

Modeling friction in cable-actuated soft robots using an ALE formulation and an augmented Lagrangian approach

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Abstract

In cable-driven mechanisms, cables typically slide through pulleys, sleeves, or cavities. These interactions result in small and precisely localized contact regions, while the rest of the cable remains contact-free. Modeling these contact zones with classical Lagrangian finite elements requires an excessively fine mesh, leading to computational inefficiencies. Consequently, an arbitrary Lagrangian-Eulerian (ALE) approach is often preferred. This method is well-suited for problems where the cable is sliding through passing points or on a pulley, for example, as it allows the cable nodes within the contact regions to be fixed relatively to the interacting structure while enabling material flow. Meanwhile, the nodes outside of the contact patch can be treated using a standard Lagrangian description of the motion. While previous studies have explored ALE-based formulations in frictionless conditions [1, 2] or with regularized friction laws [3, 4, 5], this work focuses on a nonsmooth description of friction to capture complex phenomena, such as stick-slip transitions or hysteresis, in a quasi-static setting.

Particularly, we aim to model the frictional contact between a cable and the cavities of a cable-driven soft robot, which deforms when the cable is pulled. As the main contact points are the entry and exit points of the cable, the positions of those points are spatially fixed with respect to the robot and known *a priori*, fitting well with an ALE formulation of the cable. The friction description derives from an augmented Lagrangian formulation, avoiding the need for a regularization of Coulomb’s law.

More specifically, the ALE cable model presented in [6] is extended to a geometrically exact beam formulated on the Lie group $SE(3)$, allowing for the accurate modeling of cables or belts with significant curvature. The spatial configuration of each node is described by a frame $\mathbf{H}(s)$, where the centerline coordinate s represents the material coordinate. In a quasi-static framework, the ALE equilibrium equations are derived from the virtual work principle:

$$\delta \mathcal{W} = \delta_{\mathbf{H}} \mathcal{W} + \delta_s \mathcal{W} = 0 \quad (1)$$

where $\mathcal{W}$ denotes the total potential energy, $\delta_{\mathbf{H}}(\bullet)$ represents the variation with respect to the spatial coordinates keeping the material coordinate fixed, and $\delta_s(\bullet)$ represents the variation with respect to the material coordinate keeping the spatial coordinates fixed.

We propose a general formulation able to model the frictional interactions between the cable and a pulley, a slider, or passing points, as it is the case for the soft robot. Friction is modeled using Coulomb’s law. As each contact remains closed, the frictional conditions are:

$$|v_T| \geq 0, \quad |\lambda_T| \leq \mu \lambda_N, \quad |v_T| (|\lambda_T| - \mu \lambda_N) = 0 \quad (2)$$

supplemented by the slip rule $|v_T| \lambda_T = -|\lambda_T| v_T$, where v_T is the relative tangential slip between the cable and the structure, λ_N and λ_T are the Lagrange multipliers associated with the normal and tangential contact forces, respectively, and μ is the friction coefficient. Frictional effects are only considered in the axial direction of the cable, so that v_T and λ_T are scalar quantities. A key feature of this ALE formulation is that, unlike conventional models, the friction force contributes to the material equilibrium due to the allowed material flow at the contact points. The resulting system is solved using an augmented Lagrangian approach combined with an implicit Newton scheme.

To demonstrate the capabilities of the formulation, an in-house multi-actuated soft robot prototype is modeled. The robot consists of two relatively rigid stages linked by a soft truss-like structure, as depicted in Fig. 1a. Cables run through this soft truss, resulting in significant friction at each passing point. A total of six cables are used to actuate the robot, three per stage. Each group of three cables is attached to

