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On the motion of a snake-like soft robot

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In this work, we investigate the locomotion of a snake-like soft robot in terms of its design. Therefore the backbone of the robot is represented by a curve in plane which is actuated by a given curvature. By adding anisotropic friction between robot and surface the robot “moves” on the surface.

With this simple model we are able to predict the locomotion of the robot for certain sets of parameters. This allows to evaluate the influence of design changes and hence to facilitate the design process. As an example, we discuss results concerning the precision of actuation, the bending radius of the robot and the influence of friction between robot and surface.

1 Introduction

The development of soft robotics is especially lacking in the possibility of simulating new design approaches. This gap is gradually being filled by scientists. In our case, we are developing a snake-like soft robot in order to validate the simulation of soft robots. Snake-like robots are not common in all-day use, nevertheless researchers are striving to improve existing designs and develop new ones based on investigations on limbless motion (e.g. [1]). In contrast to other researchers who investigated snake-like soft robots (e.g. [2]), our work is focussed on improving the robots design.

In this paper, we present a simple model which helps to assess the locomotion of our robot due to anisotropic friction. The model assumes the robot as a winding curve in plane with anisotropic friction coefficients depending on the direction of sliding. By help of the model we are able to determine the influence of changes in the design on its locomotion.

2 Methods

The robot under consideration consists of a selectable number of sections in series, each able to elongate and bend with constant curvature separately. To make the robot move we are developing certain types of “skins” with anisotropic friction, which can be mounted on the robot.

The model to describe the robot's motion is based on the work of [3] and assumes the robot as a curve in plane $\mathbf{r}(s,t) = (x(s,t), y(s,t))$, where $s \in [0, L]$ is the arc-length parameter, L is the length of the robot and t is the time. The velocity and acceleration of the curve are denoted as $\dot{\mathbf{r}}$ and $\ddot{\mathbf{r}}$, respectively.

The curvature is given with $\kappa(s,t) = A\cos\left(2\pi\left(\frac{s}{L} + \frac{t}{T}\right)\right)$, where A is the maximum curvature and T the periodic time of undulation. As only the curvature is given, the absolute position is not known and needs to be determined.

For each point of the curve, the balance law

$$\rho\ddot{\mathbf{r}} = \mathbf{f}_{fric} + \mathbf{f}_{int} \tag{1}$$

needs to be fulfilled. In here, $\mathbf{f}_{int}$ is the internal force of the snake, which needs to overcome friction while following the given curvature, and $\mathbf{f}_{fric}$ is the coulomb friction force during sliding, defined as

$$\mathbf{f}_{fric} = -\rho g\left[\mu_t(\mathbf{r}_n^\perp \cdot \dot{\mathbf{r}}_n)\mathbf{r}_n^\perp + \left(\mu_f H(\mathbf{r}_n \cdot \dot{\mathbf{r}}_n) + \mu_b(1 - H(\mathbf{r}_n \cdot \dot{\mathbf{r}}_n))\right)(\mathbf{r}_n \cdot \dot{\mathbf{r}}_n)\mathbf{r}_n\right]. \tag{2}$$

ρ is the (constant) mass density per length, g is the gravitational constant, H is the Heaviside step function and μ_t, μ_f, μ_b are the coefficients of friction in transverse, forward and backward direction, respectively. Note that the subscript $(.)_n$ denotes the normalized length of a vector and $(.)^\perp$ the orthogonal of a vector.

By adding constraints for the internal force, the locomotion of the snake's center of mass $\bar{\mathbf{r}}$ and its orientation can be determined such that the differential Equation (1) is fulfilled (Figure 1 a). These constraints are $\int_0^L \mathbf{f}_{int}(s)\mathrm{d}s = \mathbf{0}$ and $\int_0^L \mathbf{f}_{int}(s) \times (\mathbf{r}(s) - \bar{\mathbf{r}})\mathrm{d}s = \mathbf{0}$ and are independent of time.

