Safe Autonomous Environmental Contact for Soft Robots using Control Barrier Functions

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I. Introduction

Robots built from soft and deformable materials are often claimed to be inherently 'safe' or 'safer' than their rigid counterparts [6], yet prior work in control of soft robots has shown that *soft robots do not satisfy safety conditions automatically*. For example, soft actuators can fail by exceeding their operational limits [8, 2], and soft robots can collide with themselves [7]. Specialized invariance-based controllers have ensured safety in those settings. This work proposes that closed-loop control is a necessary condition for safety verification of a soft robot's motion writ large, and in particular, its environmental contact forces: the reason for being of soft robots. We adapt the approach of control barrier functions (CBFs) [1, 3] to meet a set invariance condition on the end effector poses of a soft manipulator. Then, we take the proof-of-concept situation where the robot exists in a deformable environment, such as when contacting tissue in a patient, and propose a mapping to convert a constraint on external forces to a state constraint. We demonstrate that a standard formulation of CBF-based control can meet this constraint in both simulation and hardware experiments, and verify that our controller maintains a positive *safety margin* on force when an open-loop controller does not (Fig. 1).

II. Control Framework Overview

Definition 1: **Force safety.** Trajectories of a (soft) robot's end effector, $\mathbf{r}(t)$, are force-safe if the applied force at that end effector $\mathbf{F}(t)$ remains within a set of acceptable forces $\mathcal{F}^{safe}$, or equivalently, $\mathcal{F}^{safe}$ is invariant under the system's dynamics: $\mathbf{F}(0) \in \mathcal{F}^{safe} \Rightarrow \mathbf{F}(t) \in \mathcal{F}^{safe}\ \forall t$.

A. Problem Formulation and Force-Safe Set Construction

We consider a planar soft manipulator operating in a workspace that includes a deformable force plate, modeled as the face of a polytope $\mathcal{P}$. The robot's tip may contact the environment, and our goal is to ensure that any contact forces generated during this interaction remain within a known safe bound F^{max}, so $\mathcal{P} = \{\mathbf{r} | \mathbf{F}(\mathbf{r}) \in \mathcal{F}^{safe}\}$. The environment is

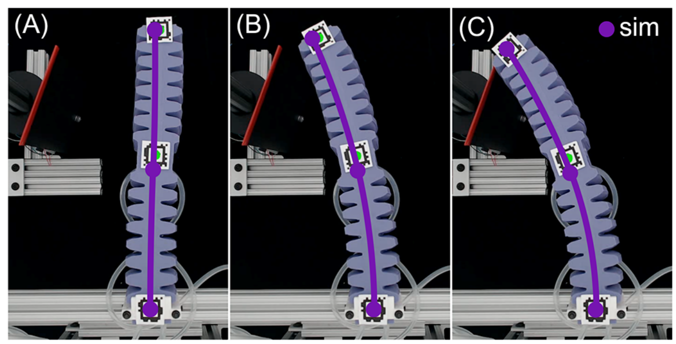

Fig. 1. Comparison of the simulation's kinematics versus hardware at three key points during a corresponding test demonstrates the alignment between the model and experiment.

characterized by elastic deformation: each face deforms only in its outward normal direction, and follows a linear spring model with known stiffness ψ. Let the no-contact region be represented as the polytope:

$$\mathcal{N} = \{\mathbf{r} \mid \mathbf{H}\mathbf{r} \leq \mathbf{h}\} \tag{1}$$

with the assumption that each face has a unique, outward normal. We derive the force-safe set $\mathcal{P} \subset \mathbb{R}^2$ as the set of tip positions r such that, under maximum contact, the corresponding contact forces remain below the critical value F^{max}. This leads to a translated polytope:

$$\mathcal{P} = \{\mathbf{r} \mid \mathbf{H}'\mathbf{r} \leq \mathbf{h}'\}, \tag{2}$$

where $\mathbf{H}'_i = \mathbf{H}_i$, and $h'_i = h_i + n^{max}\sqrt{m^2+1}$. Here, $n^{max}\sqrt{m^2+1}$ represents the maximum deflection allowable per face and m represents the slope of the given face.

B. Robot Dynamics and Control Barrier Function Formulation

We use a PCC (piecewise constant curvature) model to describe the manipulator's shape, parameterized by joint angles $\mathbf{q}$. Using the augmented body formulation by Della Santina et al. [4], the dynamics are expressed as:

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{D}\dot{\mathbf{q}} + \mathbf{K}\mathbf{q} = \Lambda\mathbf{u} \tag{3}$$

where $\mathbf{u} \in \mathbb{R}^N$ are pneumatic pressure inputs, and Λ is a gain matrix calibrated via least squares regression from real hardware input-output data.

