Continuous-curvature path planning for endovascular catheterization

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INTRODUCTION

Navigation guidance can mitigate the skill and experience requirements for percutaneous treatment of Chronic Total Occlusions (CTOs). Planning for an appropriate path for flexible catheters safely is one of the major challenges for endovascular catheterization. However, state of the art publications rarely consider kinematic constraints (e.g. curvature limitation). In our previous work, we proposed a fast path planning approach under curvature constraints, and the approach explores a path along the vascular centerline-based structure and locally optimizes the path to satisfy curvature constrains. Furthermore, we develop the path planning approach in this work, ensuring the continuity of curvature at coincident points between the vascular centerline and the locally optimized path. Particularly, the present work focuses on path planning under the framework of ATLAS project.

MATERIALS AND METHODS

- *Datasets preprocessing*

The datasets are two-dimensional images with a pixel resolution of 2822×1539, presenting the lower limb arteries. They are obtained from five subjects via automatic stitching and convolutional neural network segmentation [1]. And then centerline-based information structure is extracted via medial axis skeletonization (Voronoi diagram) from the anatomical structure. It is feed to the further path planning simulation as an input and the simulation is carried out in the PyCharm platform on a computer with Ubuntu system.

- *Algorithm*

1) Planning under curvature constraints

We define that a path is composed of m points, and each point $\boldsymbol{p_i}$ is represented by $(x_1, \dots x_n)$ that is the position representation in the n-dimensional Cartesian coordinate system. Curvature at $\boldsymbol{p_i}$ is defined in Eq. (1). The curvature constraint is formulated as Eq. (2), where s^* is the allowed maximal curvature value depending on robot capability. For example, $s^* \approx 0.08\,\mathrm{mm}^{-1}$ of the designed steerable catheter prototype in [2].

$$s_i = \frac{\sqrt{\sum_{j\neq k}^{n}(\dot{x}_j\ddot{x}_k - \dot{x}_k\ddot{x}_j)^2}}{(\sum_{i=1}^{n}\dot{x}_i^2)^{3/2}} \qquad (1)$$

$$s_i \le s^* \text{ for } i = 1, \dots m \qquad (2)$$

In our previous work, we proposed a fast path planning approach under curvature constraints. Firstly, it explores a path along the vascular centerline-based structure from a user-defined start point to an end point via traditional graph-based path searching algorithm. Then it locally optimizes the path to satisfy curvature constraints via genetic algorithm, converting the curvature constraint to a component of the objective function. For example, there is one curve segment should be optimized due to exceeding the limitation in Figure 1, marked with green color. There may be several curve segments exceeding the limitation along the centerline. In that case, parallel optimization is carried on to reduce computational time.

2) Smoothing at coincident points

In this work, we focus on connection smoothing to ensure the differentiability and continuity of curvature at the coincident points. The optimized curve segment cannot be mounted to the centerline directly (see Figure 1B), since the derivative (slope) p^- at the left side of the coincident point $\boldsymbol{p}$ has a great difference value from the one p^+ at the right side. In other words, it results in a great rotation angle θ in a short interval. It would exceed the robot kinematics and dynamics capability. Therefore, the differentiability should be respected.

To obtain a desired degree of smoothness, the coincident point not only needs to be differentiable, but also belongs to the class of C^1 and G^2 functions. The C^1 continuity is essential to ensure tangent vectors of the two connected

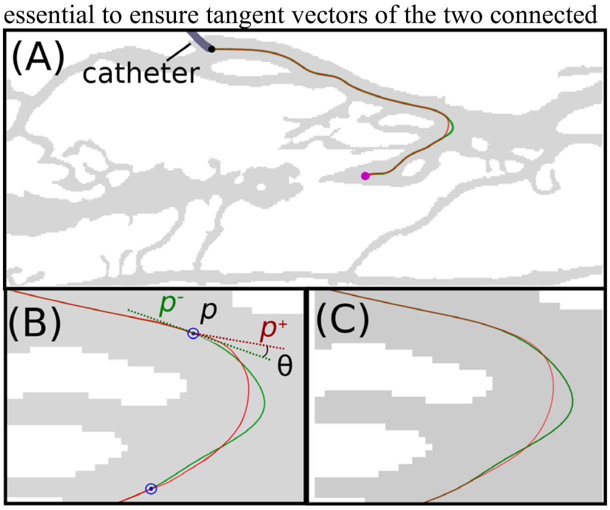

Figure 1. Path planning results on lower limb arteries: (A) the full view (B) the zoom-in view of the result before connection smoothing (C) the zoom-in view of the result via G^2 quintic Hermite curve smoothing. The initial and goal location are the black and purple points, respectively. Green line represents the curve along vascular centerlines. Red line shows the final solution after optimization. Blues depict the coincident points.

segments are equal. The G^2 continuity [3] means the 1^{st} derivatives at the coincident points are collinear, and the curvature is continuous. The continuity of curvature is essential since it indicates non-sharp changes in bending extent of a catheter.

