A novel, adaptive, partitioned gait of biological snakes helps snake robots traverse a large step

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I. Introduction

Many snakes traverse at ease complex 3-D terrain such as deserts, forests, and river valleys filled with large obstacles comparable to their body size. Similarly, snake robots have the potential to provide a versatile platform to traverse a diversity of complex 3-D terrain like earthquake rubble, underground tunnels, and cluttered building structures to help humans in many critical missions such as search and rescue, environmental monitoring, and structural examination. Although snake robots can already move in modestly complex terrain outside the lab using artificial gaits [1], their mobility in complex terrain is still dwarfed by biological snakes.

Despite many snake locomotion studies on flat surfaces or arboreal environments [2]–[4], we know little about the how snakes move in complex 3-D terrain, hindering further progress in snake robot locomotion in nature. To address this challenge, we study biological snakes and snake robots traversing a large step to begin to understand the principles of effective snake-like locomotion in complex 3-D terrain.

II. Animal Experiments

In animal experiments, we found that the variable kingsnake, a generalist that dwells in mountains and deserts, was able to consistently traverse a large step as high as 1/4 its body length (Fig. 1A). We discovered that the animal did so by using a novel, adaptive, partitioned gait. The complex, three-dimensional motion of the high degree-of-freedom, continuum body of the snake during large step traversal could be well approximated by three consecutive, orthogonal "waves" (two horizontal and one vertical) that fluidly travelled down the body as it moved forward to traverse the step (Fig. 1B).

The body sections above and below the step undulated on the horizontal surfaces to propel the body forward, while maintaining lateral stability. Remarkably, the snake's center of mass always fell within the convex hull formed by both undulating body sections in contact with the ground (99% probability). The body section in the middle cantilevered in a vertical plane to climb onto the step, much like a catenary bridging the large distance between the two horizontal surfaces. The fluidic shifting of the three waves allowed the snake body to always adapt to the large step as the animal progressed. Together, this adaptive, portioned gait allowed snakes to traverse the large step both rapidly and stably.

III. Robot Experiments

To test the usefulness of the novel gait from animal experiments for snake robots, we developed a snake robot with alternating joints oriented orthogonally, so that the robot body

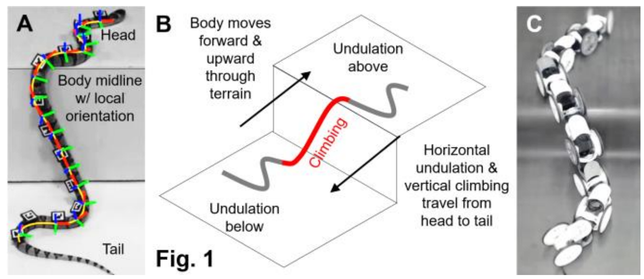

Fig. 1

can deform both laterally and vertically to achieve similar overall body deformations to that of the snake. In addition, we developed a one-direction ratchet wheel mechanism for the snake robot to achieve similar anisotropic frictional properties as found in biological snakes [2].

Using a similar adaptive, partitioned gait as that discovered from the biological snake (comprising three orthogonal waves), the snake robot was able to consistently and rapidly traverse a step as high as 1/6 its body length (100% probability) (Fig. 1C). The robot almost traversed a larger step of 1/3 body length but failed due to diminishing propulsion and stability from shorter body sections used for lateral undulation, because a longer body section must be used for cantilevering.

IV. Broader Implications

The novel, adaptive, partitioned gait that we discovered from biological snakes provided a simple, low degree-of-freedom control template for snake robots to traverse large step obstacles. This novel template is easy to implement because the shapes of the three orthogonal waves can be controlled by only a few parameters.

Our study is a first step in creating terradynamics for snake-like locomotion in complex 3-D terrain, which will provide fundamental principles for snake robots to better traverse diverse natural and artificial terrain.

References

[1] K. Lipkin *et al.*, "Differentiable and piecewise differentiable gaits for snake robots," *IEEE Int. Conf. Intell. Robot. Syst.*, pp. 1864–1869, 2007.

[2] D. L. Hu, J. Nirody, T. Scott, and M. J. Shelley, "The mechanics of slithering locomotion.," *Proc. Natl. Acad. Sci.*, vol. 106, no. 25, pp. 10081–5, Jun. 2009.

[3] H. C. Astley *et al.*, "Modulation of orthogonal body waves enables high maneuverability in sidewinding locomotion.," *Proc. Natl. Acad. Sci. U. S. A.*, vol. 112, no. 19, pp. 6200–5, 2015.

[4] B. C. Jayne, J. T. Baum, and G. Byrnes, "Incline and peg spacing have interactive effects on the arboreal locomotor performance and kinematics of brown tree snakes, Boiga irregularis.," *J. Exp. Biol.*, vol. 216, no. Pt 17, pp. 3321–31, Sep. 2013.

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