Contact-Aware Planning and Control of Soft Continuum Robots in Highly Constrained Environments

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I. Introduction

Soft continuum robots have become increasingly popular in applications that require navigating through tight, deformable, and fragile environments, such as vascular intervention, endoscopy, and inspection in confined spaces [1, 2]. In these settings, contact between the robot and the environment is often necessary for successful navigation, but unfavorable contact can degrade controllability, induce kinematic singularities, or cause irreversible damage to surrounding structures. Prior planning methods either avoid obstacles entirely or exploit contact to facilitate navigation [3–6]. These works advanced soft continuum robot deployment in constrained settings, but do not (i) distinguish between benign and hazardous contact during planning, or (ii) integrate contact-aware, closed-loop control for reliable hardware execution. Similarly, model-based and model-free control strategies use sensor feedback to address errors [7, 8], and may enforce safety via control barrier and Lyapunov functions to limit interaction forces [9, 10]. While these strategies regulate interaction and enable adaptation to errors, they generally do not assess kinematic feasibility or differentiate trajectories based on controllability during environment interaction.

As a representative use case, we consider autonomous aortic arch navigation during mechanical thrombectomy [11], where clinicians rely on controlled body contact while avoiding tip contact due to risk of vessel perforation. To address the limitations of existing methods, we introduce a unified, contact-aware planning and control framework that regulates robot-environment interaction. Our contributions are:

- **Contact-Aware Planner:** We present a model-based planner for soft continuum robot navigation in highly constrained environments that explicitly accounts for body-environment interaction, generating kinematically valid trajectories that reduce unfavorable contact and mitigate contact-induced singularities, and uses task-space partitioning to enable a dynamic action space and an informed heuristic to guide search.
- **Control:** We propose a trajectory tracking controller that requires only tip pose feedback. The controller leverages three things from the contact-aware planner: (1) precomputed tip pose waypoints, (2) joint input commands , and (3) contact-aware Jacobians to enable accurate execution with minimal sensing.
- **Integrated System Validation:** Hardware demonstration on a multi-segment soft continuum robot in anatomical models from patient scans, achieving autonomous navigation in type I, II, and III aortic arches while avoiding distal tip contact, thereby reducing the risk of vessel injury.

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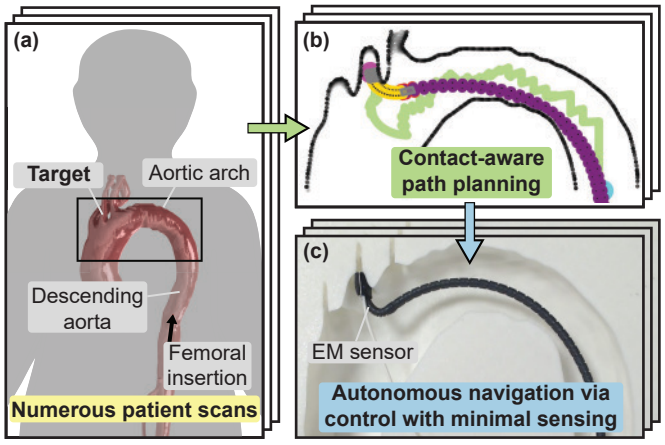


Fig. 1. Overview of the proposed contact-aware planning and control framework. (a) Patient imaging data and target location serve as inputs to (b) the contact-aware motion planner, which enables controlled environmental interaction while penalizing hazardous and unstable robot configurations. (c) The feedback controller executes the planned trajectory using closed-loop control with minimal sensing. The framework was validated across multiple environments (successful navigation in all three aortic arch types).

II. Methods

A. Contact-Aware Planning

We formulate this as a search-based motion planning problem on the robot's configuration space discretized as a graph $G = (\mathcal{V}, E)$. Each node $v \in \mathcal{V}$ represents a discretized joint configuration $\mathbf{q}_v$ and its associated shape (from the curvature vector $\boldsymbol{\kappa}_v$), and edges E connect neighboring configurations through feasible actuator increments. The cost function is:

$$\begin{aligned} \min_{v_{0:\tau},\tau} \quad & \sum_{k=0}^{\tau-1} \eta_{\text{action}}(\mathbf{q}_{v_k}, \mathbf{q}_{v_{k+1}}) + \eta_{\text{contact}}\big(\mathcal{R}(q_{\text{a},v_{k+1}}, \boldsymbol{\kappa}_{v_{k+1}})\big) \\ \text{s.t.} \quad & \mathbf{p}(q_{\text{a},v_\tau}, \boldsymbol{\kappa}_{v_\tau}) \in \mathcal{G}, \\ & (v_k, v_{k+1}) \in \mathcal{U}_\ell\big(\mathcal{R}(q_{\text{a},v_k}, \boldsymbol{\kappa}_{v_k})\big) \subseteq E, \\ & \boldsymbol{\kappa}_{v_{k+1}} = \mathcal{F}\big(\mathbf{q}_{v_{k+1}}, \boldsymbol{\kappa}_{v_k}\big). \end{aligned} \tag{1}$$

Here η_{action} penalizes robot motion while η_{contact} penalizes contact based on the robot points $\mathcal{R}(\cdot)$ with contact at the end of the continuum segment (ECS) having a higher penalty. The function $\mathcal{R}(q_{\text{a},v}, \boldsymbol{\kappa}_v)$ denotes the robot geometry at node v, and $\mathbf{p}(\cdot)$ extracts the corresponding tip pose, which is required to reach the goal set $\mathcal{G}$. The constraint $(v_k, v_{k+1}) \in \mathcal{U}_\ell$ enforces the partition-dependent action space and restricts transitions in E based on the partition ℓ of the robot tip. Given the updated joint command $\mathbf{q}_{v_{k+1}}$, the new set of

curvatures $\boldsymbol{\kappa}_{v_{k+1}}$ updates based on the contact-aware motion model $\mathcal{F}(\cdot)$. We adapt a contact-aware motion model in [4, 12] for a two-segment soft continuum robot and extend it to handle non-convex environment geometry. We use weighted A* for planning and the heuristic is based on task-space motion.

