Principles of multi-legged locomotor transitions in complex 3-D terrain

Ratan Othayoth, Qihan Xuan, Yaqing Wang, Chen Li
Department of Mechanical Engineering, Johns Hopkins University
ratan@jhu.edu, https://li.me.jhu.edu

1 Introduction

Animals and robots must transition between different modes of locomotion (e.g., walk, run, climb) [1] when moving on complex 3-D terrain with obstacles as large as themselves. While animals can transition robustly by making effective physical interaction with the terrain [2], robots that use obstacle avoidance (Fig. 1a-c) often fail. This is because most of our mechanistic understanding is on how to generate and stabilize near-steady-state locomotion in a single mode [3], [4]. We do not yet understand how animals use physical interaction to make robust locomotor transitions, and how robots should do so (Fig. 1d-e) in complex 3-D terrain with large obstacles.

Here, we describe our recent progress [5] towards filling this knowledge gap by discovering terradynamic principles of multi-legged locomotor transitions. We first focused on understanding passive mechanical interactions and studied cockroaches during their rapid, bandwidth-limited escape [6]–[10] or self-righting response [11], [12] and feed-forward-controlled robotic physical models [6]–[10], [13]. This provided a foundation for understanding sensory feedback control, and the intelligence aspect of locomotor-terrain interactions. A detailed overview video of this work is available at: https://doi.org/10.6084/m9.figshare.14207927.v2

2 Methods

We abstracted complex terrain as a composition of diverse large obstacles (Figure 1d, e) that present distinct locomotor challenges (Fig. 1f). We created simplified robotic physical modes of each model system to generate relevant locomotor behavior [5]. To enable systematic experiments we created a terrain testbeds that allow controlled, systematic variation of model system properties [5]. We developed tools to address the technical challenges in measuring locomotor transitions in complex 3-D terrain.

To understand physical principles of locomotor transitions, we created potential energy landscapes for our model systems (Fig. 2a,b) [5]. We hypothesized that locomotor transitions are barrier-crossing transitions between basins of potential energy landscapes. In addition, to begin to understand transition dynamics, we also developed dynamical templates [9], [14] and multi-body dynamics simulations [15].

3 Principles and insights from simple model systems.

For each model system, we discovered physical principles of locomotor transitions and how transitions depend on system properties. These principles are generalizable over the relevant parameter space and led to new insights.

For all model systems, locomotor modes are stereotypical, with qualitatively similar body postural changes (Fig. 2a). Transitions between modes occur stochastically and the probability of using or transitioning to a mode strongly depends on locomotor and terrain parameters.

Locomotor transitions are destabilizing, barrier-crossing transitions on a potential energy landscape (Fig. 2b). For all systems, the system state in each mode is strongly attracted to a local minimum basin of the energy landscape. Because the landscape basins are strong attractors, transition from one mode to another requires escaping from a basin and falling into another by overcoming an energy barrier. For both robots and animals, feed-forward self-propulsion, and resulting passive mechanical interaction, destabilizes the system and induces stochastic, barrier-crossing locomotor transitions. In addition, animals also use feedback-controlled active adjustments [16] to facilitate or enable desired transitions when feed-forward self-propulsion is insufficient.

