Tracking the 3D Shape of Steerable Catheters with Helical Markers

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***Abstract*—This work presents the design of helical markers and application of neural network to enable full-length monitoring of the 3D shape and orientation of an active (steerable) catheter from isolated 2D images.**

I. Introduction

Accurate performance of minimally invasive surgeries (MIS) requires intra-operative feedback on catheter position and configuration. For active catheters, their steerability necessitate tracking of an extended section along the length to avoid damages from unintended operations. This study introduces a system of markers and a neural network (NN) to detect full shape and orientation of active catheters without additional device or computational cost. Similar to band markers for tip orientation tracking[1] and helices for curvature sensing[2], the markers were adapted from an *in vivo*-validated active catheter (Fig. 1A)[3]. The system can potentially generalize to ultrasound[4] and magnetic resonance[5] tracking.

II. Methods

A prototype of catheter[3] and markers at ~2x scale was made from a torque coil and compression springs (Fig. 1B). Images of the prototype in varying configurations were taken by a Siemens' Artis zeego (Fig. 1C). The configurations were defined by yaw, pitch, roll (Fig. 1D), and by bending angle (Fig. 1E). This preliminary work included 142 roll angles (θ_{roll}, range = 56.4°) and 5 bending angles (θ_{bend}, range = 63.7°), yielding 710 configurations. On each image, the peaks of the helical marker were identified (Fig. 2A) by algorithms based on regions of connected pixels and convex hulls.

III. Results

Information of all the peaks in each frame (Fig. 2B) was converted into single "predictors" related to local distances and slopes. A two-layer feedforward NN was trained with nonlinear least square fitting algorithm by training (70%) and validating (15%) datasets. Among tested predictors, the average inter-peak distances and the angle of catheter projection sufficiently characterized the configurations of an independent testing dataset (15%, n = 107). Compared with ground truth (Fig. 2C), the two variables had the following errors: 1.13°±0.12°(SE) for θ_{roll} and 0.95°±0.21° for θ_{bend}.

In addition, a separate simulation was performed, with the same geometric features as the prototype, to test the detection of three variables. With three predictors, the correlations between defined and detected angels are R = 0.88 for θ_{bend}, R = 0.84 for θ_{pitch}, and R = 0.70 for θ_{roll}.

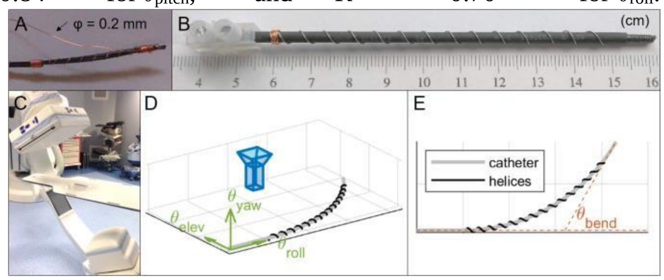

Figure 1. (A) The interior of the active catheter in [3]. (B) The prototype of catheter and markers in this study. (C) Imaging device. (D) The variables for orientation with respect to the imaging plane (in blue), and (E) for shape.

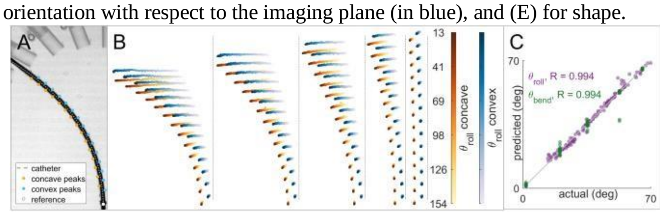

Figure 2. (A) Image of an example configuration, overlaid with extracted features. (B) The projections of peaks at varying θ_{roll}. Each of the subplots (divided by dashed lines) contains data of one θ_{bend}. (C) Correlations between NN prediction and ground truth.

IV. Discussion & Conclusion

To promote the safety and precision of minimally invasive interventions, NN was trained to recognize the full-length shape and orientation of a 3D active catheter based on 2D projections of helical markers. The system was able to detect high θ_{bend} and θ_{roll} with average errors of ~1° and has been shown to support θ_{pitch} detection. Once trained with simulated dataset, the NN is expected to achieve higher accuracy and number of variables with simplicity and efficiency.

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