Planar steady-state physical model for a soft cable-driven octopus-like arm manipulator

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Introduction

The effort to enhance the performance of robot manipulators has resulted in an increased attention towards continuous soft robots and in particular towards "biologically inspired" soft robots [1,2]. A continuous soft robot (CSRobot) can be thought of as a continuous bending robot composed by several elastic elements with ideally infinite degrees of freedom. They pertain to the class of hyper-redundant robots which consist of a high number of short rigid links [3]. This structural paradigm is easily found in Nature, for examples in elephant trunks, cephalopod tentacles and mammalian tongues, which are commonly known as muscular hydrostats.

Problem Statement

The control and modelling of soft manipulators is not a trivial task because it requires a continuum approach and presents several degrees of non-linearity. Nowadays many researchers are involved in this stimulating challenge, but the problem is yet far from being solved. Most of the approaches currently in use are limited to piecewise-constant-curvature approximation [4] or are restricted to the kinematic analysis [5], but also exact solutions do exist [6]. The bottle neck of the problem, in any case, is the real time implementation of the model due to the computational effort required [3]. This suggests the necessity of a smart simplification. In this work we present a first result in the development of a continuum model of a cable-driven CSRobot.
The approach undertaken in this work is based on two hypothesis:
- force control rather than position control is more suitable for accounting for the external body forces and use them as "indirect actuator";
- the curvature of the whole arm is the parameter that governs the manipulation skill of the CSRobot. A decoupling between reaching the object and manipulating is postulated.

Technical Approach

The basic idea is to determine the relation between actuator force and the curvature of the manipulator. The manipulator is a conical silicone structure with one cable immersed inside the body and anchored at a distance **L** from the base. The cable lays within the silicone beam according to specific trajectories, as briefly explained later (for a detailed description see [7]). The arm is assumed to move in a planar space neglecting the effect of gravity. For the experimental tests this condition has been reproduced using several floats on the arm to avoid any kind of friction.
Our model is developed exploiting a Cosserat approach [8], namely considering the arm like a mono-dimensional backbone parameterized by the curvilinear variable **s**. The configuration of the curve on the plane is determined in a Frenet-Serrat framework where **<u>u</u>(s)** is the position vector, **<u>t</u>(s)** is the unit vector tangent of the curve, **<u>n</u>(s)** is the unit vector normal to **<u>t</u>(s)**. **k(s)** and **q(s)** are respectively the dual of the momentum and the strain of the arm at the section **s**. The radius of the section is **R(s)** that decreases linearly with **s**.

The momentum and the stress force acting on the beam owing to the tension of the cable are the only ones linked to a strain energy, employing the Euler-Bernulli hypothesis [8]. The most important approximation is the linearity of the constitutive equation that guarantees a significant simplification. The applied strength is determined by a concentrated force at the spot where the cable is fastened and a distributed force along the cable trajectory which is proportional to the curvature of the cables [9].
The position of the cable with respect to the backbone of the arm is proportional of a factor **a** to the radius of the section, this ratio remains constant along the arm.

Results

Below the two equations for strain and for the momentum's dual are presented, the second one is a non-homogeneous final-value first order differential equation with final value **K(L)**:

- $q(s) = \frac{T(aR(s)K(s)-1)}{E\pi R(s)^2}$
- $$\begin{cases} \grave{K} = k\left\{\frac{\grave{R}R(s)\left[-E\pi R(s)^2 - T2a^2\right]}{R(s)^2\left[E(\pi/4)R(s)^2+Ta^2\right]}\right\} + \left\{\frac{Ta\grave{R}}{R(s)^2\left[E(\pi/4)R(s)^2+Ta^2\right]}\right\} \\ k(L) = \frac{TaR(l)}{Ta^2R(l)^2 + E(\pi/4)R(l)^2} \end{cases}$$

where **E** is the Young modulus and **T** is the applied force.
From the three Frenet-Serrat equations the curvature of the arm is **(1+q(s))k(s)** because **s** is referred to the un-deformed backbone. The equations were solved in Matlab® (MatLab R2009a, The Mathworks Inc., Natick, MA) using ode23 function.