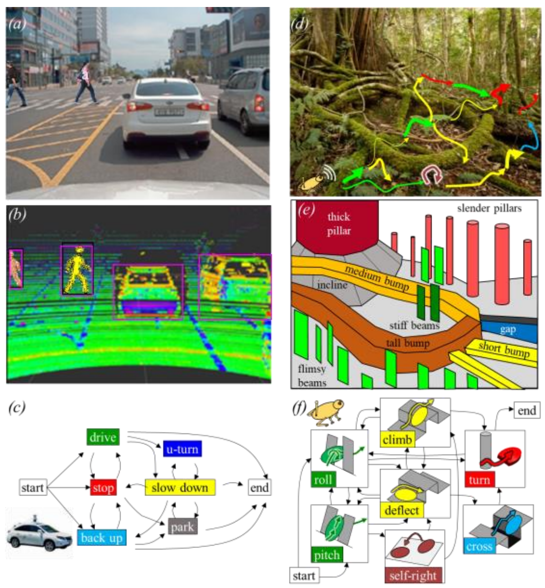

Fig. 1: Multi-pathway transitions to avoid and traverse obstacles. (a) View from a self-driving car. (b) Scanned geometric map. (c) Multi-pathway driving mode transitions to avoid obstacles. (d) Envisioned capability of robots traversing complex 3-D terrain with many obstacles as large as itself. (e) Abstracted challenges from diverse large obstacles. (f) Envisioned multi-pathway locomotor mode transitions.

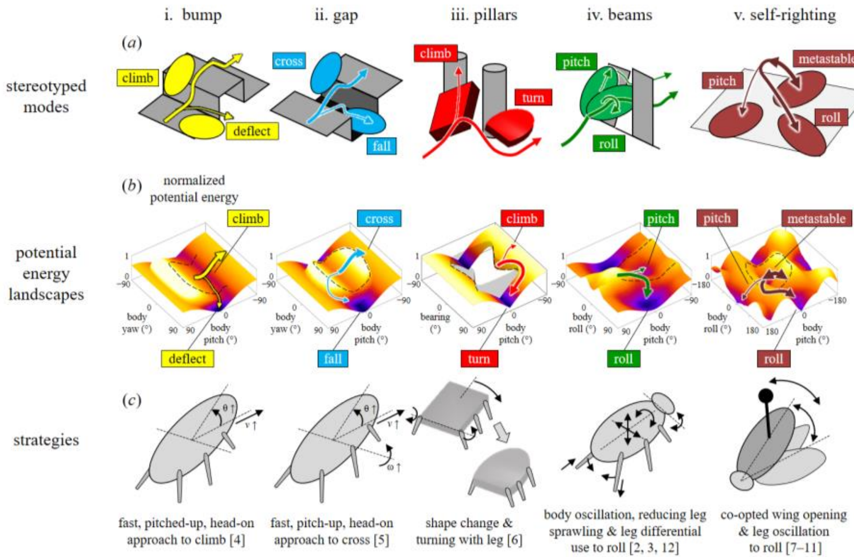

Fig. 2: Locomotor transitions on potential energy landscapes. (a) Stereotyped locomotor modes. (b) Potential energy landscapes. Black dashed curve is the energy barrier that must be crossed to make locomotor transitions. Arrows in (a, b) show representative system state trajectories; thicker arrows show more desirable modes. (c) Strategies that can increase the probabilities of desired modes and facilitate transitions to overcome locomotor challenges.

Based on these insights, we discovered a suite of strategies to make desired transitions more probable for each model system (Fig. 2c). This owes to the fact barrier-crossing transitions on landscape can be enhanced or suppressed by steering the system state on the energy landscape, changing landscape barriers, or even modifying landscape topology (the number of basins). These strategies increased robot performance or even enabled new capabilities.

Finally, these results showed that there is a potential energy landscape-dominated regime, in which self-propulsion does not guarantee overcoming potential energy barriers. In this regime, our approach is powerful for understanding how to self-propel to make locomotor transitions.

4 Towards multi-pathway locomotor transitions

Considering the generality of physical principles across diverse simple model systems, we posit that multi-pathway locomotor transitions in heterogeneous terrain can be understood by composing larger scale, higher dimensional potential energy landscapes from simple landscapes. Furthermore, potential energy landscape theories with the addition of intelligence can help understand and predict how the animal's nervous system [2] or robots' sensing, control and planning systems [17] mediate physical interaction to generate multi-pathway locomotor transitions. Such predictive energy landscape approaches will complement existing geometry-based obstacle avoidance [18] approach in robotics (Fig. 1a-c) and help robots better use physical interaction to traverse currently unreachable complex 3-D terrain.

