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Autonomous Path Planning for Vascular Interventional Surgical Robots: From Virtual Simulation to Physical Validation

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***Abstract*—An autonomous navigation framework for vascular interventional surgical robots is proposed in this study, with a focus on path planning based on virtual vascular models and real-time execution control. A complete navigation pipeline is developed, including 3D vessel reconstruction, centerline extraction, fully connected graph construction, and A* search-based optimal path generation. A set of geometric quality metrics, such as path length, curvature, and vessel compliance are used to quantitatively evaluate the feasibility of each planned path. The navigation system is implemented in the SOFA simulation environment with real-time feedback control, and further validated on a physical robotic platform. Experimental results from six navigation trials under different target settings demonstrate that the proposed method enables stable, accurate guidewire advancement with high success rate. The system effectively bridges virtual planning and physical control, providing a robust foundation for intelligent robotic navigation in vascular intervention.**

***Index Terms*—Vascular intervention surgical robot, autonomous navigation, path planning, A* algorithm**

I. Introduction

Endovascular intervention is a minimally invasive medical technique that has been widely applied in the treatment of complex diseases such as coronary artery disease, cerebrovascular disease, and peripheral vascular disorders. Traditional endovascular procedures heavily rely on manual manipulation of instruments such as catheters and guidewires, which places high demands on the surgeon's experience and dexterity. Moreover, it is challenging to maintain consistent precision over long periods of operation. In addition, surgeons are continuously exposed to ionizing radiation during procedures, posing significant health risks in the long term. To address these limitations, the development of vascular interventional surgical robots with autonomous navigation capabilities has emerged as a promising solution [1].

In recent years, the rapid advancement of robotic surgical technologies has opened new possibilities for endovascular interventions. By enabling robot-assisted or even fully autonomous execution of surgical tasks, such systems can significantly reduce the physical workload on surgeons, improve procedural accuracy, and mitigate radiation exposure risks. However, current research on vascular interventional robots primarily focuses on manual teleoperation or semi-autonomous systems, while the development of autonomous navigation remains underexplored. In particular, achieving accurate path extraction and reliable autonomous navigation in complex vascular structures presents substantial technical challenges that demand further investigation.

Virtual Reality (VR) technology provides an ideal experimental platform for verifying path planning and autonomous navigation strategies in vascular interventional robotics. Virtual environments can realistically simulate patient-specific vascular anatomy and physical properties, enabling algorithm validation and navigation strategy optimization prior to clinical deployment. Effective extraction of virtual navigation paths can offer more accurate and reliable guidance for surgical robots, thereby enhancing the safety and success rate of endovascular procedures.

In recent years, the development of autonomous navigation techniques for vascular interventional robots has gained increasing attention across multiple research domains. In 2021, Fan et al. [2] proposed a hybrid path planning algorithm that combines an improved Rapidly-exploring Random Tree (RRT) with an artificial potential field (APF) method to achieve real-time obstacle avoidance in simulated vascular environments. Their method optimized path length and safety while addressing the local minimum problem. In 2022, Konitzny et al. [3] explored global force-based navigation for micro-particle swarms within vascular-like mazes using time-varying magnetic fields. A reinforcement learning approach was trained to gather particles efficiently under global control, demonstrating strong robustness in both simulation and physical mazes. Later in 2022, Li et al. [4] introduced a two-phase path planner that integrates breadth-first search (BFS) with a genetic algorithm (GA) for fast re-planning under catheter curvature constraints. Their method leveraged vascular centerline extraction and parallel optimization to achieve high-frequency updates suitable for real-time operations. In 2023, Karstensen et al. [5] proposed a deep reinforcement learning framework for guidewire navigation in a simulated porcine liver vascular system. The neural network controller, trained without human data, reproduced human-like ”wiggling” behavior with high accuracy in simulation, although its real-world transferability remained limited due to anatomical variations.