The controller aims to ensure that the robot's tip remains inside the safe set $\mathcal{P}$. Let $r(q)$ be the forward kinematics of the end effector. We define scalar barrier functions:

$$b_i(\mathbf{x}) = \mathbf{h}'_i - \mathbf{H}'_i \mathbf{r}(\mathbf{q}), \qquad i = 1 \dots P \tag{4}$$

and construct a relative degree-two CBF:

$$B_i(\mathbf{x}) = -\ln\left(\frac{b_i(\mathbf{x})}{1 + b_i(\mathbf{x})}\right) + a_E \frac{b_E\, \dot{b}_i(\mathbf{x})^2}{1 + b_E\, \dot{b}_i(\mathbf{x})^2} \tag{5}$$

with tuning parameters $a_E, b_E > 0$ affecting conservativeness. The force safety controller is synthesized via a QP:

$$\begin{aligned} \mathbf{u}^*(\mathbf{x}) = \ & \arg\min_{\mathbf{u}} \quad \mathbf{u}^\top \mathbf{u} - 2\mathbf{u}^\top \mathbf{u}_{nom} \\ & \text{s. t.} \qquad \mathbf{A}(\mathbf{x})\mathbf{u} \leq \mathbf{b}(\mathbf{x}) \end{aligned} \tag{6}$$

where $\mathbf{u}$ is our decision variable since $\mathbf{x}$ remains constant at each timestep. The matrix-vector pair $\mathbf{A}$ and $\mathbf{b}$ of safety constraints are formulated in detail in our manuscript [5].

III. Experimental Setup and Validation

Simulation: We simulate the soft manipulator using calibrated parameters: segment lengths, masses, and stiffness coefficients match hardware values. The robot is driven with sinusoidal open-loop nominal control, then filtered via the CBF-QP. Results show in Fig. 3 that without the CBF, the robot violates safety constraints, while with the CBF, it maintains a positive margin $\rho(t) = (F^{max} - F(t))/F^{max}$.

Hardware: The system consists of a two-link soft pneumatic limb with antagonistic actuation. Bending angles are extracted using AprilTags and computer vision. Pneumatic pressures are actuated via microcontroller-driven pumps and valves, with feedback provided by pressure sensors. The environment is a deformable ABS sheet mounted on a calibrated force sensor (black and red plate in Fig 1). The experimental controller runs in real-time using ROS2 and MATLAB. Across all tested levels of conservativeness (High, Medium, Low), the CBF-modified control ensures the force remains under the safety limit as seen in Fig. 4. Only the 'None' case, using unfiltered nominal control, leads to unsafe contact. Results in both simulation and hardware experiments on a pneumatic soft robot are consistent and confirm that the proposed safety-critical control approach successfully satisfies an invariance condition on the force applied by a soft robot tip as seen in Fig. 1.

IV. Conclusion

We have introduced a control framework for ensuring provable force safety in soft robot manipulators interacting with deformable environments. By mapping physical contact force limits into geometric constraints on end-effector pose and enforcing them with control barrier functions, we bridge the gap between morphological compliance and formal safety. Our results, validated in both simulation and hardware, highlight the feasibility and necessity of feedback-based safety guarantees in soft robotics.

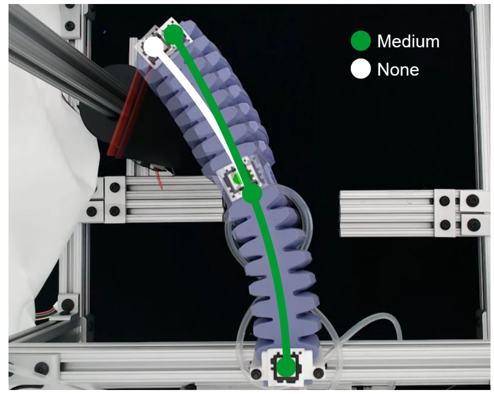

Fig. 2. Snapshot of hardware tests at $t = 30$s with no CBF (white) superimposed onto 'Medium' conservativeness CBF (green). Including the CBF visually limits the end effector's position.

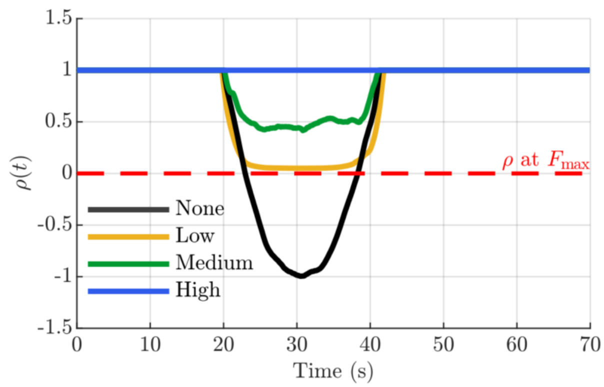

Fig. 3. All simulations with CBF-based control show a positive safety margin on force application. The most conservative CBF tuning (blue) prevents all environmental contact.

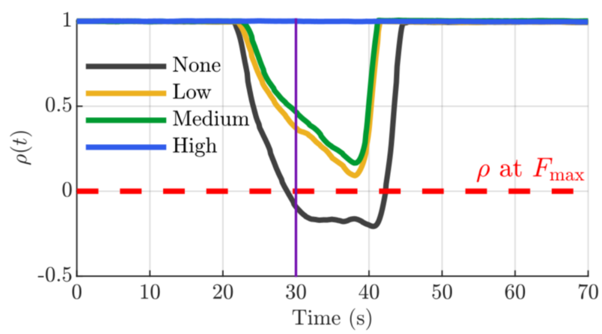

Fig. 4. Safety margin $\rho(t)$ for the hardware experiments. The red, dashed line, outlines the minimum allowed ρ value to guarantee force safety. The purple thin line at $t = 30s$ allows for quick comparison of the ρ value for the superimposed cases in Fig. 2.

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