B. Control

Precomputed joint values from the contact-aware motion planner provide sufficient accuracy for simple motions in localized environments. However, tasks involving high curvatures or long trajectories require closed-loop control to compensate for tendon friction, inter-segment coupling, and environment misalignment [2, 8, 11]. The controller combines feedforward and feedback components:

$$\mathbf{u}_t = \beta\, \mathbf{u}_t^{\mathrm{FF}} + (1-\beta)\, \mathbf{u}_t^{\mathrm{FB}}, \tag{2}$$

with $\mathbf{u}_t^{\mathrm{FF}} = \mathbf{u}_k$ coming from the plan. The tracking error is $\mathbf{e}_{k,t} = \mathbf{p}_k - \mathbf{p}_t^*$, and feedback uses a damped pseudo-inverse of a contact-aware robot Jacobian $\mathbf{u}_t^{\mathrm{FB}} = (\mathbf{J}_k^{\Delta})^{\dagger}\,(\mathbf{K}_p\mathbf{e}_{k,t} + \mathbf{K}_d\dot{\mathbf{e}}_{k,t})$ where $\mathbf{J}^{\Delta}$ is obtained offline by perturbing each joint and measuring the resulting changes in tip position and orientation. This provides a local linear mapping between joint and task space that varies with robot configuration and contact conditions but remains sufficiently accurate for closed-loop trajectory tracking.

III. Results

We validated the integrated planning and control framework on a two segment soft continuum robot with an EM tip sensor in 3D-printed aortic arch models created from patient scans (Fig. 2). Across three trials per arch (nine trials total), the robot reached the target vessel while avoiding distal tip contact. Mean tracking errors were 1.9 ± 0.5 mm (type I), 1.2 ± 0.1 mm (type II), and 1.7 ± 0.2 mm (type III). Ablation studies showed that penalizing end-of-continuum-segment (ECS) contact improved manipulability and prevented hardware failures.

IV. Conclusion

Autonomous navigation of soft continuum robots in confined anatomical environments is an important yet challenging problem, as unavoidable contact with surrounding structures can degrade manipulability, induce singularities. and introduce safety risks. We present a contact-aware planning and control framework that produces kinematically feasible, safe trajectories for soft continuum robots in highly constrained environments and executes them with a minimal-sensing feedback controller.

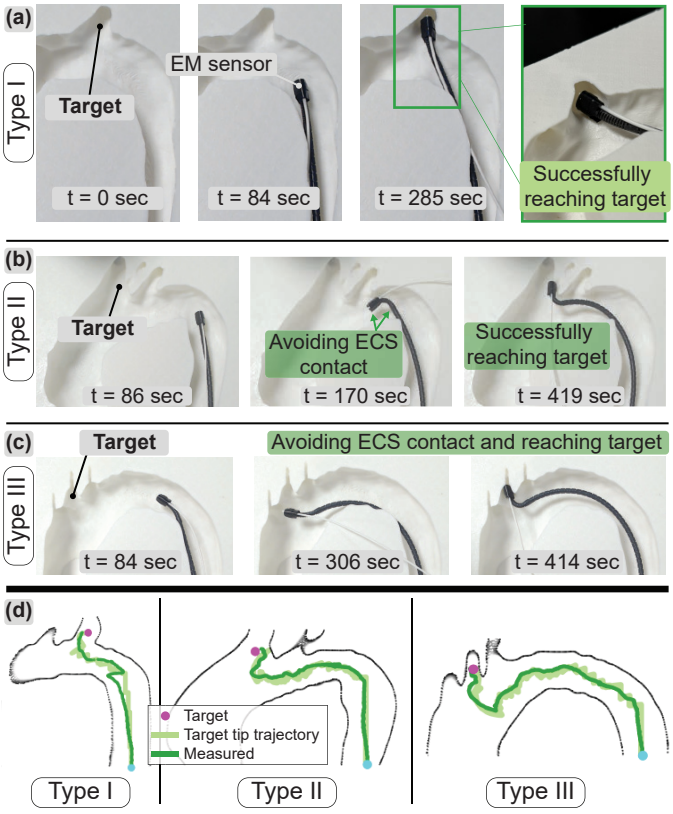


Fig. 2. Hardware experiments evaluated the proposed contact-aware planning and control framework in three anatomical environments: (a) type I, (b) type II, and (c) type III. (d) Measured tip position (dark green) with the target trajectory (light green) from one trial from each arch type. We conducted three trials in each environment (nine total trials), demonstrating that the proposed planning and control framework enabled reliable navigation in highly constrained environments while avoiding dangerous tip contact.

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