Safe Supervisory Control of Soft Robot Actuators

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***Abstract*—Although soft robots are claimed to show safer interactions with their environment than traditional robots, soft mechanisms and actuators still have significant potential for damage or degradation. This article introduces a feedback strategy for safe soft actuator operation during control of a soft robot during unmodeled environmental contact. To do so, a supervisory controller monitors actuator state and dynamically saturates control inputs to avoid conditions that could lead to physical damage. We prove that, under certain conditions, the supervisory controller is stable and verifiably safe. We then demonstrate completely onboard operation of the supervisory controller using a soft thermally-actuated robot limb with embedded shape memory alloy (SMA) actuators and sensing. We present experiments which show that our approach prevents overheating during contact (including environmental constraints and human contact) or when infeasible motions are commanded from learning from demonstration. This supervisory controller, and its ability to be executed with completely onboard sensing, has the potential to make soft robots reliable enough for practical use.**

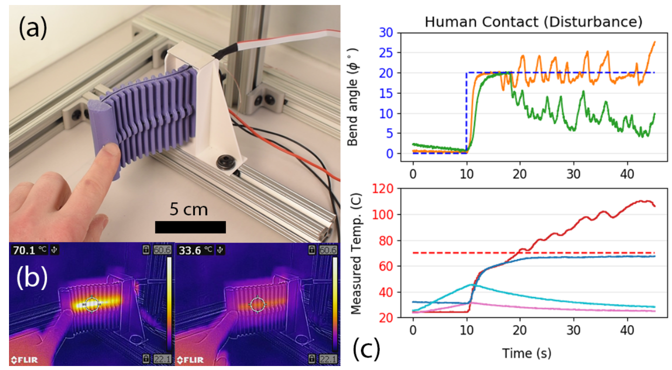

Fig. 1: Operation of the safe supervisory control scheme on a thermally-actuated shape memory alloy (SMA) soft robot limb during human contact (a) prevents overheating (b). Results using onboard temperature and position sensors verify safe temperatures (c), in blue, versus unsafe control, in red.

I. Introduction

One of the most prevalent claims about soft robots is their intrinsic safety when interacting with humans or the environment (Laschi et al. [4], Majidi [5]). Less commonly discussed are new challenges in safety introduced through the use of novel soft actuators required for generating robotic motion. Soft actuators can fail dramatically, as practitioners may recognize. Informally, pneumatic balloons can pop, thermal actuators can overheat and cause fire risks (Soother et al. [8]), and dielectrics can cause dangerous arcing (Bilodeau and Kramer [1]), among others. As of yet, these risks have been mitigated by simple bespoke system designs, hard limits on actuation input (Yee Harn Teh and Featherstone [10]), or open-loop actuation (Patterson et al. [6]). Incorporating automatic control into soft robots demands more generalizable and robust approaches to actuator safety.

This work proposes a feedback control framework that ensures safety of a class of soft robot actuators. The framework employs a model-based supervisor that dynamically saturates a primary, unspecified, control strategy - which we term the *pose* controller (Fig. 1(a)). Our work takes inspiration from other approaches for safe supervisory control in electromechanical systems, where reachability computations are used to determine when to switch to the supervisor (Zhang et al. [11]). We demonstrate our framework on a soft robot limb with embedded position and temperature sensing for two thermally-stimulated shape memory alloy (SMA) actuators, using two different pose controllers, in the presence of environmental contact (Fig. 1(b)-(c)). This task presents a generalizable challenge since the cause of failure (excess heat) can only be indirectly monitored and controlled.

II. Framework Overview

We consider soft robot actuators that can be modeled as affine systems, a general class that includes the thermally controlled activation of SMA wires (Wertz et al. [9]) as well as modern data-driven methods that admit linear systems (Bruder et al. [2]). If an individual actuator's internal state is w and an affine-augmented state is $\widetilde{\mathbf{w}} = [w, \quad 1]^\top$, we assume the actuator dynamics are

$$\widetilde{\mathbf{w}}(k+1) = \mathbf{A}\widetilde{\mathbf{w}}(k) + \mathbf{B}u(k)\,. \tag{1}$$

