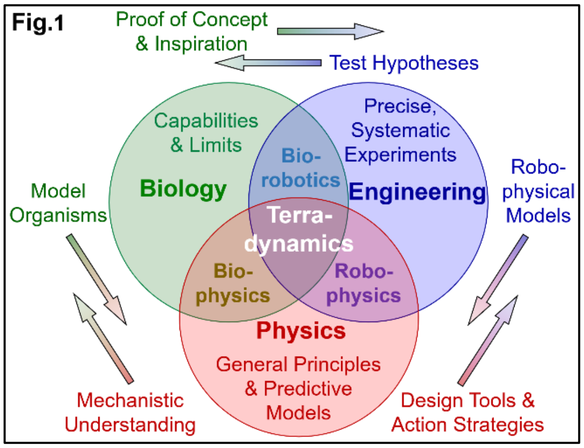
Research Statement – Chen Li, Johns Hopkins University

RESEARCH VISION

Fig.1



Similar to personal computers a few decades ago, mobile robots are now on the verge of becoming a major part of society. Previous research has provided the foundation for modern robots like self-driving cars, Boston Dynamics Spot (a dog-like robot), and Mars rovers. These robots can robustly traverse modestly complex terrains. Yet robots have struggled to reliably traverse a diversity of complex terrains like sand, mud, earthquake rubble, dense vegetation, rocks and boulders, and extreme terrains on the moon and Mars. To deal with these realities, robots often treat these challenges as obstacles to be avoided, missing a major opportunity to help mankind in critical missions. By contrast, animals are adapted to traverse vastly diverse and complex terrains. My scientific vision is to **understand the physical principles of animal locomotion in complex terrains and to use these principles to help robots achieve animal-like mobility in diverse, complex terrains and to unlock the potential of advanced robots to make broader positive contributions to mankind.** To this end, my research aims to:

1. Discover how movement in complex terrains emerges from locomotor-terrain interaction.
2. Understand how such interaction can be sensed, controlled, planned to generate effective movement.
3. Create first-principle models of interaction to explain and predict how to attain performance.

Aero- and hydrodynamics of fluid-structure interactions have advanced our understanding of the way in which animals fly and swim and the mobility of flying and underwater vehicles and robots. Similarly, my research is helping to establish an **emerging field of "terradynamics"**. Terradynamics is the understanding of locomotor-terrain interaction for biological and robotic locomotion in complex terrains. Similar to aero- and hydrodynamics research, my interdisciplinary program integrates complementary approaches—from engineering and physics and, in this case in particular, biology (**Fig. 1**).

Initial research in terradynamics (some of which I led during my PhD[1]) recently enabled legged robots to robustly run like animals on sand[2]. **Principled understanding of terradynamics must be further developed for a diversity of complex terrain because real-world terrestrial environments are highly heterogeneous**[1,3]. Towards this end, my lab has identified and made major advancements in three areas:

Area 1. Establishing a terradynamics of multi-legged locomotion in complex 3-D terrains
Area 2. Advancing understanding of limbless locomotion in complex 3-D terrains
Area 3. Elucidating physical principles of dynamic ground self-righting

Since starting at JHU in 2016, **my lab's independent and lead efforts (as senior corresponding author) have led to 20 peer-reviewed papers in top journals** (*PNAS*, *eLife*, *J. Exp. Biol.*, *Biomimetics & Biomimetics*, *Intl. J. Robotics Research*, *IEEE Robotics & Automation Lett.*, etc.), plus 8 collaborative papers (with 4 as corresponding first author). I have an **established record of externally funded research**, having obtained ~$2M external funding (including ~$1.5M as sole-PI and ~$500k to me as co-PI).

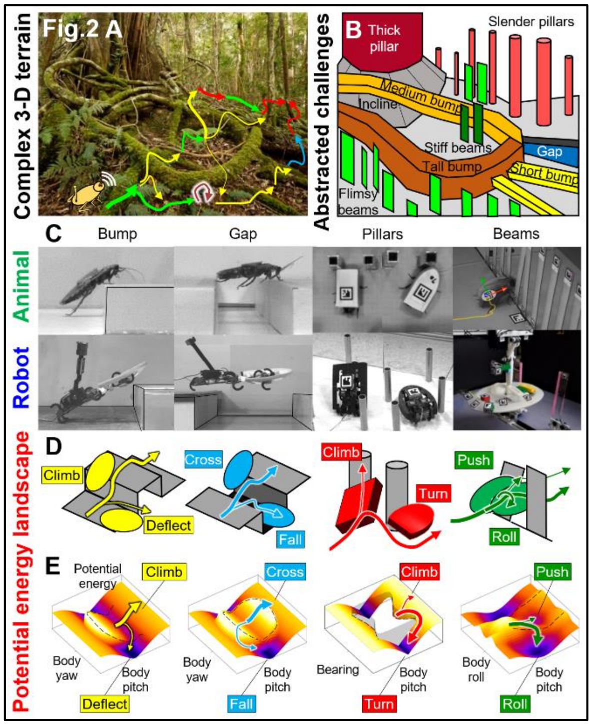
ESTABLISHED AREAS: ACCOMPLISHMENTS & NEXT STEPS

