Vibration helps robots explore locomotion energy landscapes and transition to more favorable locomotor modes

Ratan Othayoth, George Thoms, Qihan Xuan, and Chen Li (chen.li@jhu.edu, https://li.me.jhu.edu)
Department of Mechanical Engineering, Johns Hopkins University

I. Introduction

Mobile robots are on the verge of becoming a major part of society to assist humans in applications as diverse as search and rescue, structural examination, environmental monitoring, and planetary exploration. However, even the best mobile robots still struggle to traverse complex 3-D terrain like earthquake rubble, construction sites [1]. By contrast, animals move well through almost any terrain such as forest floor, mountain boulders, and desert bushes, easily transitioning between different locomotor modes [2]. A major challenge to understanding animal locomotion and advancing robotic locomotion in complex 3-D terrain is the relative lack of physics models to describe locomotor-terrain interaction and understand locomotor transitions [3], [4].

II. Locomotion Energy Landscape Hypothesis

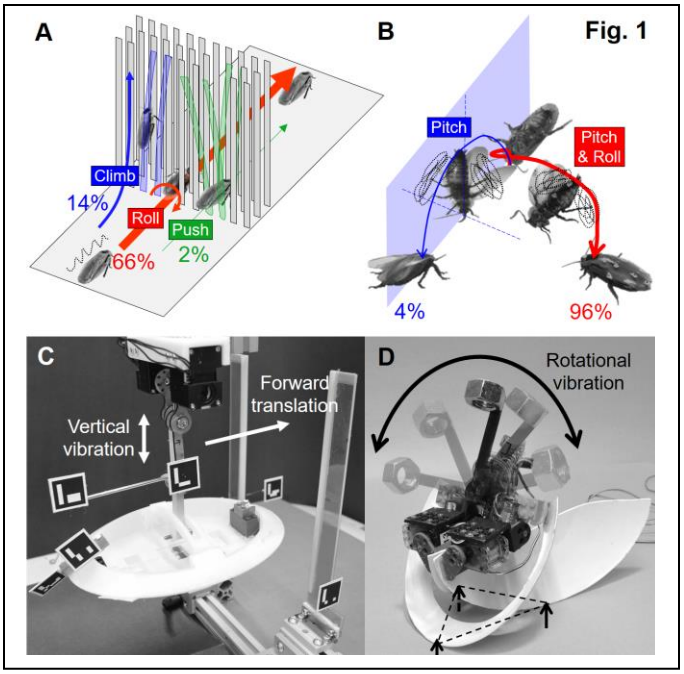
The emerging field of terradynamics [3], [4], analogous to aero- and hydrodynamics of flying and swimming, has begun to advance understanding of terrestrial locomotion in complex terrain. Recent studies using controlled lab platforms enabled discovery and quantification of legged locomotor transitions in complex 3-D terrain. For example, to traverse grass-like beam obstacles, insects push across, climb over, or roll their body to maneuver through gaps (Fig. 1A) [4]. When flipped over, they use wings to rapidly push against the ground to self-right either by somersault (pure body pitching) or diagonal somersault (simultaneous body pitching and body rolling) (Fig. 1B) [5].

In particular, these studies demonstrated that (1) statistically, animals use the easiest (fastest) locomotor modes more frequently, and (2) animals' body vibrated vigorously, due to either oscillatory pushing of the legs against the ground during obstacle traversal (Fig. 1A) or oscillatory flailing of the legs in the air during winged self-righting (Fig. 1B). Inspired by these observations, we hypothesized that the kinetic energy fluctuation of body vibration, induced by oscillatory leg movement, can help legged locomotors explore a locomotion energy landscape and overcome potential barriers to find more favorable locomotor modes.

III. Methods, Results, & Discussion

Here, we developed new robophysical systems to enable control and variation of body kinetic energy fluctuation to test this hypothesis experimentally during both beam obstacle traversal (Fig. 1C) and self-righting (Fig. 1D). We developed locomotion energy landscape models for both systems and used experimentally measured system states to reconstruct how the systems evolved on the landscape.

This work is supported by an ARO YIP (grant # W911NF-17-1-0346), a BWF CASI, and JHU WSE startup funds to C.L.



For both systems, as body kinetic energy fluctuation increased, the system was more likely and took shorter time to transition to more favorable locomotor modes—those that overcome lower potential barriers to traverse or self-right.

Our study is a major step in establishing terradynamics of locomotion in complex 3-D terrain. Analogous to free energy landscapes that have allowed understanding and prediction of protein-folding pathways [6], we envision that the novel physics framework of locomotion energy landscapes will help understand and predict how to make locomotor transitions for animals and robots to traverse diverse complex 3-D terrain.

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