5 Acknowledgements

We thank previous members of the Terradynamics lab, especially Sean Gart and Yuanfeng Han, for contribution to the previous studies, Dan Goldman, Simon Sponberg, Bob Full, Dan Koditschek, Shai Revzen, and Noah Cowan for discussion. This work is supported by Army Research Office, Burroughs Wellcome Fund, Arnold & Mabel Beckman Foundation, and Johns Hopkins University.

References

[1] R. J. Lock, S. C. Burgess, and R. Vaidyanathan, "Multi-modal locomotion: from animal to application," *Bioinspir. Biomim.*, vol. 9, no. 1, p. 011001, Dec. 2013.

[2] 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*, vol. 288, no. 5463, pp. 100–106, Apr. 2000.

[3] R. Blickhan and R. J. Full, "Similarity in multilegged locomotion: Bouncing like a monopode," *J. Comp. Physiol. A*, vol. 173, no. 5, pp. 509–517, 1993.

[4] A. A. Biewener and M. A. Daley, "Unsteady locomotion: Integrating muscle function with whole body dynamics and neuromuscular control," *J. Exp. Biol.*, vol. 210, no. 17, pp. 2949–2960, Sep. 2007.

[5] R. Othayoth, Q. Xuan, Y. Wang, and C. Li, "Locomotor transitions in the potential energy landscape-dominated regime," *Proc. R. Soc. B* , vol. 288, no. 1949, p. rspb.2020.2734, Apr. 2021.

[6] 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," *Bioinspir. Biomim.*, vol. 10, no. 4, p. 46003, 2015.

[7] R. Othayoth, G. Thoms, and C. Li, "An energy landscape approach to locomotor transitions in complex 3D terrain," *Proc. Natl. Acad. Sci.*, vol. 117, no. 26, pp. 14987–14995, Jun. 2020.

[8] S. W. Gart and C. Li, "Body-terrain interaction affects large bump traversal of insects and legged robots," *Bioinspir. Biomim.*, vol. 13, no. 2, p. 026005, Feb. 2018.

[9] S. W. Gart, C. Yan, R. Othayoth, Z. Ren, and C. Li, "Dynamic traversal of large gaps by insects and legged robots reveals a template," *Bioinspir. Biomim.*, vol. 13, no. 2, p. 026006, Feb. 2018.

[10] Y. Han *et al.*, "Shape-induced obstacle attraction and repulsion during dynamic locomotion," *Int. J. Rob. Res.*, vol. 40, no. 6–7, pp. 939–956, Mar. 2021.

[11] C. Li, T. Wöhrl, H. K. Lam, and R. J. Full, "Cockroaches use diverse strategies to self-right on the ground," *J. Exp. Biol.*, vol. 222, no. 15, p. jeb186080, 2019.

[12] R. Othayoth and C. Li, "Propelling and perturbing appendages together facilitate strenuous ground self-righting," *bioRxiv*, no. 2021.04.06.438657, 2021.

[13] C. Li, C. C. Kessens, R. S. Fearing, and R. J. Full, "Mechanical principles of dynamic terrestrial self-righting using wings," *Adv. Robot.*, vol. 31, no. 17, pp. 881–900, Sep. 2017.

[14] Q. Xuan and C. Li, "Coordinated appendages accumulate more energy to self-right on the ground," *IEEE Robot. Autom. Lett.*, vol. 5, no. 4, pp. 6137–6144, Oct. 2020.

[15] Q. Xuan and C. Li, "Randomness in appendage coordination facilitates strenuous ground self-righting," *Bioinspir. Biomim.*, vol. 21, no. 1, pp. 1–9, Aug. 2020.

[16] Y. Wang, R. Othayoth, and C. Li, "Uncovering the role of head flexion during beam obstacle traversal of cockroaches," in *Integrative and Comparative Biology 61*, 2021, p. e959.

[17] A. J. Ijspeert, "Biorobotics: using robots to emulate and investigate agile locomotion.," *Science*, vol. 346, no. 6206, pp. 196–203, 2014.

[18] O. Arslan and D. E. Koditschek, "Sensor-based reactive navigation in unknown convex sphere worlds," *Int. J. Rob. Res.*, vol. 38, no. 2–3, pp. 196–223, 2019.