MAE 249 Mini Project

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1 Introduction

This mini project strives to delve deeper into the application of safety algorithms on a soft robot to ensure safety is met. Soft robots are typically considered to be safer than rigid robots, primarily because of their materials or behaviours. However, soft robots can still behave in an unsafe manner such as flexing beyond a permissible limit or reaching an end-effector location that is unsafe, causing significant safety violations. Instead of looking at traditional soft robotic methods for safety, such as changing materials or physical design of the robot, this project strives to explore safety from a control theory approach. There are numerous safety algorithms that can be used to ensure safety: control barrier functions (CBF), Hamilton-Jacobi reachability (HJR), and reinforcement learning based control. This mini-project incorporates a CBF to explore whether it can guarantee safety of a soft robot by preventing it from exceeding a certain curvature limit. It is assumed that this soft robot has the ability to perform computations online (ie: there is a microcomputer within the robot that can handle calculations and measure internal states).

2 Derivation

Firstly, a set of dynamics is needed to model the behaviour of a soft robot. For this demonstration, a simple system modelling curvature and curvature rate was derived for a single segment soft robot

The state was chosen to be of the form

$$\dot{x} = f(x) + g(x)u \quad \text{where} \quad f(x) = \begin{pmatrix} \dot{\kappa} \\ 0 \end{pmatrix}, \quad g(x) = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

For designing the controller for the system, a nominal controller and a safety controller are needed. The nominal controller was chosen to be a proportional-derivative (PD) controller

$$u_{\text{nom}} = k_p(\kappa_{desired} - \kappa) - k_d\dot{\kappa}$$

with tuned parameters

$$k_d = 2 \quad \text{and} \quad k_p = 5$$

The safety controller, which is the CBF, was determined to be

$$h(x) = \kappa_{\max}^2 - \kappa^2 \quad \text{(safe when } h(x) \geq 0)$$

Lie derivatives were calculated that were used in the constraints for the optimisation problem

$$\begin{aligned} L_f h(x) &= -2\kappa\dot{\kappa} \\ L_f^2 h(x) &= -2\dot{\kappa}^2 \\ L_g L_f h(x) &= -2\kappa \end{aligned}$$

The high-order CBF condition is:

$$L_f^2 h(x) + L_g L_f h(x) u \geq -(\gamma_1 L_f h(x) + \gamma_2 h(x))$$

Recognising that $\dot{h} = L_f h(x)$, the constraint is:

$$L_g L_f h(x) u \geq -L_f^2 h(x) - (\gamma_1 \dot{h} + \gamma_2 h)$$

The safety-critical control input u^* is found by solving the following Quadratic Program:

$$\begin{aligned} \min_u \quad & \|u - u_{\text{nom}}\|_2^2 \\ \text{subject to} \quad & L_g L_f h(x) u \geq -L_f^2 h(x) - (\gamma_1 \dot{h} + \gamma_2 h) \end{aligned}$$

This ensures that the nominal controller will be in use at all times unless the robot is approaching an unsafe set, after which the CBF will activate. Using the convex optimisation library CVXPY, the trajectory and states were plotted with just a nominal controller and one that included the CBF to explore whether the CBF was able to keep the robot within a specific curvature limit.

3 Results

The results indicate that the nominal controller exceeded the limit at times in order to hit the desired curvature value, whereas the CBF was successful in maintaining a safe level of curvature without exceeding the limit (at the expense of not successfully reaching the desired value). Figure 1 shows the behaviour of the nominal controller, where it successfully reached the desired curvature value of 0.9 by violating the upper safety limit of 0.75. Figure 2 shows the behaviour of the CBF, where it successfully maintained the safety limit of 0.75 at the expense of not being able to reach the desired value of 0.9. Figures 3 and 4 show the nominal controller was activated the entire time since the robot was well within the safety limit at all times. Since maintaining safety takes precedence over reaching a desired goal, the CBF results show great promise in incorporating safety methods on soft robots.

