Continuation-Based Design of Self-Contacting Soft Robotic Manipulators

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Abstract. We create a design tool that allows for modeling the behavior of soft robotic manipulators consisting of serially-concatenated, fiber-reinforced elastomeric enclosures (FREEs) as they are pressurized. This tool uses numerical continuation to solve the governing multi-segment boundary-value problem as the actuation pressure is varied, accounting for self-contacts via imposition of constraint normal forces. The methodology highlights limitations of existing design techniques for multisegment FREEs that only consider the configuration at the final pressure; achieving complicated tasks such as self-knotting requires considering self-contact in the design process. It is also shown that multiple equilibrium shapes of a multisegment FREE can co-exist across ranges of the actuation pressure. At the extremes of such ranges, we anticipate that small changes in the actuation pressure will result in large changes to the manipulator configuration.

Introduction

FREEs are rod-shaped, soft robots that are naturally straight but deform into helical shapes upon pressurization. Concatenating several FREEs into a multi-segment manipulator allows for more complex shapes to be created, while only requiring a single pressure valve for control. Design techniques can be used to find lengths and fiber angles for each segment that allow the overall manipulator to attain a desired spatial curve at the final actuation pressure [1]. Existing techniques for designing a FREE to match a desired 3D shape fail to account for self-contacts that may occur as the robot is pressurized, preventing it from reaching the desired final shape. This is of particular concern for creating shapes such as knots, for which intermediate configurations free of self-contact are difficult to realize [2], as illustrated in figure 1.

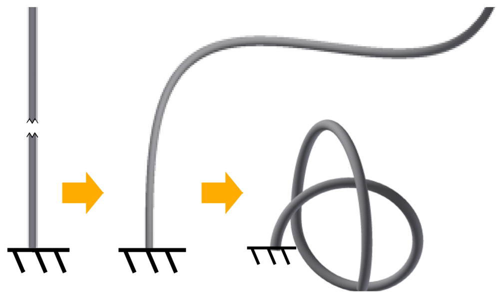

Figure 1: Schematic of an initially straight FREE which begins to bend and twist upon pressurization and eventually exhibits self-contacting behavior

In this work, we create a design tool using the technique of numerical continuation to track continuous families of shapes that a multi-segment FREE-based manipulator may attain under variations in the actuation pressure. Here, equilibrium configurations of the manipulator are modeled by an 18-dimensional, nonlinear, multi-point boundary-value problem, inspired by [2]. Given appropriate boundary conditions, as the pressure is increased, the intrinsic curvature and torsion of each segment change, causing the manipulator to deform. When self-contact must occur, contact forces are applied at the corresponding points. The value of the contact force necessary to maintain a non-penetration constraint is tracked as the pressure continues to vary. If this force decreases to zero, then contact is terminated and the force is removed.

Results and Discussion

The continuation-based design tool can be used to compute continuous families of shapes that a FREE-based multi-segment manipulator may attain as it is pressurized while also accounting for the effects of gravity, a variety of end-point conditions, and self-contact normal forces. As an example, using this tool, we verified that a manipulator designed to form a trefoil knot in its final configuration [1] experiences self-contact at an intermediate configuration which prevents it from completely knotting. Future work will leverage the continuation framework in the design process so that actuators can be designed to achieve automated self-knotting.

For certain actuator designs, the design tool predicts the co-existence of multiple non-self-contacting equilibrium configurations across ranges of the actuation pressure, distinguished, e.g., in terms of an overall rod twist. At the extremes of such ranges, we anticipate small changes in the actuation pressure resulting in large changes in the configuration of the manipulator. Designs that leverage such behavior could be utilized to make actuators that can rapidly deform when a critical pressure value is reached, similar to those actuators studied in [3]. Future work will investigate the associated rod dynamics and possible control system designs (e.g., inspired by the control-based continuation paradigm) to attain dynamically unstable shapes that could not be reached through the standard strategy of solely increasing the pressure.

References

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