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FEM-based model for cable-actuated continuum robots

C. Cignolini, B. Rosa, and H. Courtecuisse

ICube, UMR 7357 CNRS-Université de Strasbourg, France

INTRODUCTION

Continuum robots have emerged as promising tools for minimally invasive surgery (MIS), offering flexible and curvilinear accessibility through small incisions or orifices. Achieving precise motion control of these robots is challenging due to their deformable nature and interactions with anatomical structures. Among the different designs, cable-driven continuum robots have gained significant popularity due to their high payload capacity, large range of curvature, and manipulation accuracy.

To accurately acquire the shape and motion of continuum robots, it is crucial to characterize not only the kinematic aspects like driving cable lengths but also external loading, actuating frictions, and contact forces within the mathematical model. Prior research has made notable efforts to improve the modeling accuracy of continuum robots in this regard. The prevailing model utilized in the field is the Cosserat model [1], which effectively represents the continuum mechanics of soft robots. However, its reliance on the assumption of negligible friction restricts its accuracy in scenarios where friction plays a significant role. A potential approach to enhance modelling accuracy, incorporating non-linear effects such as friction, is to employ Finite Element Methods (FEM) based models.

The Simulation Open Framework Architecture (SOFA) [2], is a real-time simulation framework based on FEM, offering a powerful tool for modeling cable-driven continuum robots. It enables accurate simulation of contact with the environment and the implementation of friction, allowing for more realistic representations of robot behavior.

In this paper two real time SOFA-based models for cable-actuated continuum robot have been explored. The main objective is to develop a model that attains a level of accuracy comparable to the well-established Cosserat model. Leveraging the capabilities of SOFA, the objective is to improve the model's fidelity, enabling more precise motion control and accurate representation of the robot's shape.

MATERIALS AND METHODS

The cable-driven continuum robot used in this study consists of equidistant spacer disks connected to a central backbone and four elastic tendons (see Figure 1). The tendons are equally spaced from each other and the backbone,

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attaching only to the end disk while sliding through holes in the base and spacer disks. By independently pulling the tendons, bending motions of the continuum robot can be achieved, enabling the desired actions.

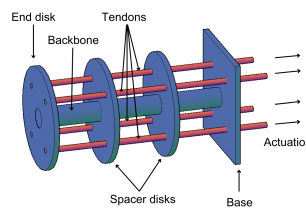


Fig. 1: Schematic structure of a cable-driven robot.

The cable-driven robot used in this study exhibits a notable difference in rigidity between the tangential and bending directions, with high tangential rigidity approaching inextensibility and low bending rigidity approaching perfect flexibility. To address this anisotropy, the two proposed models incorporate the Articulated Mapping plugin from SOFA to model the tendons. In both models the tendons are discretized into a finite set of points, with the initial point of the tendon defined with six degrees of freedom (three translations and three rotations). Subsequent points along the tendon have two angular degrees of freedom, representing bending motion in the 2-direction. The angular displacement of each tendon point is calculated as an angular force between the first point of the cable and the corresponding subsequent point. The tendons are characterized by reduced angular stiffness and negligible mass, allowing for the transmission of force to the backbone without significantly affecting deformation while maintaining the overall length of the robot.

In the first model, the backbone is designed as a series of consecutive Timoshenko beam segments [3]. Each segment is characterized by specific parameters, including mass, radius, Young's modulus, and Poisson's ratio, which accurately represent the mechanical properties of the backbone (Figure 2). In the second model, the robot's shape is meshed using linear tetrahedral elements with specific Young's modulus and Poisson ratio values, offering a more realistic representation as shown in Figure 3. The different models are coupled together using Lagrangian Constraints to ensure their cohesive behavior (see Figure 4).

It is important to note that the SOFA models do not explicitly incorporate the physical modeling of disks, and the tendons lack a direct physical model. Therefore, the mechanical parameters do not have a one-to-one correspondence be-

tween the Cosserat model and the proposed model. To bridge this gap, a Bayesian optimization algorithm has been implemented. This algorithm focuses on optimizing the backbone parameters by considering a range of tensions applied to the tendons. The objective is to minimize the tip error between the proposed model and the previously implemented and validated continuum Cosserat model by Rucker et al. [1], considering a range of tendon tensions.

