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Flexing into motion: A locomotion mechanism for soft robots

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ABSTRACT

Several recent designs of soft robots feature locomotion mechanisms that entail orchestrating changes to intrinsic curvature to enable the robot's limbs to either stick, adhere, or slip on the robot's workspace. The resulting locomotion mechanism has several features in common with peristaltic locomotion that can be found in the animal world. The purpose of the present paper is to examine the feasibility of, and design guidelines for, a locomotion mechanism that exploits the control of intrinsic curvature on a rough surface. With the help of a quasi-static analysis of a continuous model of a soft robot's limb, we show precisely how locomotion is induced and how the performance can be enhanced by controlling the curvature profile. Our work provides a framework for the theoretical analysis of the locomotion of the soft robot and the resulting analysis is also used to develop some design guidelines.

1. Introduction

The soft robot's unique promise for enabling inherently safe and adaptive features has made it one of the most appealing emerging fields in robotics. Recent advancements in the field of soft robots includes the development of bodyware control and engineered adhesive materials (see, e.g., [2,4,5] and the three examples shown in Fig. 1). For some soft robot designs, such as the quadruped shown in Fig. 1(a) from [1], locomotion is achieved by using the coordinated interaction of four soft limbs with the external surface. Each of the limbs in this design contain a set of pneumatic actuators which change the intrinsic curvature and flexural rigidity of the limb [6].

Other notable examples of locomoting soft robots include worm- or snake-like designs where serpentine locomotion is enabled by using either a traveling wave generated by a fluidic elastomer actuator [3], or hydraulic pressure [7] or shape memory alloys [8]. These designs are similar to those featuring in the so-called continuum or serpentine robots which feature in surgical and industrial applications [9]. As discussed in [10], similar locomotion mechanisms can be found in certain other robots such as the ETH-Zürich MagMite [11,12], the University of Texas at Arlington ARRIpede robot [13,14], a design from the University of Trento [15,16] and a design from Carnegie-Mellon University [17] that features an electromagnetic drive. The designs listed above that feature varying curvature and adhesion of limbs also have their natural counterparts in a wide variety of creatures who move using limbless crawling (peristaltic locomotion [18–20]). In these animals, varying curvature is realized by muscles and adhesion is achieved either by the use of bristles or mucus [21].

The wealth of designs and implementations in the aforementioned works make it difficult to gain a perspective on how locomotion can be induced by properly coordinating the interaction of the limbs with the ground plane on which the robot moves. In order to examine this issue, a rod-based, flexible model for a limb which is attached to a mass m is developed and examined. Referring to Fig. 2, we consider a block of mass m that is free to move on a rough horizontal surface. The block is attached to a flexible rod whose intrinsic curvature κ_0 is assumed to be controllable. By varying the profile $\kappa_0(s)$ of the intrinsic curvature, the contact between the rod and the ground can be changed. In particular, we seek to examine the best profiles $\kappa_0(s)$ which enable a locomotion of the block such as that shown in Fig. 3.

While the majority of works in the application area of interest have addressed hardware design and fabrication, less attention has been devoted to a numerical analysis of relevant theoretical models. Such analyses are challenging because the behavior is often governed by non-linear PDEs and recourse to numerical methods is typical. The present paper provides a systematic analysis of the feasibility of a locomotion scheme using a quasi-static analysis. While we do not specify on the precise mechanism by which the intrinsic curvature is changed, there has been an increased interest in the development of mechanisms for changing κ_0 in components of soft robots. The interested reader is referred to [22–26] for examples of these mechanisms.

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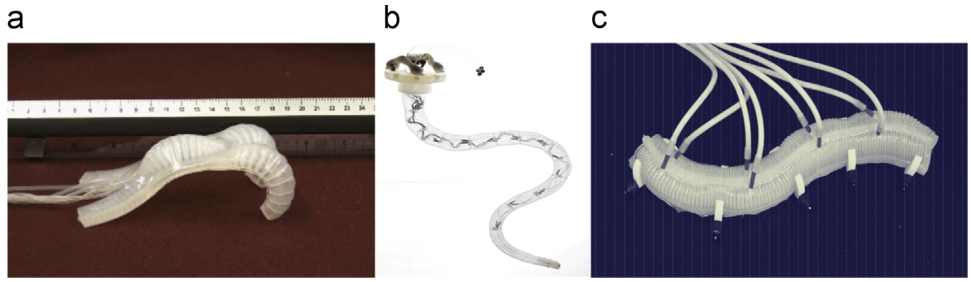

Fig. 1. Examples of soft robots. (a) Quadruped with inflatable bending actuators from [1]. (b) Octopus-like soft robot from [2], and (c) soft robot with fluidic elastomer actuator from [3].

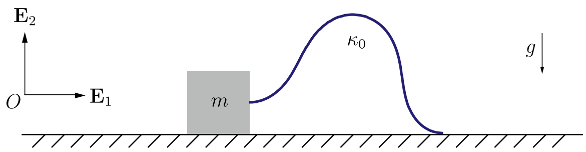

Fig. 2. Schematic of a rod-based model for the soft robot. One end of the rod is attached to a mass *m*.

