Cable-Actuated Soft Finger Modeling Using an ALE Approach

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EXTENDED ABSTRACT

1 Motivation

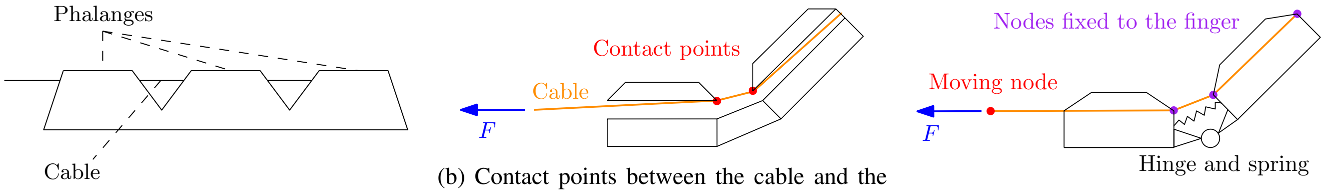
Soft robots, such as soft grippers, are a relatively new class of robots made of soft materials, namely silicon or plastic. They exhibit various advantages. Indeed, their manufacturing processes, often relying on 3D printing, are inexpensive. Soft grippers, which enter in the scope of the industry 4.0 development, grant flexibility to the tasks to be accomplished. For instance, the same programming sequence making use of adequate force and torque sensors can be used for the grasping of objects of different sizes and consistencies, as it can be the case in the food industry [1, 2]. The consequence is that almost no damage is done to the manipulated parts. Moreover, in the context of human-robot collaboration, soft robots are safer to the user because of their deformable nature and their lighter design.

The actuation of soft robots may rely on 3 different techniques. The first and most natural one is to make use of a linear actuator on one or several points of the deformable structure to induce a motion. The second one relies on pressure and vacuum by inflating or deflating deformable chambers inside the robot, enabling bending, for example. The third technique is to use a cable going through the structure and attached to one or several key points, pulling the deformable robot in the desired direction. Considering more specifically the case of a soft finger composed of phalanges, attaching a cable to the upper phalange and pulling it produces the bending of the finger. The objective of this work is to develop numerical methods for the simulation of such cable-actuated robots, as illustrated in Figure 1a. It implies several numerical challenges. For instance, an accurate cable model, accounting for its extension and capturing the contact and friction phenomena inside the finger, must be developed. In order to numerically approach the simulation of such flexible systems, a nonlinear finite element method (FEM) is often followed thanks to its versatility. In this context, the cable is discretized into several elements, enabling the precise description of these contact phenomena.

Nevertheless, it should be noted that, often, the need to discretize the cable into small elements is only needed in some key regions which interact with the structure. This situation is comparable to the case of reeving systems, where small elements are needed around the pulley, but larger elements could be used anywhere else. However, because the cable is moving around the pulley with time, one is thus often constrained to work with smaller elements than needed along the whole cable in order to accurately represent contact and friction happening between the pulley and the cable. In order to circumvent this difficulty, a popular option is to work with an arbitrary Lagrangian-Eulerian (ALE) formulation [3, 4, 5].

2 Method

In an ALE formulation, the positions of some nodes of the finite element discretization remain fixed during the simulation, while the cable is flowing through these nodes, inducing a mass flow, as it would be the case in an Eulerian formulation. However, it also enables mesh motion, which is an advantage in the modeling of a cable-actuated finger. Indeed, the contact and friction locations occurring due to the change of direction of the phalanges under the cable action are known *a priori*, as shown in Figure 1b, while the rest of the cable is contact-free. From a mesh point of view, these points are modeled using nodes of the cable which are constrained to the finger where a flow of material occurs. The other nodes of the cable can follow the material particles, as shown in Figure 1c.



(a) Soft cable-actuated finger. (b) Contact points between the cable and the inside of the finger. (c) Numerical model of the finger.

Figure 1: Soft finger, occurrence of contact due to the cable actuation and associated numerical model.

In this work, an ALE formulation for a simple cable element is presented. Based on [6], it gives a continuous formulation embedded in a consistent variational framework starting from the Dirichlet principle, which can be later discretized. The novelty consists in the addition of constraints to recover the equations of motion in a multibody set-up expressed in a Lie group formalism [7, 8]. The global idea is to write the equations of motion in terms of a reference configuration that does not necessarily match neither with the material nor the spatial configurations. In the resulting equations of motion two sets can be identified. The first one represents the spatial motion problem, where the spatial location of material particles is tracked, whereas the second set represents the material motion problem, where this time the material particle corresponding to a specific spatial location is tracked. These two sets of equations give interesting features in a discretized context. For the spatial motion problem, a residual force is nothing else than a classical body force commonly met in Lagrangian FEM. However, a residual material force, emanating from the other set, can be understood as a force arising, noticeably, from a non-optimal mesh placement, meaning that a vanishing material force represents an optimal material placement of the node. In other words, in this formulation, nodes which are not materially nor spatially constrained will move to reach a global minimum of the potential energy.

3 Results

This ALE cable formulation is applied to a soft finger model. The problem consists in a finger where phalanges are assimilated to rigid bodies linked by joints and torsion springs. The cable is attached to the last phalange and pulled from the other end, in a similar fashion as in Figure 1c. In addition, the contact between the phalanges is modeled. This leads to obtain nonsmooth equations of motion which are integrated using the nonsmooth generalized-α method [9, 10]. It must be emphasized that, in this case, the cable is considered massless and that no friction develops between the cable and the phalanges. The modeling of these effects will be subject of a future work.

It is shown that contact between the cable and the finger is captured by the introduction of a bilateral constraint and the points at which contact occurs see a flow of mass of the cable, as expected. Moreover, contact between the phalanges is precisely accounted for. This model is a promising first step towards a multibody representation of a soft finger.

4 Conclusion

As a conclusion, the ALE formulation proposed in this work can be successfully applied to cable modeling, noticeably in a soft robot actuation context. Compared to [3, 4, 5], the procedure starts directly from the variational principle and leads to the equations of motion in a systematic manner. The method also builds on the work from [6] by the addition of constraints and the inclusion of this formulation within a multibody framework in a Lie group formalism.

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