J. Mech. Phys. Solids 99 (2017) 304–320

Contents lists available at ScienceDirect

Journal of the Mechanics and Physics of Solids

journal homepage: www.elsevier.com/locate/jmps

A novel slithering locomotion mechanism for a snake-like soft robot

Yunteng Cao[a], Yilun Liu[b,*], Youlong Chen[a], Liangliang Zhu[a], Yuan Yan[a], Xi Chen[c,*]

[a] *International Center for Applied Mechanics, State Key Laboratory for Strength and Vibration of Mechanical Structures, School of Aerospace Engineering, Xi'an Jiaotong University, Xi'an 710049, China*
[b] *State Key Laboratory for Strength and Vibration of Mechanical Structures, School of Aerospace Engineering, Xi'an Jiaotong University, Xi'an 710049, China*
[c] *Columbia Nanomechanics Research Center, Department of Earth and Environmental Engineering, Columbia University, New York, NY 10027, USA*

ARTICLE INFO

Keywords:
Slithering locomotion
Rotational velocity field
Traveling wave
Poisson's ratio
Snake-like soft robot

ABSTRACT

A novel mechanism for slithering locomotion of a snake-like soft robot is presented. A rectangular beam with an isotropic coefficient of friction of its contact surface with the flat ground can move forward or backward when actuated by a periodic traveling sinusoidal wave. The Poisson's ratio of the beam plays an important role in the slithering locomotion speed and direction, particularly when it is negative. A theoretical model is proposed to elucidate the slithering locomotion mechanism, which is analogous to the rolling of a wheel on ground. There are two key factors of slithering locomotion: a rotational velocity field and a corresponding local contact region between the beam and ground. During wriggling motion of the rectangular beam, a rotational velocity field is observed near the maximum curvature point of the beam. If the beam has a negative Poisson's ratio, the axial tension will cause a lateral expansion so that the contact region between the beam and ground is located at the outer edge of the maximum curvature (the largest lateral expansion point). The direction of the beam's velocity at this outer edge is usually opposite to the traveling wave direction, so the friction force propels the beam in the direction of the traveling wave. A similar scenario is found for the relatively large amplitude of wriggling motion when the beam's Poisson's ratio is positive. Finite element method (FEM) simulation was conducted to verify the slithering locomotion mechanism, and good agreement was found between the FEM simulation results and theoretical predictions. The insights obtained here present a simple, novel and straightforward mechanism for slithering locomotion and are helpful for future designs of snake-like soft robots.

1. Introduction

Recently, soft robots have attracted significant interest of both scientists and engineers. Due to their softness and body compliance, some of the limitations of traditional hard robots may be overcome; examples of these limitations include instability when moving in complex environments, limited motion constrained by hard actuators and structures (e.g., metal rods, mechanical joints and electric motors) and difficulty in manipulating unknown or soft objects (Rus and Tolley, 2015). Therefore, soft robots hold great potential for applications in search-and-rescue operations (Tolley et al., 2014), environmental monitoring (Muth et al., 2014;

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* Corresponding authors.
E-mail addresses: yilunliu@mail.xjtu.edu.cn (Y. Liu), xichen@columbia.edu (X. Chen).

http://dx.doi.org/10.1016/j.jmps.2016.11.019
Received 22 July 2016; Received in revised form 24 November 2016; Accepted 30 November 2016

Vogt et al., 2013), soft-robotic manipulators (Mazzolai et al., 2012) and medical and wearable applications (Park et al., 2014a, 2014b; Polygerinos et al., 2015), to name a few. Inspired by biological systems, many designs of soft robots have been proposed, such as snake-inspired locomotion (Onal and Rus, 2013), caterpillar-inspired locomotion (DeSimone et al., 2015; Lin et al., 2011, 2013), a multi-gait quadruped (Shepherd et al., 2011; Tolley et al., 2014), worm-inspired locomotion (Seok et al., 2010) and jellyfish-inspired swimming (Nawroth et al., 2012). Many of these previous studies focused on the design and optimization of the gaits of soft robots to make them easy to fabricate, actuate and control and able to adapt to severe and complex environments. Among limbless animals, the slithering locomotion of snakes is fast and can adapt to complex terrestrial and aquatic environments. Additionally, slithering locomotion is easy to activate; i.e., a slender beam can be activated by a simple periodic traveling wave. Therefore, slithering locomotion underpins the construction of snake-like soft robots.