Experiments

To corroborate the above model a procedure divided into two steps has been followed.
1. A FEM model (on MARC®/Mentat® 2010, MSC Sofware) with the same parameters of the analytical model has been used to validate the algebraic correctness of the equations.
2. A silicone arm has been built and a Plexiglas tank has been set up to measure the curvature of the real arm and compare it with the analytical model.
On one side of the tank we fixed a silicone arm with the following characteristics: **L**=270 mm, the basis radius **R(0)**=15 mm, the tip radius **R(L)**=7.4 mm, **a**≈1/3 and **E**=110 Kpa (stress-strain linear approximation for compression). Finally we exerted various tensions to the cable and we took pictures of the arm by means of a camera fixed upside the plane of motion. The backbone was manually extrapolated and processed in Matlab® for the comparison with the respective backbones obtained with the model. The distance between the curves is calculated for each point at the same arm index (percentage of arm length).

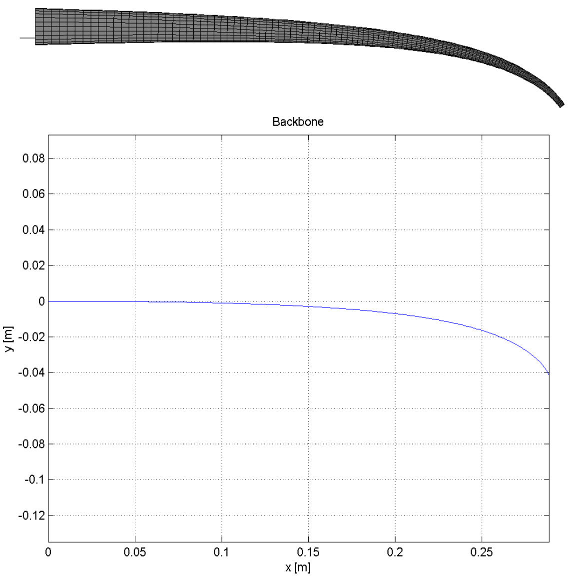

Figure 1: FEM model (top) and analytical model: (bottom) with the same parameters the two models have a very similar result.

Main Experimental Insights

In the first comparison an almost perfect correlation has been obtained and it can be seen in the figure 1. For these tests an arm with length **L** equal to 300 mm has been used and the maximum error detected on the

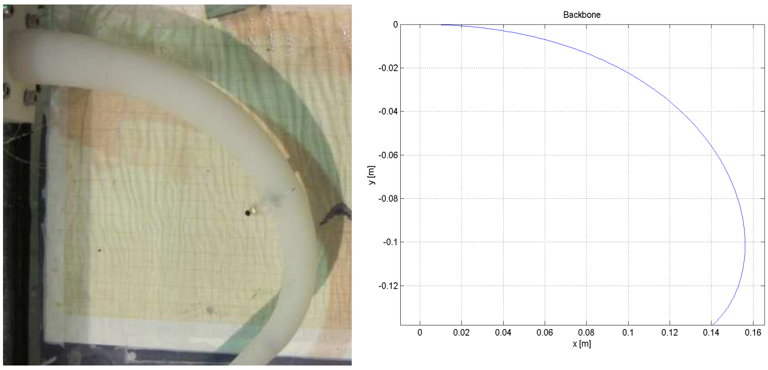

Figure 2: Comparison between the real silicone arm (left) and the model (centre) highlights a very little difference on the backbone configuration.

tip of the arm model is 1 mm.

In figure 2 the real arm and the model configurations have been shown. Numerical comparison on their backbones highlights a very little discrepancy (19 mm maximum). The error generally is higher on the distal part of the manipulator and varies with respect to the tension of the cable decreasing whit it, but always ranging between 19 and 9 mm. The highest errors are probably due to the non-linearity of the material, the friction of the cable and the human error in the extrapolation of the backbone from the pictures.

This work is part of a more complex study aimed at obtaining a model suitable for the real time control of a completely soft manipulator driven by cables. The results obtained by now demonstrate the possibility to use such a model to envisage its steady-state planar behaviour and it can be used as the base for a more complete model that takes into consideration the 3D dynamics of the structure too.

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