Although the aforementioned studies have significantly advanced the intelligence of vascular interventional robotic systems, current autonomous navigation methods still face multiple challenges in terms of path extraction precision, navigation strategy robustness, and clinical adaptability. Therefore, further research and innovation in path extraction and autonomous control strategies are urgently required to enhance the safety and effectiveness of robotic-assisted endovascular interventions [6].

To address these challenges, this study proposes an autonomous navigation method for vascular interventional surgical robots based on virtual path extraction and conducts a comprehensive implementation and validation in a simulated environment. First, the centerline path is extracted from a three-dimensional virtual vascular model to serve as the spatial reference for robot navigation. Then, a navigation graph is constructed based on the extracted path, and a feasible trajectory is generated using a heuristic search algorithm, followed by geometric optimization through smoothing. Finally, a series of navigation tasks are designed to evaluate the quality of the generated paths, verifying the proposed method’s effectiveness in terms of navigational feasibility, geometric consistency, and execution stability. Experimental results demonstrate that the proposed method is capable of producing navigation paths that meet surgical requirements and exhibit desirable robustness and adaptability. This work provides a new approach toward the full autonomy of vascular interventional surgical robots, offering both theoretical significance and practical application value [7]. A photograph of the physical guidewire actuation module is shown in Fig. 1, illustrating the experimental hardware used in real-world validation.

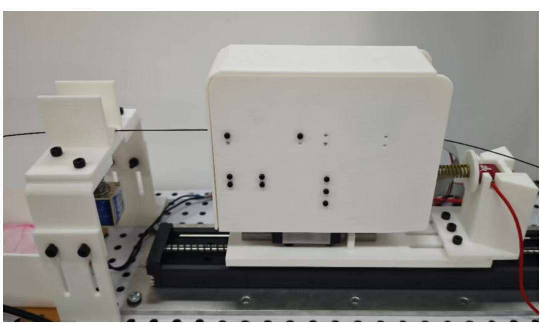

Fig. 1. Physical actuation module for guidewire advancement and rotation used in the real-world experiment platform.

II. System Design and Implementation

To enable autonomous navigation of vascular interventional surgical robots in a virtual environment, this study designs and implements a complete simulation-based navigation system on a computer platform. First, the system utilizes medical imaging processing software such as 3D Slicer or ParaView to obtain patient-specific three-dimensional vascular geometric models in VTP file format. These 3D models preserve the full topological structure and spatial geometry of the vasculature, faithfully representing the complex anatomical features, and serve as a precise foundation for subsequent navigation experiments. Subsequently, the system projects the 3D vascular model onto a two-dimensional plane using a spatial mapping algorithm, generating a 2D topological representation of the vessel network that facilitates intuitive understanding and interaction for the operator. Through a graphical user interface, the user selects a desired target location on the 2D vascular image, and the system automatically maps this selection back to its corresponding 3D coordinates in the original vascular model, thereby obtaining the precise spatial position of the navigation target for downstream path planning.

After determining the target position, the system employs an autonomous path planning algorithm to generate a feasible 3D navigation trajectory from the vascular entry point to the target. The path generation process takes into account both spatial constraints within the vessel lumen and safety/efficiency principles, ensuring that the resulting trajectory is both optimal and clinically viable. The planned path is then smoothed and stored as a sequence of 3D coordinates, which are transmitted in real time to the robot motion control system via a dedicated data interface, providing direct reference for guidewire movement.

The robot motion control is implemented based on SOFA (Simulation Open Framework Architecture), an open-source real-time physics simulation platform widely used in surgical simulation and robotic control research [8]. SOFA provides robust capabilities for simulating the physical behavior of flexible instruments such as guidewires, including their deformation, contact, and frictional interaction with complex anatomical environments. In particular, the BeamAdapter plugin in SOFA enables the modeling of guidewires using beam theory, where the guidewire is discretized into multiple rigid segments connected by spring-damper elements. This approach allows for realistic simulation of guidewire bending, twisting, deformation, and interaction with vessel walls, thereby achieving high-fidelity replication of real interventional scenarios [9].

