimally invasive techniques. The tests described in this study applied ICE catheter position and orientation kinematics together to robotically enhance visualization. The system demonstrated accurate position control by navigating the tip of the ICE catheter to reach a series of specified positions in different regions of the workspace. A control strategy for rotating the imager while maintaining constant position was demonstrated with accurate results. This will enable clinicians to move ICE to a safe location and image structures that are difficult to focus on by manual manipulation.

The control strategy presented here may also be useful for the development of flexible tools and procedures that rely on achieving a target orientation with

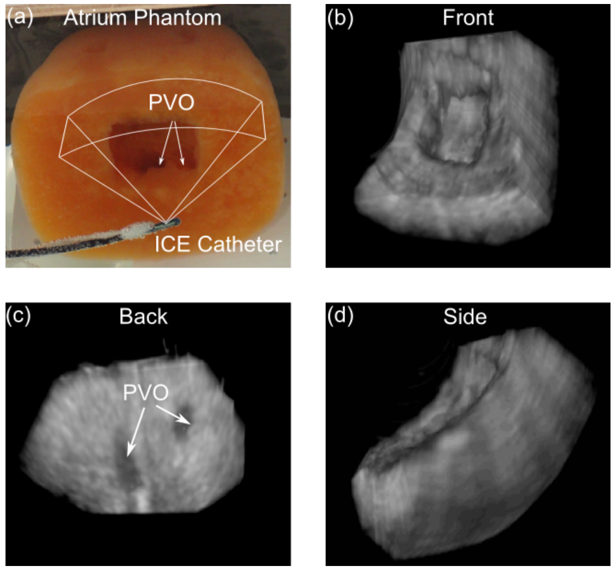


Fig. 7. (a) Phantom left atrium, (b)-(d) US image slices stitched into a volume. Simulated pulmonary openings can be seen in (d).

respect to the tissue. For example, an endoscope with a different type of imaging probe or a pair of biopsy forceps may rely on orientation at the tip to complete a task. Kinematic algorithms for imaging can be applied to many procedures involving visualization of various organ systems via long, thin, flexible imaging tools. Reconstructed volumes can be useful in performing diagnoses or lesion/tumor margin assessments.

Future work aims to correct for system inaccuracies in robotically controlled catheters (such as friction, backlash, non-circular catheter curvature, plastic degradation effects, etc.). Additional modeling will also focus on the interactions between the catheter body and the vasculature, as well as the bending section and the endocardium. Safety boundaries inside the heart may be constructed with known locations of delicate cardiac structures (i.e. valve leaflets). With the incorporation of real time US visualization and image processing, the robot will be able to process images of cardiac structures and use kinematics to navigate the imager while maintaining specific relationships with other objects in the heart. Robotic control of ICE promises to shorten procedure times, improve patient outcomes, and reduce the training time required to master ICE.

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