MAE 249 Final Proposal
Kaustubh Kanagalekar

Modern Safety-Based Control on Soft Robots

Soft robots are typically considered to be safer than rigid robots, primarily because of their material composition and geometry. However, they can behave in an unsafe manner where they can compromise the safety and efficacy of the robot and its surroundings. For example, the robot could flex beyond compliance and reach end effector positions that cause the robot to be unsafe. Traditional methods of safety considerations have involved changing material type or robot hardware design, however this can be expensive or challenging to implement in certain situations. Instead of exploring traditional safety methods, this research strives to study the application of safety control algorithms on soft robots to guarantee safety. There have been numerous advances in developing safety algorithms for safety critical applications such as developing control barrier functions (CBFs), Hamilton-Jacobi Reachability (HJR), and recently, reinforcement learning based control (RL), however they have been widely implemented in rigid robot applications.

For example, the authors in [3] show multiple applications of CBFs; the authors in [4] explore the HJR framework in depth; the authors in [5] explore RL methods for safety. There is a growing interest in utilising these methods in soft robots, as seen in the works of [1] and [2]. In the work of [1], the authors use an RL based approach called Q-learning and apply that towards a soft robotic limb. In the work of [2], the authors use a CBF to control the limit of the end effector position to prevent it from crossing a certain limit. These works greatly advance the application of modern safety on soft robots, however they are lacking in complexity or the proper direction in safety. [1] focuses on RL which cannot provide full safety guarantees. [2] focuses on end-effector positioning, which is a low dimensional constraint. [3] focuses on rigid robots such as drones; The methods in [4] are computationally expensive and are restricted to low dimensional systems; [5] lacks full guarantees in safety. Present research has been implementing safety on extremely simplified, low dimensional dynamical models that do not capture complexities such as non-linearities, higher dimensional spaces, and coupled dynamics.

This research proposal will strive to build upon present work of higher order CBFs to validate it on more complex, non-linear dynamical models (such as on multiple piecewise constant curvature and Discrete Cosserat Rod models) for the purposes of achieving safety in curvature (and if resources permit, self-collision avoidance). This approach is non-incremental because it requires the reformulation of multiple mathematical dynamics, resulting in a significant change from the simplified dynamics used in prior studies.

Implementation of Proposed Idea:

The main goal of this proposal is to successfully implement higher order CBFs to highly complex, non-linear soft robot models (such as piecewise constant curvature and Discrete Cosserat Rod models) for the purposes of achieving safety in distributed maximum curvature limit across all segments of the robot. This would be implemented in a python simulation environment. Once this is achieved, additional constraints can be incorporated such as self-collision avoidance limits, with the goal of deploying them to soft robots in real life scenarios.

The higher order CBF framework can be developed for a complex soft robot as stated above by properly modelling the complex dynamics of such a system, deriving the required Lie derivatives, and solving the resulting optimisation problem. By attempting all of these steps, safety guarantees can be obtained on the robot without much compromise on its regular operation.

Mathematical Derivation:

A two segment Discrete Cosserat Rod model will be derived and analysed. This model will accurately capture coupled bending, shear, and environmental effects such as gravity. States will be complex and will capture many variables such as position, time derivatives, and orientation.

There will be safety constraints for all the discrete segments of the Discrete Cosserat Rod model, however a global CBF will be applied to the most conservative constraint found. This ensures that safety guarantees for this minimum apply to the entire system. After this step, high dimensional Lie derivatives will be derived for the non-linear equations of motion. Since the derivatives will be complex, sophisticated software will be used such as the Sympy library from python.

Performance Validation:

Once the constraint has been identified, it will be integrated into a quadratic program optimisation, which will minimise the deviation from a nominal controller (which can be set to a simple proportional-integral-derivative or linear quadratic regulator controller). The nominal controller will purposely try to bring the robot to an unsafe state by violating the curvature limit in both segments of the Discrete Cosserat Rod model. A convex optimisation program like CVXPY will solve the quadratic program at every step. Safety will be guaranteed if the higher order CBF will prevent the robot from exceeding curvature limits in all of its segments during the python simulation. Another validation to check will be to determine if the nominal controller is the only controller that is acting on the robot if it is well within the safe regions.

Uncertainty and Robustness:

Once higher order CBF safety has been validated, uncertainty will be introduced to the Young's modulus, which is typically hard to model. The higher order CBF will be run for 100 trials with this uncertainty incorporated to check if the CBF successfully keeps the soft robot safe. After all of this has been successfully concluded, hardware testing will occur to verify if simulation results can be replicated in real life.