The slithering locomotion mechanism of snakes has long been studied in the literature. In general, the slithering locomotion is represented by the motion of the central line of the contact surface between the snake and ground (Alben, 2013; Goldman and Hu, 2010; Hu et al., 2009). The propulsive force is usually derived from lateral pushing against rocks and branches (Gray, 1946; Gray and Lissmann, 1950; Guo and Mahadevan, 2008; Jayne, 1986; Mahadevan et al., 2004; Mosauer, 1932), and the friction of the snake on the ground (Gray and Lissmann, 1950; Hazel et al., 1999; Hirose, 1993; Hu et al., 2009). The coefficient of friction between the belly snakeskin and the flat ground is anisotropic (Gray and Lissmann, 1950; Hu et al., 2009); that is, the coefficient is largest in the transverse directions of the snake and smallest in the forward direction. Therefore, a net propulsive force is generated by the wriggling motion of the snake. Inspired by snake-slithering locomotion, several snake-like robots have been proposed, including both a snake-like hard robot (Hirose, 1993; Liljebäck et al., 2011; Ma, 2001; Ute and Ono, 2002; Wright et al., 2007) and a snake-like soft robot (Onal and Rus, 2013). The snake-like hard robots consist of several rigid blocks connected by joints and springs; the wriggling motion is actuated by the rotation of the joints. For the snake-like soft robot, the whole body is a soft actuator that actuates the wriggling motion. However, in all of these previous snake-like robots, the propulsive force is generated by the friction anisotropy; this requires passive wheels to sustain the difference in the coefficients of friction between the lateral and forward directions. A major disadvantage is that the rigid encompassing of passive wheels defeats the purpose of a true soft robot. From the soft robotic perspective, a simpler material design is desired.

In addition, most previous studies of snake-like slithering locomotion treated the motion as simply that of the central line of the contact surface. However, a rectangular beam actuated by a periodic traveling sinusoidal wave that defines the wriggling motion has a complex velocity distribution. A rotational velocity field is observed near the maximum curvature point of the beam, as shown in Fig. 1. A snake-like robot can also be driven by the well-known rolling mechanism of a wheel on ground if the contact region between the robot and ground is always located at the rotational velocity field region (the maximum curvature point). However, during wriggling motion, the position of the maximum curvature point of the beam changes over time; hence, the difficulty is how to make the contact region between the beam and ground change over time to follow the maximum curvature point of the wriggling motion. New theoretical perspectives need to be established to better control the slithering locomotion.

In this work, a new slithering locomotion mechanism is proposed utilizing the rotational velocity field of wriggling motion to drive a snake-like soft robot. This mechanism does not require friction anisotropy or lateral pushing against rocks and branches (as for generating propulsive force in conventional models). Additionally, this type of soft robot has a very simple material structure and is easy to actuate with a simple periodic traveling wave. Thus, the new mechanism enables many potential applications in soft robots. The organization of the paper is as follows. In Section 2, a theoretical model is proposed to elucidate the slithering locomotion mechanism. Based on this mechanism, a new type of snake-like soft robot is developed and an analytical solution of the slithering locomotion speed is obtained. In Section 3, finite element method (FEM) simulations are conducted to verify the slithering locomotion mechanism; good agreement is found between the FEM results and theoretical predictions. The effects on the slithering locomotion speed of a snake-like soft robot of its mechanical properties and geometry, of the loading method and of uneven ground are systematically studied. Two strategies for fabrication of a snake-like soft robot are illustrated in Section 4, followed with discussions of the efficiency of the slithering locomotion in Section 5. Conclusions are given in Section 6.

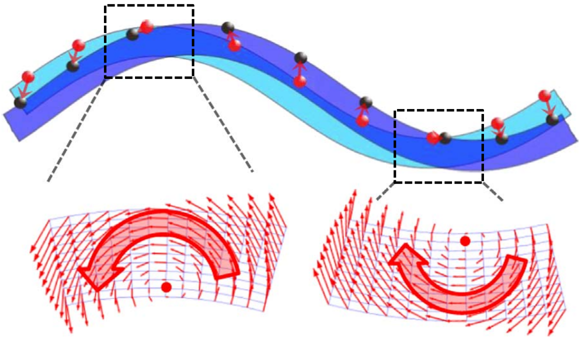

Fig. 1. Schematic diagram of the wriggling motion of a beam. The upper figures are two snapshots of the beam at two instants of time, where the arrows indicate the velocity of the particles on the beam during wriggling motion. The bottom figures give the velocity field of the beam near the maximum curvature points; the rotational velocity field is observed near maximum curvature points.