In this study, G^2 continuous quintic Hermite spline is proposed for connection smoothing. And it is compared with C^1 continuous cubic Hermite spline. With the cubic Hermite spline, four parameters are needed: two control points and their related derivatives. To obviate loops, cusps or folds, an optimized geometric Hermite has been considered. It is defined by optimizing the magnitudes of the endpoint tangent vectors in the Hermite interpolation process so that the strain energy of the curve is a minimum. With the quintic Hermite spline, not only the continuity of first derivative is ensured, but also curvature gaps in the connections will be reduced. In this case, the values of second derivatives are also needed to calculate such a polynomial.

RESULTS

The proposed method is performed on the datasets, and the result is shown in Figure 1. It shows that G^2 quintic Hermite curve method (M_2, Figure 1C) generates a smoother connection at the coincident points than the planning without smoothing (M_0, Figure 1B). Compared with the C^1 cubic method (M_1), M_2 indicates a better performance in curvature continuity (see Figure 2). Moreover, the differentiability and curvature continuity are reported in Table I, and 40 trails for each set of (s^*, M_i) are performed. Two criteria are defined: difference of derivatives $f_d = |p^+ - p^-|$ between both sides of the coincident point; difference of curvatures $f_c = |s^+ - s^-|$. By comparison, the differentiability and continuity of curvature is improved using the quintic Hermite interpolator. The reported values validate that a great improvement in the continuity of the curvature was obtained with the G2 quintic Hermite method, because its main strength is the control over the second derivative.

CONCLUSION AND DISCUSSION

In this work, a continuous-curvature path planning method is proposed for endovascular catheterization. The direct connection between two curve segments would lead to non-differentiability at the coincident setpoints. G2 continuous quintic Hermite splines are proposed to handle the connection problem to ensure differentiability and continuity of the curvature itself. In the future, some other factors will be considered for developing intra-operative navigation: (i) the unpredictable environment deformation; and (ii) the uncertainties of model sensing (e.g. the tip position and vascular model).

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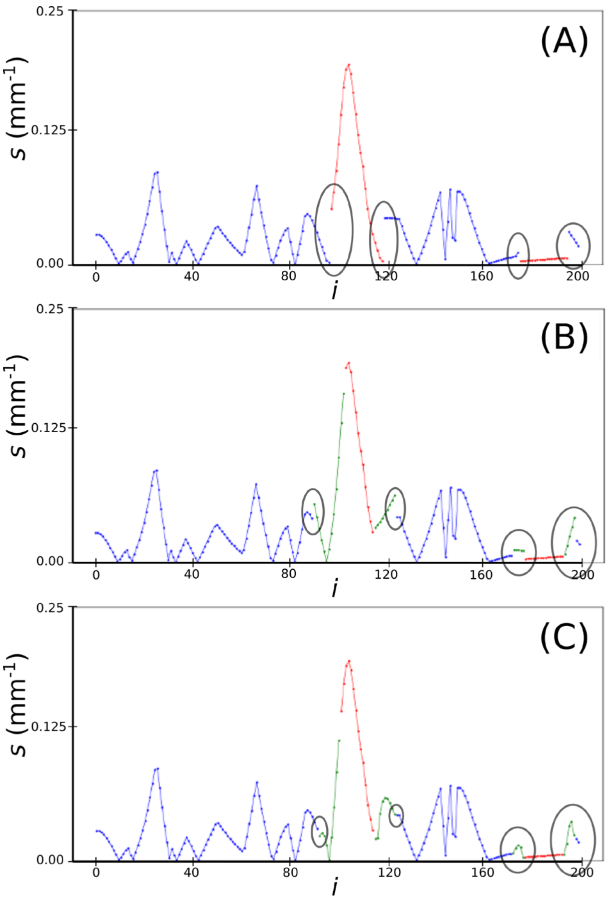

Figure 2. Curvature of the planned path via method (A)-M_0 (B)-M_1 (C)-M_2. Blues represent curvature of the curve along vascular centerlines. Reds are curvature of the optimized path. Greens depict curvature after connection smoothing.

Table I. Performance comparison. The marks (*, $p < 0.05$ Kruskal-Wallis test) represent the statistical significance of (M_0, M_1), (M_1, M_2), (M_0, M_2), respectively.

s^*		M_0	M_1	M_2	p
0.40	f_d	6.06±3.14	0.30±0.19	0.20±0.04	(***)
	f_c	0.356±0.238	0.041±0.008	0.016±0.005	(***)
0.46	f_d	5.80±3.85	0.23±0.08	0.22±0.09	(* *)
	f_c	0.365±0.243	0.041±0.013	0.011±0.011	(***)
0.54	f_d	5.25±3.28	0.23±0.09	0.20±0.08	(***)
	f_c	0.405±0.257	0.024±0.011	0.019±0.008	(***)

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