Findings Based on Preliminary Testing and Anticipated Results

For a preliminary demonstration, a simple system modelling curvature and curvature rate was derived for a single segment soft robot. These dynamics are linear, making it simple to test and trial. These serve as a precursor to the actual motivation behind the research project, which strives to incorporate non-linear and complex additions to the system for testing and analysis. The nominal controller was chosen to be a proportional-derivative (PD) controller. The safety controller, which is the higher order CBF, was determined to be the current curvature pose squared subtracted from the maximum curvature limit squared. Lie derivatives were calculated that were used in the constraints for the optimisation problem. Using the convex optimisation library CVXPY, the trajectory and states were plotted with just a nominal controller and one including the CBF to explore whether the CBF was able to keep the robot within a specific curvature limit.

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.

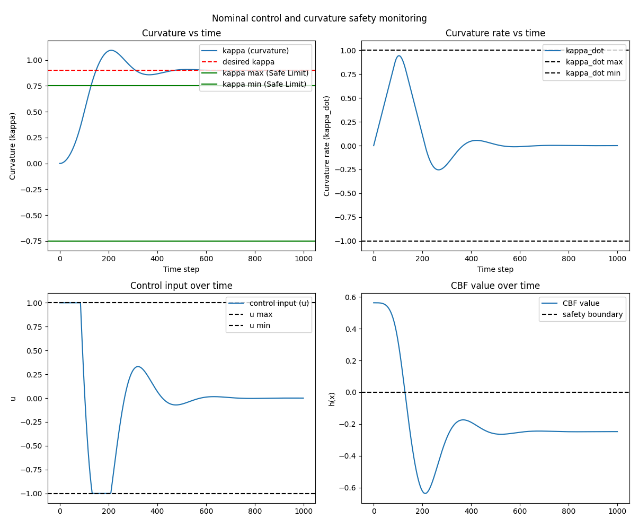


Figure 1

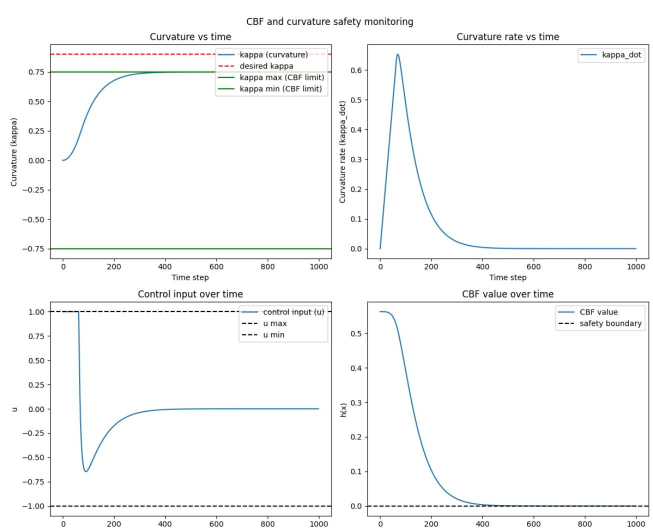
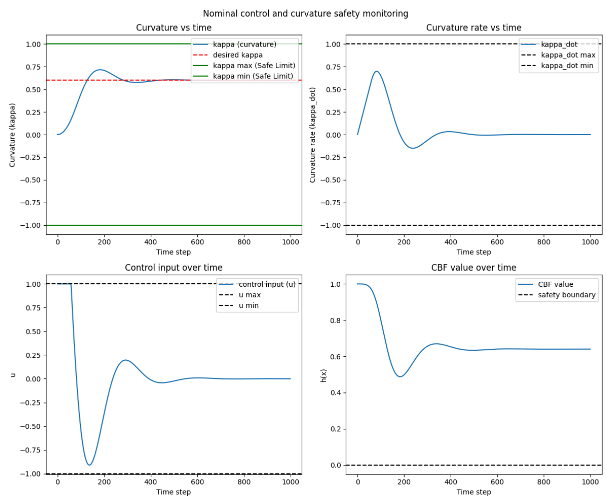