Within the SOFA-based simulation environment established in this study, the dynamic behavior of the guidewire was modeled in real time using the BeamAdapter plugin. This plugin simulates the guidewire as a flexible structure composed of multiple interconnected rigid elements, enabling accurate representation of bending, twisting, and deformation. The position of the guidewire tip was continuously fed back to an autonomous navigation controller, which computed the deviation from the preplanned reference trajectory. A closed-loop control algorithm was then used to adjust the guidewire’s advancement speed, rotation angle, and insertion direction in real time, ensuring precise path tracking during navigation [10].

In addition to simulation-based validation, a physical robotic platform was also developed to verify the practical executability and structural stability of the planned paths. The platform includes a motorized guidewire actuation unit capable of advancement and rotation. This prototype system was used to conduct open-loop path-following experiments based on the trajectories generated in the virtual environment.

III. Path Planning Method

This study proposes a path planning method tailored for autonomous navigation of vascular interventional surgical robots. The algorithm implementation consists of two primary steps: construction of a navigation graph and path generation based on the A* search algorithm. First, a set of centerline points is extracted from a virtual vascular model. A fully connected graph is then constructed using these points as nodes. Subsequently, the A* algorithm is employed to traverse the graph and generate an optimal navigation path from the entry point to the target location. [11]

In detail, the nodes of the navigation graph are derived from the spatial centerline points within the vessel lumen, where each node represents a specific 3D position. All nodes are fully connected, meaning an edge exists between every pair of nodes. The weight of each edge corresponds to the Euclidean distance between two nodes in three-dimensional space. The navigation graph is denoted as $G = (V, E)$, where V is the set of all centerline points.The distance transform heatmap of the vascular structure is shown in Fig. 2.

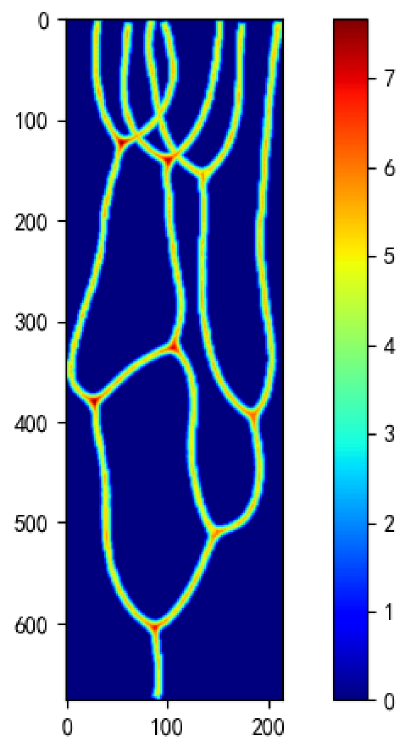

Fig. 2. Distance transform heatmap of the vascular structure, with distance values measured in millimeters (mm). Warmer colors indicate regions farther from the vessel boundary.

For any two nodes v_i and v_j, the weight of the edge $e_{ij} \in E$ is defined as:

$$w(e_{ij}) = d(v_i, v_j) = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2} \quad (1)$$

where (x_i, y_i, z_i) and (x_j, y_j, z_j) are the coordinates of nodes v_i and v_j, respectively. The edge weight $w(e_{ij})$ represents the spatial cost of moving the guidewire from node v_i to v_j. Once the navigation graph is constructed, the A* algorithm is applied to perform path search. As a classic heuristic-based path planning method, A* is capable of efficiently finding the shortest path in a complex graph structure. The evaluation function $f(n)$ for each node n is defined as:

$$f(n) = g(n) + h(n) \quad (2)$$

Here, $g(n)$ represents the actual cumulative cost from the start node n_{start} to the current node n, and $h(n)$ is a heuristic function estimating the minimum remaining cost from node n to the goal node n_{goal}. In this study, the heuristic function is also defined as the Euclidean distance between the current node and the goal node:

$$h(n) = \sqrt{(x_n - x_{\text{goal}})^2 + (y_n - y_{\text{goal}})^2 + (z_n - z_{\text{goal}})^2} \quad (3)$$