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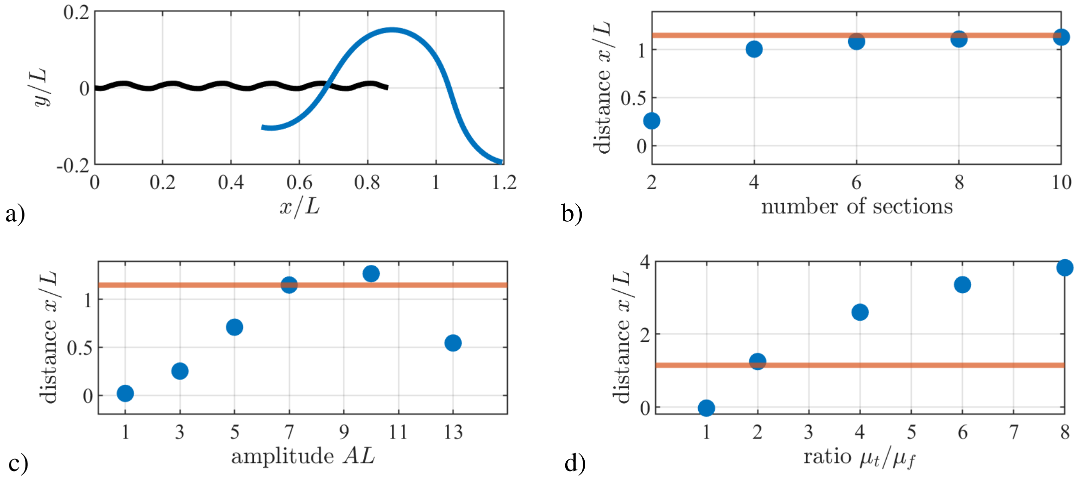

Fig. 1: a) Path of the snake's center of mass (black) and shape of the snake at time $t = 6T$, b)-d) distance of center of mass in x-direction covered after eight cycles of undulation for varying b) number of sections, c) amplitude A of curvature and d) ratios of transverse coefficient of friction vs. forward coefficient of friction. Orange lines indicate result of reference parameters.

3 Results

In order to achieve comparable results, a set of parameters observed on real milk snakes is chosen, similar to [3]. As processes in nature are often very efficient, the efficiency of real snakes represents a comparative value that should be achieved by the robot as far as possible. The velocity of the center of mass, expressed by the distance covered after eight cycles of undulation, serves as reference value.

One important property of the design is the number of sections of the robot (Figure 1 b), which influences the precision of actuation in terms of approximating a sinusoidal curvature. Hence, the arc-length is divided into a certain number of sections with equal length. Each section has a constant curvature which is equal to the mean value in the section in case of a continuous curvature. The results indicate that already four modules sufficiently approximate a real snake, whereas six and more modules almost perfectly approximate the continuous curvature.

Another important property of the design is the maximum curvature the robot is able to perform. A variation of the amplitude A of the curvature illustrates a strong influence on velocity (Figure 1 c). On the one hand, a small amplitude results in little propulsion. On the other hand, a huge amplitude slows down motion due to high impact of transverse friction. Real snakes seem to adapt their curvature to a reasonable value, as indicated by orange line in Figure 1.

The artificial skin of the robot provides anisotropic friction. A variation of the ratio of coefficient of friction in forward direction μ_f to the one in transverse direction μ_t points out the sensitivity of this property (Figure 1 d). The higher the ratio, the faster the robot will move forward.

4 Discussion

The presented model offers the possibility to analyse the influence of single parameters on the locomotion of our snake-like soft robot. This is shown by three different examples. The results of the number of sections and the amplitude of curvature will be considered when revising the robot's design, whereas the ratio of friction in forward direction to transverse direction highlights the importance of the skin.

As the current simulation is based on the behaviour of real snakes, these investigations will be replaced experimentally and numerically with the parameters of our current soft robot design.

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