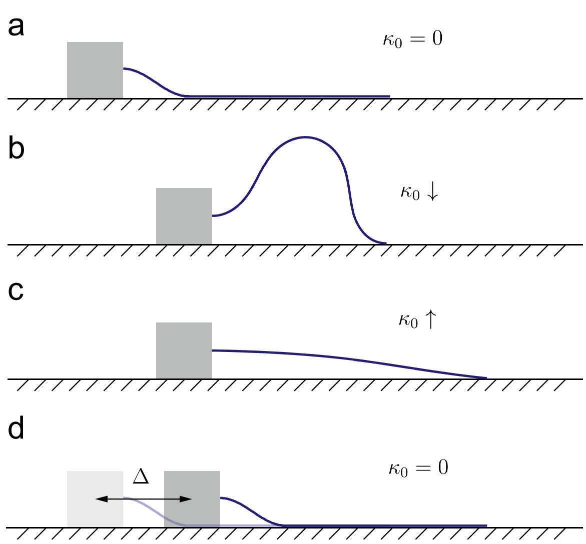

Fig. 3. Illustration of the locomotion for the model system shown in Fig. 2. In (a) the system is at rest and the soft limb is attached to the ground, then in (b) the profile $\kappa_0(s)$ of the intrinsic curvature changes and the block attached to the soft limb moves forward. In (c), the intrinsic curvature is relaxed, the block sticks to the ground, and the tip of the soft limb slips forward. In (d), the soft limb in contact with the ground plane forms a dry-adhesive bond with the plane and a single cycle of the locomotion mechanism is complete. The net displacement Δ for a single cycle is also shown.

The paper is organized as follows: in the next section, Section 2, a model for the system shown in Figs. 2 and 3 is established using rod theory and the governing equations for the two configurations shown in Fig. 3 are derived using variational principles. We follow [27,28] in the treatment of stability criteria for the dry adhesion of rods. In Section 3, numerical integrations of the governing equations are analyzed. Furthermore, the stability of these solutions is discussed in Section 4. Our analyses demonstrate how controlling the intrinsic curvature can coordinate the interaction between the soft robot and ground plane in a manner that leads to effective locomotion of the system. We conclude the paper with a discussion on different curvature profiles in Section 5 and a set of design recommendations for optimal performance of soft robot featuring varying curvature and adhesion.

2. A simple model for a soft-limbed robot

We are interested in developing a simple model to analyze the salient features for the locomotion of a soft robot. Referring to

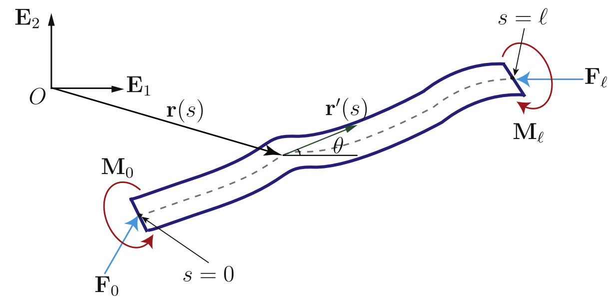

Fig. 4. Schematic of a flexible elastic rod which is subject to a terminal force $\mathbf{F}_0$ and terminal moment $\mathbf{M}_0$ at $s=0$ and a terminal force $\mathbf{F}_0$ and terminal moment $\mathbf{M}_\ell$ at the end $s=\ell$. The coordinate s parameterizes the centerline of the rod.

Fig. 2, the model has two components: a rigid mass and a heavy flexible elastic component. Thus one approach to modeling the robot is to use Euler's theory of an elastic rod which is known as an elastica. Euler's theory can be readily modified to include varying intrinsic curvature and terminal loads due to added mass or friction forces. Our developments and notation closely follow our earlier works [27,28] on adhered intrinsically curved rods.

2.1. Background

The rod is modeled using Euler's theory of an elastica as a uniform rod of length ℓ which has a flexural rigidity EI, mass per unit length ρ and an externally controlled intrinsic curvature κ_0. As discussed in [6], the pneumatic actuation system in some soft robots induces changes to EI and ρ but we do not consider these effects here. Incorporating them into the model would follow the lines of similar developments in models for growing plant stems that are discussed in [29,30]. We also note that the rod is assumed to be inextensible and unshearable. Adding these two kinematic features would entail using a more elaborate rod theory.

Referring to Fig. 4, the arc length of the centerline of the rod is parameterized using a coordinate $s \in [0, \ell]$. The position vector of a material point at $s = s_1$ on the centerline of the rod has the representation

$$\mathbf{r}(s=s_1) = X(s=s_1)\mathbf{E}_1 + Y(s=s_1)\mathbf{E}_2, \tag{1}$$

where the Cartesian coordinates X and Y are defined by

$$X(s=s_1) = X(s=0) + \int_0^{s_1} \cos(\theta(\xi))\,\mathrm{d}\xi,$$
$$Y(s=s_1) = Y(s=0) + \int_0^{s_1} \sin(\theta(\xi))\,\mathrm{d}\xi. \tag{2}$$

In (2), the angle θ is defined as the angle that the unit tangent vector $\mathbf{r}'$ makes with the horizontal $\mathbf{E}_1$ direction

$$\mathbf{r}' = \cos(\theta(s))\mathbf{E}_1 + \sin(\theta(s))\mathbf{E}_2 \tag{3}$$

where the prime denotes the partial derivative with respect to s.

In addition to a gravitational force per unit mass $-\rho g\mathbf{E}_2$ and an adhesive potential energy Ω on certain segments of the rod's