

# Legged robots use terradynamic shapes and adjust legs to escape obstacles and traverse cluttered terrain

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## I. INTRODUCTION

Cluttered terrain such as earthquake rubble, forest floor, and cluttered building structures filled with multiple 3-D obstacles as large as robots themselves challenges even the best terrestrial robots. This is largely because robots heavily rely on planning and control based on terrain geometry, and there is a relative lack in our understanding of the physics of locomotor-terrain interaction and how to design and control robots to interact with complex terrain physically to traverse.

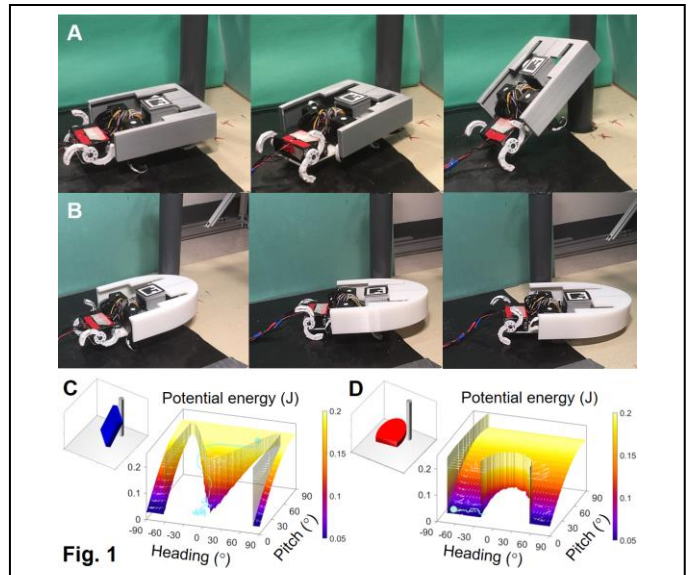
Many small terrestrial animals move through cluttered terrain, where their body and appendages constantly interact physically with the environment. Analogous to aerial and aquatic animals and vehicles with aerodynamic and hydrodynamic body shapes that facilitate locomotion in water and air, there may exist “terradyamic” shapes whose physical interaction with the terrain during locomotion can help animals and robots better traverse cluttered terrain. For shapes whose interaction with the terrain is undesired, understanding the physics can also help overcome such interaction.

## II. METHODS & RESULTS

The emerging field of terradynamics [1], [2], analogous to aero- and hydrodynamics of flying and swimming, has begun to advance understanding of the physics of terrestrial locomotion in complex terrain. For example, a recent study discovered that a “terradyamically streamlined”, ellipsoidal body shape helps insects and legged robots roll their body to traverse grass-like beam obstacles by reducing terrain resistance [2]. This is analogous to streamlined shapes that reduce drag in fluids.

Here, to discover and understand terradyamic shapes more broadly, we systematically compared how a cuboidal body shape, found in many legged robots, and a novel elliptical body shape affected how insects and a legged robot traversed large pillar obstacles. We discovered that the cuboidal body shape almost always attracted the animal ( $88 \pm 5\%$  probability) and the robot ( $100 \pm 0\%$  probability) towards the obstacle (Fig. 1A). Continued pushing against the obstacle resulted in the robot body pitching up and eventually flipping over (Fig. 1A). The animal almost always overcame this by active leg adjustments. By contrast, the elliptical body almost always repelled the animal ( $95 \pm 2\%$  probability) and the robot ( $100 \pm 0\%$  probability) away from the obstacle, facilitating traversal (Fig. 1B). In addition, these interactions are governed by locomotor shape but insensitive to the shape and orientation of the obstacle.

To gain insight into how body shape affects locomotor-terrain interaction and provide a means to predict how to use effective shape or overcome ineffective shape to traverse, we developed a novel locomotion energy landscape model. Our



model demonstrated that a cuboidal shape resulted in an attractive potential energy landscape and attractive torque towards and up against the obstacle (Fig. 1C), useful for initiating climbing and perching. By contrast, an elliptical shape resulted in a repulsive potential energy landscape and repulsive torque away from the obstacle (Fig. 1D), useful for traversal.

## III. BROADER IMPLICATIONS

We demonstrated how our results are broadly useful by three additional experiments. First, an elliptical body increased the probability by 13 times and the distance progressed by 200% for a sensorless legged robot to dynamically traverse a cluttered pillar obstacle field. Second, our locomotion energy landscape enabled the design of a novel gait for legged robots with a traditional cuboidal body to traverse by adjusting its leg motion to overcome attraction towards and pitching up against the obstacle. Finally, an elliptical body enabled a sensorless drone to traverse cluttered pillars, and a cuboidal body enabled it to perch onto pillars using attraction towards them.

By discovering new terradyamic shapes and principles to design and control legged robots to traverse cluttered terrain, our study is a major step towards establishing the new field of terradynamics of locomotion in complex terrain [1], [2].

## REFERENCES

- [1] C. Li, T. Zhang, and D. I. Goldman, “A terradynamics of legged locomotion on granular media,” *Science* (80-. ), vol. 339, no. 6126, 2013.
- [2] C. Li, A. O. Pullin, D. W. Haldane, H. K. Lam, R. S. Fearing, and R. J. Full, “Terradyamically streamlined shapes in animals and robots enhance traversability through densely cluttered terrain,” *Bioinspir. Biomim.*, vol. 10, no. 4, p. 46003, 2015.