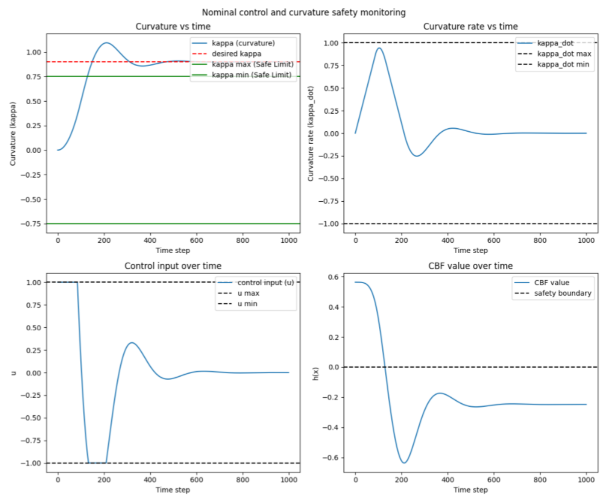

Figure 1: Results after enabling nominal controller with desired curvature outside safety limit.

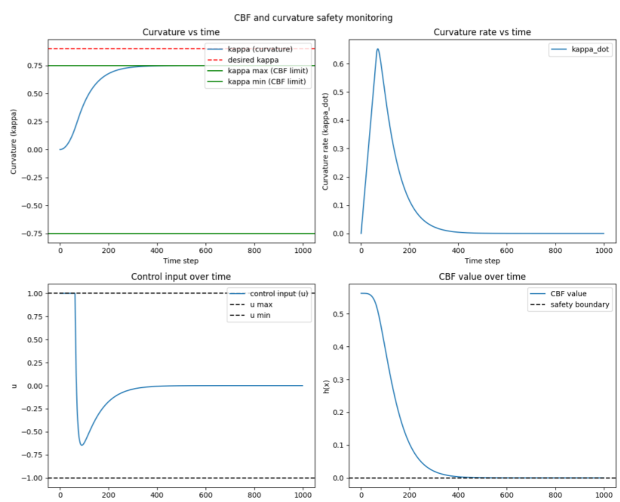

Figure 2: Results after enabling CBF with desired curvature outside safety limit

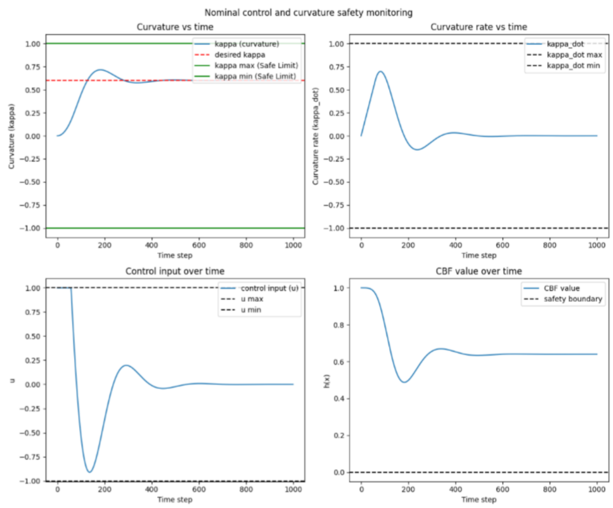

Figure 3: Results after enabling nominal controller with desired curvature inside safety limit

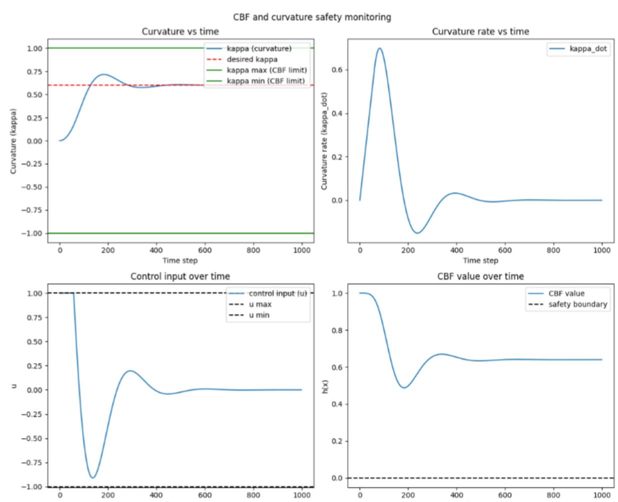

Figure 4: Results after enabling CBF with desired curvature inside safety limit

4 Future Works and Improvements

Future improvements would be adding complexities to the system model and dynamics so that it is more representative of the curvature of a soft robot. Since this project modelled curvature using simple dynamics, a more complex model could provide additional information on the efficacy of CBFs. Additionally, future work can include optimisation and analysis of the parameters in this CBF for improved performance.

5 Code

The code for this mini-project can be accessed here.