Insects adjust body and appendages to traverse cluttered obstacles

Yaqing Wang, Ratan Othayoth, Chen Li
Johns Hopkins University, Baltimore, MD, USA
ywang460@jhu.edu, https://li.me.jhu.edu/

1 Introduction

Robots are more and more involved in our daily life. There are scenarios where the robots are required to navigate rough terrains with large obstacles, like earthquake rubble. Although legged robots have already shown superior performance in the rough terrain compared to wheeled robots, they are still far from being agile. On the other hand, insects like cockroaches are exceptional at navigating complex terrain with cluttered, large obstacles [1]. Understanding the physical mechanism of how the animals traverse such rough terrain can provide insight into how to create more agile mobile robots.

In a recent study [2], we found that the animal traversed a layer of grass-like beams by transitioning from a "pitch" mode to a "roll" mode (fig. 1A). In the "pitch" mode, the cockroach pitched up its body after approaching the beam and tried pushed against the beam to ram through. In the "roll" mode, the animal rolled its body into a gap between two beams. Using a potential energy landscape approach, the study showed that the transition emerged when the system jumped from a "pitch" local minimum basin to a "roll" basin on the landscape, by crossing a barrier between the two (fig. 1B). The study also showed that the kinetic energy fluctuation from body oscillation facilitates this transition. However, the study also showed that the animal transitioned from the pitch to the roll mode before the kinetic energy fluctuation reaches the same level as the energy barrier. This suggested that the animal may be using active strategies via sensory feedback [3].

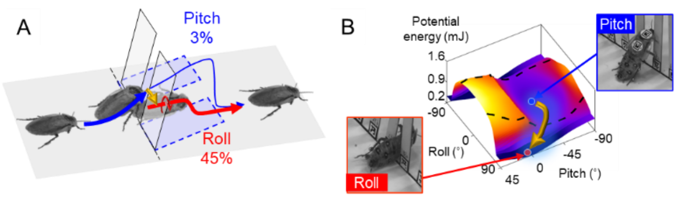

Figure 1: A. Mode transition in beam traversal. **B.** Potential energy landscape. Blue dot: "pitch" local minimum. Red dot: "roll" local minimum. Yellow arrow: Transition from "pitch" to "roll" basin. Black dot line: Energy barrier.

Here, we test the hypothesis that the animal actively sense the terrain and adjusted its body and appendages to facilitate this pitch-to-roll mode transition and traversal. We measured the animal's active adjustments, including head, abdomen, and legs. We are also creating a robophysical model to systematically study how to use force sensing and feedback control to facilitate traversal and make use of these active adjustments to get better traversal performance.

2 Methods

First, we challenged the discoid cockroaches *Blaberus discoidalis* to traverse a layer of high-stiffness (K = 2.5 mN·m/rad) grass-like beams (N = 3 animals, n = 36 trials) and recorded the cockroach motion using eight synchronized high-speed cameras. We tracked the markers attached to the animal's head, body, and legs in camera view using DeepLabCut [4] and BEEtag tracking code [5], [6]. And using these markers, we reconstructed 3-D kinematics of the animal locomotion. (In fact, we had collected 133 trials with 8 animals, but because digitizing one trial took about 4 hours of manual effort even using DeepLabCut, we were only able to analyze 36 trials.) Then we quantified active adjustments in the animal's head, abdomen, and legs, and proposed hypothesized functions for these adjustments. Finally, we created a robot with the functions of the active adjustments similar to the animal.

3 Results

We observed that the animal made four kinds of active adjustments during exploring around the beam and rolling into the gap, compared approaching the beams.

(1) It repeatedly flexed its head up and down (Fig. 2A) while exploring round the beams and while rolling.

(2) It flexed its abdomen in large amplitude (Fig. 2B) when it was stuck between the beams.

(3) It sprawled the hind legs outward (Fig. 2C) when it pitched its body up and pushed against the beams but tucked them inward just before rolling.

(4) It extended one hind leg and retracted the other (Fig. 2D) just before rolling.

We speculated that these active adjustments all contribute to the pitch-to-roll transition.

(1) The animal flexed its head to sense the terrain shape and physical properties (stiffness, surface friction coefficient, etc.) when exploring around the beams or pitching up against the beams [7], and to lead the body into the gap when rolling.

(2) When the animal become stuck between the beams, repeated abdomen flexion could help propel the body and reduce terrain resistance.

(3) By sprawling the leg outward while pushing the beams, the animal could increase its roll stability and pushing force. By tucking the legs inward while rolling into the gap, the

cockroach could reduce roll stability to facilitate rolling.

(4) By extending and retracting the hind legs differentially at the same time, the cockroach could generate a torque to roll.