During the execution of the algorithm, the node with the smallest $f(n)$ value in the open set is selected for expansion at each iteration and moved to the closed set. When the goal node is reached, the algorithm terminates, and the optimal path is reconstructed by backtracking through the predecessor nodes. The final navigation path is denoted as:

$$P^* = \{n_{\text{start}}, n_1, n_2, \ldots, n_{\text{goal}}\} \quad (4)$$

The proposed method not only yields the shortest path between the start and target locations, but also records the complete set of intermediate coordinates, which serve as precise spatial references for robotic guidewire control. This enables real-time feedback correction based on positional deviation.

Unlike conventional shortest-path algorithms, the method proposed in this study also emphasizes the geometric quality of the generated path. Therefore, after path generation, a series of quantitative metrics are employed to assess the path structure, including: Path Length (PL), Mean Curvature (MC), Maximum Curvature (MaxC), Smoothness Score (SM), Vessel Rate (VR).

These indicators will be thoroughly analyzed in the following analysis to evaluate the quality and yield of the generated navigation paths. The integration of structural and spatial assessments ensures that the generated path is not only geometrically feasible but also physically executable by the robotic system.

IV. Geometric Path Quality Evaluation and Validation

After completing path planning based on vascular centerlines, this study further performs a systematic analysis and validation of the generated paths from a geometric perspective, in order to assess their feasibility and applicability in vascular interventional procedures. Unlike traditional path planning methods that focus solely on minimizing path length, the proposed approach emphasizes spatial continuity, smoothness, structural rationality, and anatomical compliance with the vessel lumen. These factors directly influence the controllability of the guidewire, navigation stability, and procedural safety, thus making the construction of a robust path quality evaluation framework essential.

Upon completion of path generation, three-dimensional spline interpolation is applied to enhance geometric continuity and eliminate discontinuities or sharp turns caused by discretized centerline points. The smoothed path is uniformly resampled into a set of discrete points $\{P_1, P_2, \ldots, P_N\}$, where each point is represented as $P_i = (x_i, y_i, z_i)$, and used for subsequent geometric analysis [12].

The first metric is the path length (PL), which reflects the navigation cost and overall path efficiency, and is computed as:

$$PL = \sum_{i=1}^{N-1} \sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2 + (z_{i+1} - z_i)^2} \tag{5}$$

To evaluate bending behavior, the local curvature κ_i is estimated using a three-point sliding window as:

$$\kappa_i = \frac{\|(P_{i+1} - P_i) \times (P_i - P_{i-1})\|}{\|P_{i+1} - P_i\|^3}, \quad i = 2, \ldots, N-1 \tag{6}$$

Based on this, the mean curvature (MC) and maximum curvature (MaxC) of the path are defined as:

$$MC = \frac{1}{N-2} \sum_{i=2}^{N-1} \kappa_i, \quad MaxC = \max_{i=2,\ldots,N-1} \kappa_i \tag{7}$$