From linear systems theory, the control input that brings our system state to a desired setpoint $\widetilde{\mathbf{w}}^{SET}$ in one timestep is

$$u(k)^{SET} = \mathbf{B}^\top(\mathbf{B}\mathbf{B}^\top)^\dagger(\widetilde{\mathbf{w}}^{SET} - \mathbf{A}\widetilde{\mathbf{w}}(k))\,. \tag{2}$$

If this system is a *monotone* control system, in that $u_a \leq u_b \Rightarrow w_a(k+1) \leq w_b(k+1)$, it is intuitive that applying "less" control will keep $\widetilde{\mathbf{w}} < \widetilde{\mathbf{w}}^{SET}$. We propose the following controller for the supervisor:

$$\begin{aligned} u(k)^{MAX} = \gamma\mathbf{B}^\top(\mathbf{B}\mathbf{B}^\top)^\dagger(\frac{1}{\gamma}(\mathbf{I} - \dots \\ (1-\gamma)\mathbf{A})\widetilde{\mathbf{w}}^{MAX} - \mathbf{A}\widetilde{\mathbf{w}}(k))\,, \end{aligned} \tag{3}$$

where $\gamma \in (0,1)$ is a tuning parameter, and the *SET* point has been adjusted to a *MAX* point with some manipulation of the system model. We can readily prove that the resulting closed-loop error dynamics in the form of $\mathbf{e}(k+1) = (1-\gamma)\mathbf{A}\mathbf{e}(k)$, where the error is $\mathbf{e} := \widetilde{\mathbf{w}} - \widetilde{\mathbf{w}}^{MAX}$, are stable if the open loop system is stable.

More importantly, we can integrate the supervisor with some other feedback controller on the whole system state $\mathbf{x}$ that includes the pose dynamics. Denoting the pose controller as $v(\mathbf{x})$, we now close the loop as

$$u(\mathbf{x}(k)) = \begin{cases} v(\mathbf{x}(k)) & \text{if} \quad v(\mathbf{x}(k)) \leq u^{MAX}(\mathbf{x}(k)) \\ u^{MAX}(\mathbf{x}(k)) & \text{else} \end{cases} \tag{4}$$

where the actuator states are implicitly elements of $\mathbf{x}$. The closed loop system is in $\mathcal{C}^0$ and is Lipschitz continuous (if $v(\mathbf{x})$ is so). We arrive at the following theorem.

Theorem 1. *For the closed-loop system defined by eqns. (1), (3), (4), consider a polytope* $S = \{\mathbf{e}|\mathbf{He} \leq \mathbf{h}\}$ *where* $\mathbf{e} = 0$ *is the upper bound. If a maximum invariant set calculation verifies that* $\mathcal{S}$ *is positively invariant under* $u = u(k)^{MAX}$*, then* $\mathcal{S}$ *is also positively invariant under* $u = u(\mathbf{x}(k))$.

In other words, if $\widetilde{\mathbf{w}}(0) \leq \widetilde{\mathbf{w}}^{MAX}$, and we close the loop with $u(\mathbf{x}(k))$, safety verification reduces to the well-known invariant set calculation using the *Pre* operator. For SMA thermal dynamics as given in Wertz et al. [9], we have verified computationally that $\mathcal{S}$ is invariant for any $\gamma \in (0, 1)$.

III. Results

An implementation of this feedback controller and a resulting hardware test is shown in Fig. 1). We have verified these behaviors using multiple different $v(\mathbf{x})$, with the reported tests using a sliding mode controller motivated by Elahinia and Ashrafiuon [3]. With the tuning parameter set at $\gamma = 0.3$, the SMA wire temperatures (as measured by an internal thermocouple per Sabelhaus et al. [7]) remained below a maximum despite forceful interaction with a human operator. Additional tests have demonstrated this same behavior when our soft robot limb contacts a wall, or is commanded to reach an infeasible pose.

IV. Conclusion

The supervisory control framework proposed here is able to maintain safe soft robot actuator states, in the form of the temperature of an SMA wire, without knowledge of the underlying pose controller or environmental contact conditions. We anticipate this controller opening new directions for soft robot motions without fear of robot failure or degradation. In particular, ongoing work seeks to incorporate this controller into state feedback for a soft walking robot.

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