Area 1. Establishing a terradynamics of multi-legged locomotion in complex 3-D terrains

Importance & Knowledge Gap. Research on leg-ground interaction has enabled legged robots to robustly walk and run on relatively flat, rigid ground, by rejecting perturbations from small surface unevenness to self-stabilize[4]. Yet for important tasks like search and rescue over rubble, environmental monitoring across forest vegetation (**Fig. 2A**), package delivery to remote mountain areas, and planetary exploration through lunar and Martian rocks and boulders[5], robots must traverse complex 3-D terrains with cluttered obstacles comparable to or even larger than themselves. To do so, they must transition across different modes of locomotion (**Fig. 2A**). Legged robots still cannot do so robustly. This is largely because previous research has focused on **avoiding sparse large obstacles using a geometric map** of the environment, and we still lack a principled understanding of how to use, sense, and control **direct physical interaction** with large obstacles to make locomotor transitions. As an example, robot aerobatics and parkour by Boston Dynamics were achieved through tuning and are still not robust.

<u>**Advancements.**</u> **1a. We discovered how locomotor transitions emerge from locomotor-obstacle interaction and can be controlled by modulating interaction.** We performed systematic experiments of animals (the discoid cockroach) and their robophysical models (RHex-class robots) interacting with diverse large obstacles that present distinct locomotor challenges (**Fig. 2B, C**). These include: horizontal obstacles with large height increase or decrease like a bump[6] or a gap[7]; rigid or flexible cluttered large obstacles like pillars[8] or beams[9–11]. For each obstacle type, physical interaction with the obstacle can result in a few distinct locomotor modes with large 3-D body rotations (**Fig. 2D**). Animals and robots can use diverse strategies to modulate obstacle interaction, to either facilitate transitions to desirable modes that lead to traversal, or suppress transitions to undesirable modes that lead to failure. Our robot that integrates strategies achieved high traversal performance across diverse obstacles[12].

1b. We established a potential energy landscape approach to modeling locomotor transitions and understanding and predicting strategies to make transitions. Across diverse large obstacles, locomotor-obstacle interaction results in a potential energy landscape over relevant body degrees of freedom (translation and rotation through world). With continual "jittering" from leg-ground interaction, the animal or robot tends to fall into one of a few attractive landscape basins (like a particle with thermal noise tends to fall into an energy well) (**Fig. 2E**), which emerges as one of the few observed locomotor modes (**Fig. 2D**). Thus, locomotor transitions are barrier-crossing transitions on the landscape[6,8,9]. Strategies that facilitate transition to the desirable modes (basins) fall into three categories: (a) use large kinetic energy fluctuation to cross potential energy barriers by chance[9]; (b) steer on the landscape to cross in the direction of lower barriers (saddles)[6–8,10]; and (c) add basins of desirable modes and remove basins of undesirable ones[8]. For a review, see[13].



1c. We revealed how sensing physical interaction can guide transitions to traverse. To make transition to the desirable modes, the easiest way is to find and cross saddle points that have the lowest barrier. Thus, animals may, and robots should, sense its physical interaction with obstacles and use this information to guide traversal. We discovered that the animal indeed actively adjusted its body and legs during traversal, likely guided by tactile and proprioceptive sensing[10]. We developed a robot capable of sensing forces and torques from obstacles and are developing methods to use this information to reconstruct the landscape locally and guide saddles-crossing transitions[14]. We developed methods to use the sensed obstacle forces to control robots to increase traversal performance[11]. We also created a "terrain treadmill" to continuous study large obstacle traversal over ~10^3 cycles or body lengths at high spatial resolution[15].

It is worth noting that our approach to enable locomotor transitions can achieve **traversal of the same obstacle using a much smaller robot, or traversal of much larger obstacles using the same robot**[5].