To evaluate smoothness, we calculate the first-order difference of curvature:

$$\Delta\kappa_i = \kappa_{i+1} - \kappa_i \tag{8}$$

The smoothness score (SM) is then defined as the reciprocal of the standard deviation of $\Delta\kappa$, with a small regularization term ε to avoid division by zero:

$$SM = \frac{1}{\sigma_{\Delta\kappa} + \varepsilon} \tag{9}$$

To ensure spatial compliance with the vascular structure, the vessel rate (VR) is defined as the proportion of path points that remain within the vessel lumen, expressed as:

$$VR = \frac{1}{N} \sum_{i=1}^{N} \mathbb{I}[P_i \in \text{Vessel}] \tag{10}$$

Finally, we define a navigation success criterion (SP) that determines whether a generated path meets all geometric requirements. A path is considered valid if:

$$SP = (PL < L_{\max}) \wedge (MaxC < \kappa_{\max}) \wedge (VR \geq \eta) \wedge (SM > \delta) \tag{11}$$

where $L_{\max}, \kappa_{\max}, \eta, \delta$ are predefined evaluation thresholds based on anatomical parameters and guidewire constraints. The experimental setup is illustrated in Fig. 3. In this study, six navigation experiments were conducted under different target locations, each following a complete path planning, quality evaluation, and navigation feasibility validation process. The quantitative results are summarized in Table I. All six planned paths successfully met the predefined evaluation criteria, demonstrating good geometric continuity, smooth curvature distribution, and full vessel compliance. No critical deviations or control failures were observed. The overall path yield rate was therefore 100%, indicating the robustness and consistency of the proposed method in various navigation scenarios.

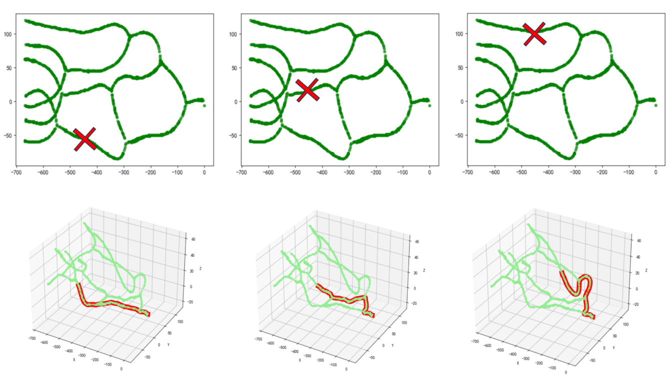

Fig. 3. A parts of experimental setup and target distribution in the vascular environment.

TABLE I
EVALUATION METRICS OF CENTERLINE NAVIGATION PATHS.

Path	PL (mm)	MC (1/mm)	MaxC (1/mm)	SM	VR	SP
1	449.13	0.0148	0.0953	140.88	1.000	True
2	480.34	0.0140	0.1295	93.77	1.000	True
3	477.43	0.0155	0.1077	118.61	1.000	True
4	462.47	0.0159	0.1193	125.92	1.000	True
5	449.36	0.0135	0.0923	141.97	1.000	True
6	476.07	0.0151	0.0908	148.19	1.000	True

The path quality evaluation mechanism proposed in this chapter not only confirms the geometric feasibility of the planned trajectories but also provides a theoretical basis for subsequent motion control. Compared with visual inspection or heuristic filtering, this quantitative evaluation approach establishes a unified and extensible standard, suitable for complex vascular networks.

V. Simulation and Physical Experiments

To validate the feasibility and reliability of the proposed autonomous navigation path planning method in practical applications, two sets of verification experiments were conducted, including virtual simulation and physical platform testing. Through the integration of software and hardware-level testing, the system's overall performance and the controllability of the generated paths were comprehensively evaluated.

A. Simulation:

A high-fidelity vascular navigation simulation was developed using the SOFA (Simulation Open Framework Architecture) platform. This simulation environment integrates a realistic vascular model, a guidewire physical modeling module (BeamAdapter plugin), and an autonomous control system. To enable efficient interaction between the control logic and the physical simulation engine, the autonomous control module was implemented in Python and interfaced with the SOFA framework, forming a simplified closed-loop navigation control system. The controller receives the real-time position of the guidewire tip, compares it with the reference path, and dynamically adjusts the advancement speed and rotation angle to steer the guidewire toward the target.