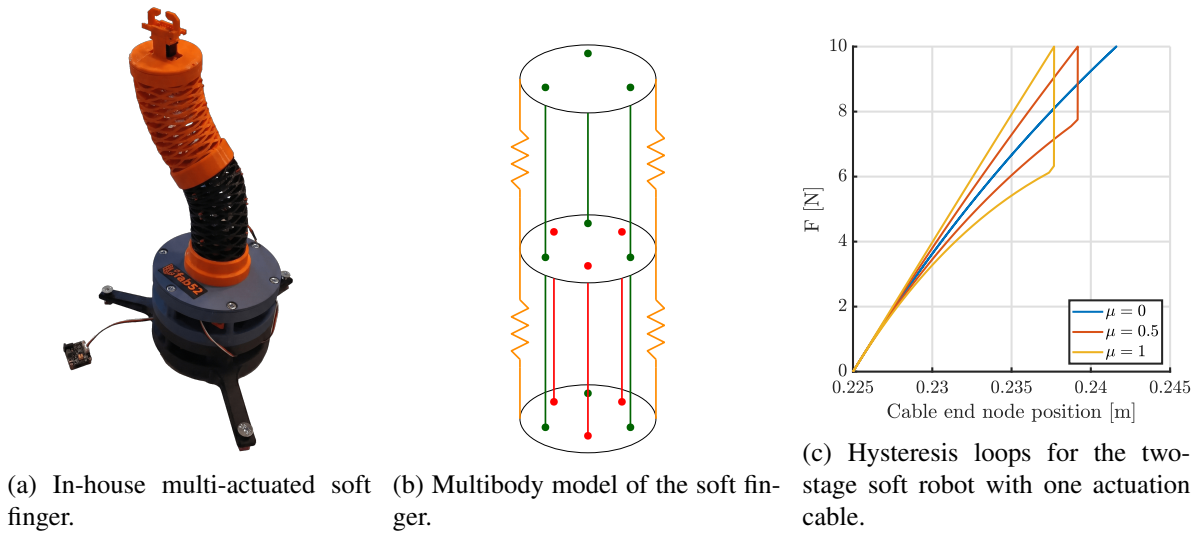


Figure 1: Soft robot, multibody model and preliminary results.

its corresponding stage while the other end of the cables is pulled by motors located at the fixed base to induce deformation and motion.

A multibody model of the soft robot is shown in Fig. 1b, where the soft trusses are modeled as deformable structural components and the stages are modeled as rigid bodies. Preliminary results are presented for this two-stage soft robot when only one cable is actuated with a traction force applied in several load steps and following a cyclic loading pattern. Figure 1c displays the displacement of the motorized end of the cable as a function of the traction force for various friction coefficients. The results highlight the ability of the model to accurately capture the macroscopic hysteresis loop arising directly from the local nonsmooth Coulomb friction at the passing points. Because of the cyclic loading, the stick-slip transitions generate this global dissipative hysteresis, an effect that intensifies with higher friction coefficients. The ultimate goal of this work is to represent the six actuation cables simultaneously.

References

- [1] Han, S., Bauchau, O. A. (2023). Configurational forces in variable-length beams for flexible multibody dynamics. *Multibody System Dynamics*, 58(3), 275-298.
- [2] Escalona, J. L., Mohammadi, N. (2022). Advances in the modeling and dynamic simulation of reeving systems using the arbitrary Lagrangian–Eulerian modal method. *Nonlinear Dynamics*, 108(4), 3985-4003.
- [3] You, P., Liu, Z., Ma, Z. (2023). Multibody dynamic modeling and analysis of cable-driven snake robot considering clearance and friction based on ALE method. *Mechanism and Machine Theory*, 184, 105313.
- [4] Oborin, E., Vetyukov, Y., Steinbrecher, I. (2018). Eulerian description of non-stationary motion of an idealized belt-pulley system with dry friction. *International Journal of Solids and Structures*, 147, 40-51.
- [5] Ntarladima, K., Pieber, M., Gerstmayr, J. (2023). A model for contact and friction between beams under large deformation and sheaves. *Nonlinear Dynamics*, 111(22), 20643-20660.
- [6] Devigne, O., Cosimo, A., Bröls, O. (2024). A quasistatic ALE cable formulation for multibody systems applications. *Multibody System Dynamics*, 1-29.