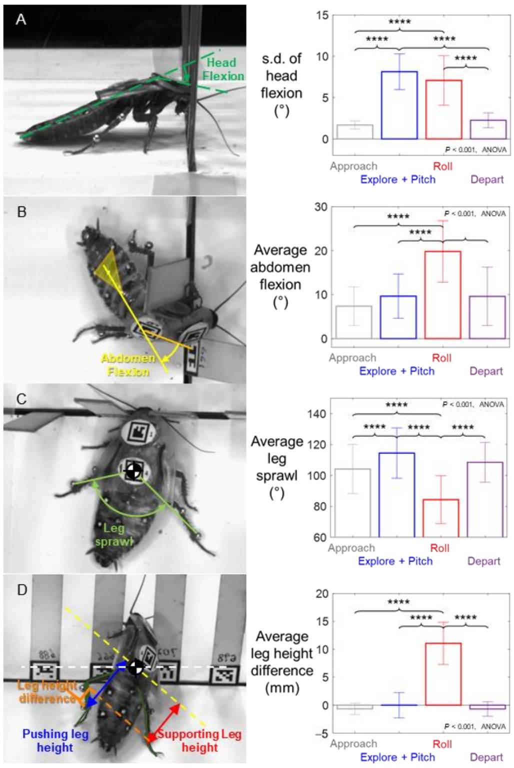

Figure 2: Active body and appendage adjustments. Left column: length or angles to quantify the adjustments. Right column: Adjustment comparison among different phases. **A.** Head flexion. **B.** Abdomen flexion. **C.** Leg sprawl. **D**. Differential leg use. Bars and error bars in the right panels are mean ± s.d. from averaging each trial temporally and then across all trials.

4 Summary and Future work

Our research suggested that, besides kinetic energy fluctuation that facilitates potential energy barrier crossing, the animals also used active sensory feedback to adjusted their body and appendages to interact with the terrain and traverse obstacles. It is most likely that these adjustments are feedback-driven because they do not display good rhythms as feedforward-controlled gaits usually have.

For future work, we will first test these hypotheses of the functions of active adjustments. For example, we can involve legs in the potential energy landscape model to test whether the leg sprawling changes the roll stability; we can add mini force plate under the cockroach's feet to measure the ground reaction force to test whether the differential use in hind legs generates roll torque.

We are also creating a robot (Fig. 3) as a robophysical model to further study the method how to take use of the sensory and active motions to better traverse obstacles. To mimic the head and abdomen motion of the animal, we designed the head (red part) and abdomen (yellow part) of the robot to be able to flex around the body (orange part). In addition, an animal or a robot moving in rough terrain cannot fully and directly control its body orientation, but only in under-actuated ways. To mimic how the leg motion affected the body motion during traversal, we added under-actuated control to the robot yaw, pitch, and roll direction, using a motor connecting to the controlled segment via a torsional spring. We also added force-torque sensors to sense the ground reaction forces.

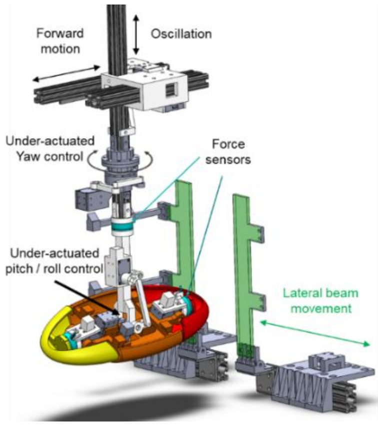

Figure 3: A robophysical model system of a cockroach traversing beam obstacles.

5 Acknowledgements

This work is supported by Arnold and Mable Beckman Foundation Beckman, Young Investigators Program; Army Research Office, Young Investigator Program; Burroughs Wellcome Fund, Career Award at the Scientific Interface; and Johns Hopkins University, Whiting School of Engineering start-up funds to C.L.

References

[1] C. Li, A. O. Pullin, D. W. Haldane, H. K. Lam, R. S. Fearing, and R. J. Full, "Terradynamically streamlined shapes in animals and robots enhance traversability through densely cluttered terrain," *Bioinspiration and Biomimetics*, vol. 10, no. 4, p. 46003, 2015, doi: 10.1088/1748-3190/10/4/046003.

[2] R. Othayoth, G. Thoms, and C. Li, "An energy landscape approach to locomotor transitions in complex 3D terrain," *Proc. Natl. Acad. Sci. U. S. A.*, vol. 117, no. 26, pp. 14987–14995, 2020, doi: 10.1073/pnas.1918297117.

[3] M. H. Dickinson, C. T. Farley, R. J. Full, M. A. R. Koehl, R. Kram, and S. Lehman, "How animals move: An integrative view," *Science (80-.).*, vol. 288, no. 5463, pp. 100–106, 2000, doi: 10.1126/science.288.5463.100.

[4] A. Mathis *et al.*, "DeepLabCut: markerless pose estimation of user-defined body parts with deep learning," *Nat. Neurosci.*, vol. 21, no. 9, pp. 1281–1289, 2018, doi: 10.1038/s41593-018-0209-y.

[5] J. D. Crall, N. Gravish, A. M. Mountcastle, and S. A. Combes, "BEEtag: A low-cost, image-based tracking system for the study of animal behavior and locomotion," *PLoS One*, vol. 10, no. 9, pp. 1–13, 2015, doi: 10.1371/journal.pone.0136487.

[6] T. L. Hedrick, "Software techniques for two- and three-dimensional kinematic measurements of biological and biomimetic systems.," *Bioinspir. Biomim.*, vol. 3, no. 3, p. 034001, 2008, doi: 10.1088/1748-3182/3/3/034001.

[7] Q. Xuan, C. Li, "An energy landscape based dynamic model to simulate locomotion in complex 3-D terrain," *Integrative and Comparative Biology*, S61, 2021, url: https://sicb.burkclients.com/meetings/2021/schedule/abstractdetails.php?id=1373.