Figure 2

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



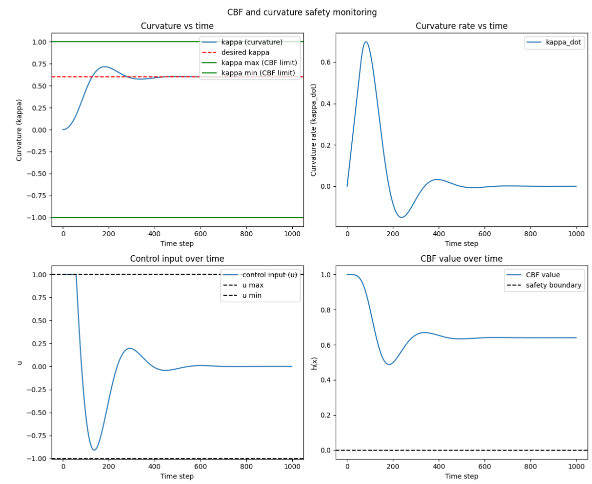


Figure 3 Figure 4

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

Anticipated Results:

Anticipated results that are expected include successful outcomes of the higher order CBF implementation on the highly complex and non-linear Discrete Cosserat Rod model. The safety constraint is never violated across any segment, regardless of the nominal controller's input. If this fails to occur, it could be because of infeasibility of the quadratic program near the safety boundary, which can occur in some cases. In this case, added robustness to the CBF model should be applied.

The CBF should also maintain safety guarantees with uncertainty added. If this fails, then a more complicated control barrier function will be needed to model and determine safety. The CBF should also allow the robot to be controllable using the nominal controller if the robot is well within the safe region if it is successful. More parameter tuning may be required if the CBF is highly conservative and or unstable even when safe.

Significance of this Undertaking

The successful completion of this project can have numerous positive impacts in daily applications. For example, current soft robots rely on passive safety. Having a framework where there is active safety would greatly improve operation speed and efficacy of the robot, which will improve productivity and deployment of the robot. This is extremely important in safety critical fields such as medical robotic surgery and medical device manufacturing where real lives are at stake. Active safety will also enable researchers to design more complex systems that will not have catastrophic failures or safety violations, thereby jeopardising the safety of everyone involved. The findings of this work can also be used in future research undertakings in creating robust control barrier functions to handle even more complex disturbances and dynamics in real life scenarios and to act as a benchmark for RL based methods.

Statement of AI Usage:

Generative AI was used in concept generation, brainstorming of a relevant research problem statement, and approaches needed to make the research successful. In addition, generative AI was partly used for editing and refining some of the text found in this proposal.

References:

[1] G. N. Sue, Y. Choudhary, R. Desatnik, C. Majidi, J. Dolan and G. Shi, "Model-Free Safety Filter for Soft Robots: A Q-Learning Approach," 2025 IEEE International Conference on Robotics and Automation (ICRA), Atlanta, GA, USA, 2025, pp. 3545-3551, doi: 10.1109/ICRA55743.2025.11128125. keywords: {Training;Limbs;Filters;Q-learning;System dynamics;Soft robotics;System recovery;Safety;Standards;Tuning},

[2] A. K. Dickson, J. C. P. Garcia, M. L. Anderson, R. Jing, S. Alizadeh-Shabdiz, A. X. Wang, … and A. P. Sabelhaus, "Safe Autonomous Environmental Contact for Soft Robots using Control Barrier Functions," arXiv preprint arXiv:2504.14755, 2025

[3] A. D. Ames, S. Coogan, M. Egerstedt, G. Notomista, K. Sreenath and P. Tabuada, "Control Barrier Functions: Theory and Applications," 2019 18th European Control Conference (ECC), Naples, Italy, 2019, pp. 3420-3431, doi: 10.23919/ECC.2019.8796030. keywords: {Surveys;Autonomous systems;Europe;Pressing;Control systems;Safety;Robots;Optimization},

[4] S. Bansal, M. Chen, S. Herbert and C. J. Tomlin, "Hamilton-Jacobi reachability: A brief overview and recent advances," 2017 IEEE 56th Annual Conference on Decision and Control (CDC), Melbourne, VIC, Australia, 2017, pp. 2242-2253, doi: 10.1109/CDC.2017.8263977. keywords: {Games;Safety;Tools;Trajectory;Tutorials;Level set;Aircraft},

[5] K. Srinivasan, B. Eysenbach, S. Ha, J. Tan, and C. Finn, "Learning to be Safe: Deep RL with a Safety Critic," arXiv preprint arXiv:2010.14603, 2020.

Code base for preliminary result: here