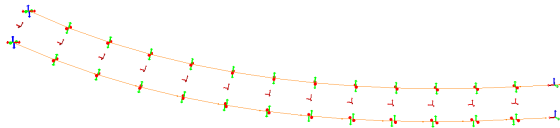


Fig. 2: Model based on Timoshenko Beam Theory

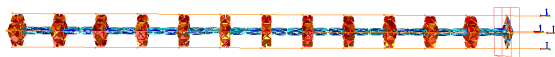


Fig. 3: Tetrahedral model. The backbone is represented with a lower Young’s modulus compared to the end disks, which are designed to be more rigid.

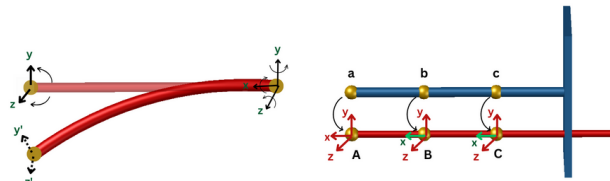


Fig. 4: Implementation of the *Articulated Mapping plugin* on the left and Lagrangian Constraints for the Cable-Driven Continuum Robot Model on the right. A bilateral constraint is established between the last points of the backbone and tendons, while sliding constraints are implemented between the remaining points. These sliding constraints enable movement along the x direction when the system is actuated.

CONCLUSIONS AND DISCUSSION

The model based on beam elements demonstrated real-time actuation within the stability range of 0 to 1 N, causing a 57 mm deflection at the robot’s tip. However, outside of this range, the SOFA model exhibited instability. Within the stability range, the average tip error between the proposed model and the Cosserat model was 0.58 mm, representing approximately 0.24% of the total robot length, indicating the accuracy within the specified range. To address any instabilities observed during large deformations, it is necessary to investigate the underlying causes and consider applying regularization techniques if the instability arises from an ill-conditioned problem.

The tetrahedral model exhibited stability during large deformations (Figure 5b) but introduced increased complexity and computational time of around 200 ms. The average tip

error between the proposed model and the Cosserat model was 3.2 mm, and an average out-of-plane bending of -1.9 mm was observed when actuated. The GPU computation and an algorithm for volume discretization are possible solutions that can be implemented to enhance the results. These improvements could lead to more accurate and efficient simulations of the tetrahedral model.

Once the model demonstrates precision and accuracy in direct comparison with the Cosserat model, subsequent steps such as incorporating friction [4], non-linear material behavior (e.g., superelastic Nitinol behavior), and inverse kinematics [5] can be easily implemented within the SOFA framework. The successful implementation of friction on the tetrahedral model (Figure 6) underscores the model’s potential for further complexity, opening doors for advancements in continuum robots and their applications.

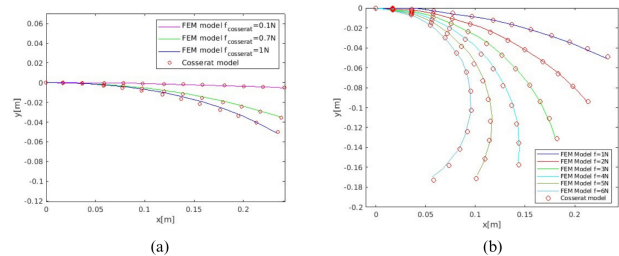


Fig. 5: Single tendon actuated without external load. (a) Model based on beam elements. (b) Tetrahedral model.

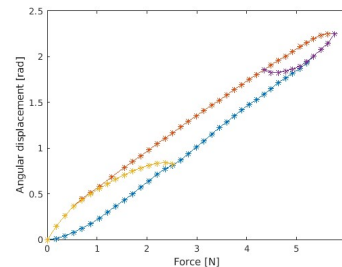


Fig. 6: Hysteresis curve of the tetrahedral model, depicting the relationship between input force and angular displacement of the robot tip.

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