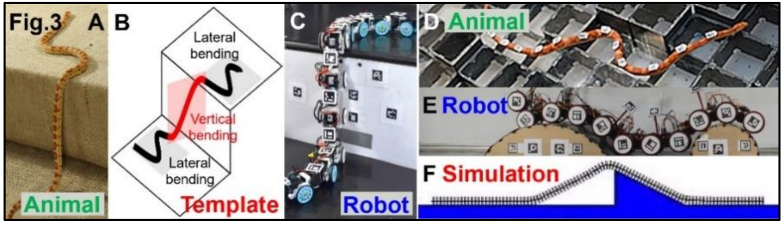
<u>**Future Directions.**</u> Ultimately, we aim to create a statistical physics-like potential energy landscape approach to enable robots to **compose dynamic locomotor transitions** to robustly traverse diverse a diversity of complex 3-D terrains. Towards this end: **1d.** We will add non-conservative forces (e.g., propulsion, friction, damping) to potential energy landscape models to statistically predict locomotor transition dynamics (e.g., via stochastic dynamics simulations[16] or Langevin models). **1e.** We will integrate

potential energy landscapes (which describe physical interaction with obstacles) and virtual potentials (which describe internal controller) (**NSF DCSD proposal submitted**) to enable lowest-resistance saddle-crossing transitions. **1f.** We will apply our approach to enable terrain sensing-guided, multi-modal locomotor transitions for low-cost scout robots to access challenging terrain for planetary exploration applications (**NASA PSTAR proposal submitted**). **1g.** We will expand our approach to model hand/foot-anchor interaction and trajectory planning in steep terrain (**NSF FRR proposal submitted**).

Area 2. Advancing understanding of limbless locomotion in complex 3-D terrains

Importance & Knowledge Gap. Snakes can traverse diverse complex 3-D terrains with large obstacles. Snake-like limbless robots hold the promise for doing the same but still struggle to do so robustly. Previous studies focused on locomotion on near flat surfaces with predominantly lateral body bending. We still lack **mechanical and control principles of locomotion in 3-D terrains requiring large vertical body bending.**

Advancements. 2a. We discovered how snakes traverse a large obstacle, elucidated stability principles, and enabled stable traversal in snake robots. When traversing larger obstacles with large vertical bending, maintaining stability is challenging. Our experiments traversing a large step obstacle[17] (**Fig. 3A**) revealed that snakes transition from lateral body bending for propulsion on flat surfaces to vertical body bending to bridge height changes (**Fig. 3B**). Lateral bending offers snakes a wide base of support to achieve perfect stability. We developed a snake robot using this gait template to rapidly traverse a large step (**Fig. 3C**), faster than almost all previous snake robots[18]. Using the robot as a robophysical model, we discovered that the stability of this gait diminishes with obstacle height—small noises in actuation and control and surface properties lead to large body wobbling. Inspired by how snakes maintain good terrain contact to achieve perfect stability, we added passive body compliance to the robot, which greatly enhanced its stability while maintaining traversal speed[18]. For a review, see[19].



2b. We revealed that vertical bending can be used to generate propulsion and how to control it to do so. On flat surfaces, snakes and snake robots bend the body laterally against surface asperities for propulsion. Yet, whether vertical bending is useful for propulsion was rarely considered. We studied snakes traversing highly uneven terrain (**Fig. 3D**) and discovered that they move forward with little lateral slip as if they were moving in a virtual tube[20]. By contrast, snake robots slip a lot in similar terrains. By developing a highly accurate method[21], we quantified the snake's terrain contacts and estimated that snakes likely use vertical bending just as frequently as lateral bending for propulsion[20]. Our snake robot experiments confirmed that vertical bending can generate propulsion against terrain unevenness, and we added force sensors to the robot to study how force feedback control modulates propulsion[22] (**Fig. 3E**). Overall, our discoveries suggested that the previous focus of snake locomotion using lateral bending is merely a special case of an inherently 3-D behavior.

