Stability benefits of body undulation and compliance for snakes and snake robots traversing large, smooth obstacles

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I. INTRODUCTION

Snakes can move across almost any terrain. Similarly, snake robots hold the promise as a versatile platform to perform critical tasks in complex terrain like earthquake rubble. Although snakes and snake robots are inherently stable motion on flat surfaces, maintaining stability becomes a challenge when they deform their body out of plane to traverse complex terrain. This is especially the case when they traverse large, smooth obstacles like felled trees and boulders that lack "anchor points" for bracing or gripping. Here, we review our group's progress in addressing this problem.

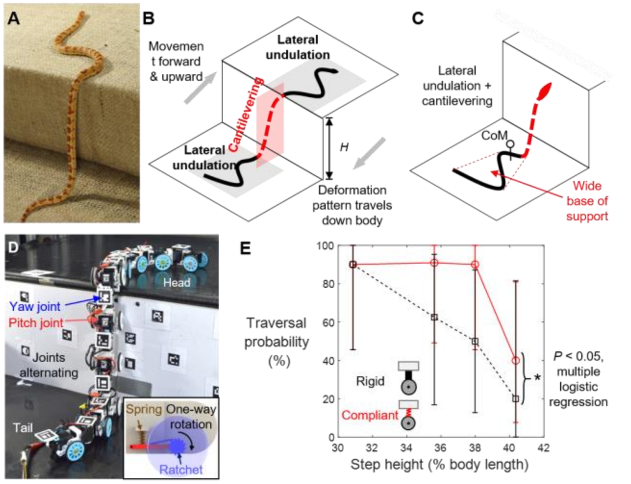
II. METHODS & RESULTS

First, we investigated the stability principles of kingsnakes traversing a step as a representative of large, smooth obstacles [1]. We discovered that the animal uses a partitioned gait (Fig. 1A): its anterior and posterior body sections undulated laterally on the horizontal surfaces above and below the step, while the body section in between bridged the height difference by cantilevering in a vertical plane (Fig. 1B). As the snake moved forward and upward onto the step, the pattern traveled down the body. We hypothesized that body undulation provided stability while cantilevering by offering more ground support in the lateral direction.

Next, to quantify the snake's stability during traversal, we developed an interpolation method to reconstruct its continuous body in three dimensions (both position and orientation) [2]. The method approximates each body segment between adjacent markers as an elastic rod subject to end constraints imposed by markers and numerically solved for an optimal solution. We found that its interpolation accuracy is higher than commonly used geometric interpolation methods like B-spline, besides providing additional local orientation information.

Using the interpolated 3-D body shape, we analyzed whether the projection of the snake's center of mass fell into the base of support formed by its body sections in contract with both horizontal surfaces. Thanks to the large base of support created by lateral undulation, the snake maintained perfect static stability (100% of the time in all trials), even when it cantilevered up to 25% body length out of plane but had not reached the surface above (Fig. 1C).

To further understand stability principles, we developed a snake robot capable of large 3-D body deformation and with one-way wheels to generate snake-like anisotropic friction (Fig. 1D), and we used it as a physical model to perform systematic experiments [3]. The robot was able to traverse a step as high as 31% body length at 90% probability (Fig. 1E, black dashed). However, traversal probability diminished quickly as step height increased. We observed that in most failed trials, the robot suffered large body rolling and eventually flipped over and fell off the step. By contrast, the snake with a compliant body never did so. This inspired us to test whether body compliance facilitates roll stability by improving surface contact, by adding a suspension system (Fig. 1C inset) to the robot. Indeed, adding body compliance improved surface contact, reduced roll instability, and helped the robot traverse high steps with higher probability (Fig. 1E, red solid).



III. DISCUSSION

Besides elucidating principles, our snake-inspired robot also achieved higher step traversal speed than most previous snake robots, although still far behind that of kingsnakes. The combination of body undulation and compliance may be useful for traversing other complex 3-D terrain with large, smooth obstacles. Future work should study how snakes, and snake robot should, use sensory feedback control to traverse complex terrain rapidly and stably.

REFERENCES

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