The simulation begins from predefined entry points, with the guidewire autonomously advancing along the reference trajectory within the virtual vasculature. Across multiple scenarios with varying target positions, the guidewire consistently reached the designated locations without human intervention. Throughout the navigation process, the actual path showed a close match with the precomputed trajectory in 3D space, with no significant deviation observed. These findings confirm that the proposed method is effective not only for path planning but also for execution-level tracking within the simulated environment, as illustrated in Fig. 4.

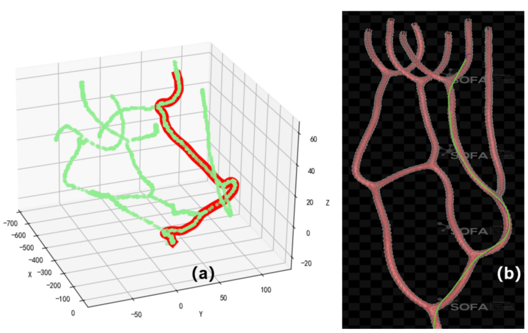

Fig. 4. SOFA-based simulation of guidewire advancement along the planned trajectory within the virtual vessel environment. (a) Path optimization and extraction from candidate centerlines; (b) Real-time path tracking in SOFA simulation.

B. Physical Experiment:

In the physical experiments, a simplified robotic platform for vascular intervention was constructed to verify the executability and stability of the planned paths under real hardware conditions. The experimental setup included a guidewire actuation unit, advancement and rotation modules, and a visual feedback system to simulate and capture real-world guidewire movements. The experiments focused on validating the spatial feasibility of the paths in a physical vessel model. The results showed that, under open-loop execution driven by preplanned instructions, the guidewire was able to advance continuously toward the target location without severe deviation or control failure. This confirms the stability and physical realizability of the planned paths on the hardware level, as illustrated in Fig. 5.

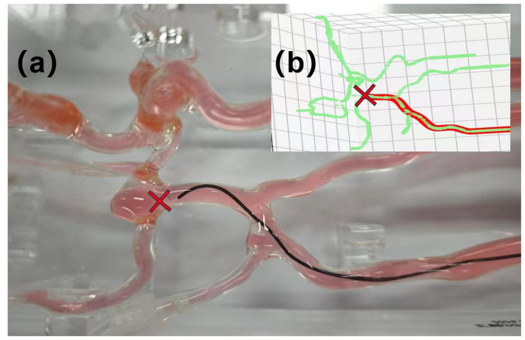

Fig. 5. Physical experimental setup for guidewire actuation and path execution validation. (a) Guidewire trajectory in a transparent 3D-printed vascular phantom; (b) Comparison with the corresponding pre-planned path from the virtual model. The red cross denotes the target location.

VI. Conclusion

This study presents an autonomous navigation method for vascular interventional surgical robots, with a focus on optimizing path planning algorithms and ensuring robust execution. A fully connected vascular navigation graph was constructed based on the extracted vessel centerline, and an A* search algorithm was employed to generate optimal paths while considering spatial continuity and curvature constraints. To evaluate the structural quality of the planned paths, a set of quantitative metrics—including path length, curvature smoothness, and vessel compliance—was introduced, forming a comprehensive evaluation framework that enhances both algorithmic robustness and clinical relevance.

Furthermore, the proposed navigation framework was implemented in a simulation environment using the SOFA platform, where a closed-loop controller was used to track the reference trajectory with high precision. In addition to simulation, physical experiments were performed on a simplified robotic prototype to validate the geometric feasibility and physical stability of the paths under real-world conditions. The consistency between simulated and physical results confirms the reliability and practicality of the method [13].

In summary, this work integrates algorithmic optimization, physical modeling, and dual-mode experimental validation, demonstrating a complete and effective solution for autonomous path planning in robotic vascular interventions. Future work will focus on integrating the real-time control system into the physical platform to achieve closed-loop autonomy in clinical scenarios.

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