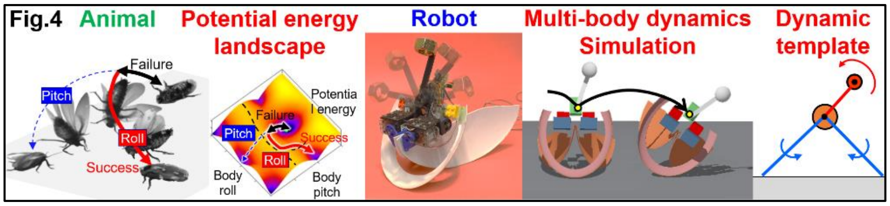
Future Directions. Ultimately, we aim to understand how to **coordinate vertical and lateral bending along the entire body** to propel and steer in complex 3-D terrains. This will drastically expand the range of terrains that snake robots can access for diverse applications. Towards this end: **2c.** We have developed a high-fidelity, low-cost 3-D force sensor, and we will integrate an array of them into a reconfigurable complex 3-D terrain platform to measure ground reaction forces distributed across a snake's body. **2d.** We have developed a dynamic simulation and will use it to study the mechanics and control of vertical bending for propulsion[23] (**Fig. 3F**). We will use these experimental and simulation tools to study this systematically (**NSF IOS proposal submitted**). **2e.** We have developed a snake robot with custom pressure sensors embedded on both sides and bottom of its body[24], and we will use it as a robophysical model to study how to use force feedback control to adapt to terrain variation.

Area 3. Elucidating physical principles of dynamic ground self-righting

Importance & Knowledge Gap. During interaction with large obstacles, legged animals and robots can flip over and must right themselves [25,26]. Previous animal studies described behaviors and studied neural and motor control of ground self-righting. Previous robot studies developed mechanisms for self-righting. Yet the physical principles of ground self-righting are relatively poorly understood.

Advancements. We studied the discoid cockroach as a model organism. When flipped over, this animal often opens its wings while flailing its legs, but neither wings nor legs alone can generate enough force/energy to self-right[25]. Similarly, ground self-righting is strenuous for most robots. We systematically studied strenuous ground self-righting (**Fig. 4**), by integrating animal experiments[27], robophysical experiments[27], potential energy landscape modeling[27], multi-body dynamics simulation[28], and dynamic template modeling[29].

Fig.4



3a. We elucidated why only combining wing propulsion and leg perturbation leads to successful righting. Wing pushing and leg flailing alone cannot overcome their respective potential energy barriers, but, when used together, the barrier is reduced by wing pushing and can be overcome by leg flailing[27].

3b. We elucidated how randomness in the animal's wing and leg motions can increase the likelihood of self-righting, by allowing the animal to find good wing-leg coordination which accumulates more mechanical energy to overcome potential energy barriers.

Future Directions. **3c.** We will apply these principles to better co-opt appendages to achieve ground self-righting for multi-modal locomotion in complex 3-D terrains (see **1f**).

NEW AREAS

To further understand biological movement and help create life-like robots, we are expanding into new areas of mechanics, sensing, planning, and predator-prey interaction in more diverse complex terrains.

4. Amphibious locomotion on mud at the water-land interface. The invasion of land by fishes led to the evolution of all land vertebrates. Previous studies focused on functional morphology, kinematics, and muscle control, mostly comparing amphibious fish locomotion on rigid ground to swimming in water. We have begun studying how fishes[30] and fish robots[31] adapt body and fin motions to the complex mechanics of wet flowable substrates like mud, whose load bearing capacity vary drastically as it changes from wet to dry (**NSF IOS proposal submitted**). Such a principled understanding will enable amphibious robots to adaptively traverse similar terrain at the water-land interface for ecological/environmental monitoring.

5. Mechanical sensing, planning, and predator-prey interaction in complex terrains. Spiders are masters at sensing and catching prey on their webs. We have created a robophysical model of the spider-web-prey system to study how orb-weaver spiders use leg behavior to modulate its vibration sensing on the web to better detect prey, a new form of active sensing[32] (**new NSF PoLS grant**). We will also study how jumping spiders hunt dangerous/volatile prey in cluttered arboreal terrain[33], which involves planning ahead of time to take detours to stalk prey (**HFSP proposal submitted**). These studies will help create robots that intelligently sense targets and plan actions for environmental monitoring and disaster response.

6. Maneuvering into packed heterogeneous terrains. No robots can yet robustly traverse packed heavy rubble after earthquakes and other disasters, leaving victims with a very low chance of survival. We have begun studying how animals and plant-inspired robots[34] can wedge into heavy rubble terrains. Similar, we have begun using robophysical modeling to study how parasites (e.g., malaria) penetrating skin (which is also a densely packed "terrain")[35], which will help develop new infection prevention strategies.

LONG-TERM POSITIVE SOCIETAL IMPACT

The terradynamical principles and models, and the design, actuation, sensing, control, planning, and multi-agent interaction strategies based on them, will advance many robot applications in the real world. Similar to machine vision-based geometric maps for obstacle avoidance already used by self-driving cars, Mars rovers, and other robots, physics-based terradynamic models and strategies **will exist in the cloud** to help robots traverse natural, artificial, and extraterrestrial terrains and serve humanity in many endeavors.

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