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Author(s)	Othayoth, Ratan; Li, Chen
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Cockroaches open wings and flail legs to self-right on the ground

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

1 Introduction

Ground self-righting is critical for animals' survival [1]. Robots must also self-right to ensure continuous operation in complex 3-D terrain [2]. When flipped over, animals and robots in principle can change their body posture arbitrarily to self-right.

However, a recent study [1] of discoid cockroaches (*Blaberus discoidalis*, $N = 7$ animals, $n = 61$ trials) discovered that during ground self-righting, although the animal's body motion are stochastic, they are not arbitrary, but stereotyped. When upside-down, the animal opens and pushes its wings against the ground in its attempt to self-right (Figure 1A). However, as the animal pitches forward it is trapped in a metastable mode due to a triangular base of support (Figure 1B). It can then self-right by either continuing to pitch and somersaulting, or by rolling sideways. However, self-righting is strenuous and the animal often succeeds only after multiple failed wing opening attempts during which the body repeatedly pitched up and down, showing stereotypy. In successful attempts the animal almost always self-rights by rolling sideways, which is also stereotyped in both body pitch and roll changes. These stereotyped changes are obvious in animal's body roll, body pitch, and center of mass height trajectories during both failed and successful self-righting attempts (Figure 1C). Curiously, the animal often flails its legs vigorously during its self-righting attempts (Figure 1B).

Here, we study the physical principles of how wing opening and leg flailing together facilitate strenuous self-righting on ground and test the hypothesis that the stereotyped self-righting body motions reflect physical constraint from the environment.

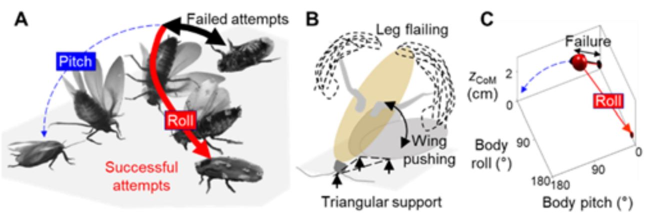

Figure 1: Cockroach self-righting (A) Snapshots of animal's successful self-righting by pitch (blue) and roll (red) modes after multiple, failed attempts. (B) Animal stuck in metastable mode. (C) Stereotyped body motion trajectories during failed and successful self-righting attempts, as shown in body pitch, body roll, and center of mass height space. Ellipsoids show the standard deviation along the three axes.

2 Robotic physical modeling

Because the animal's wing, leg, and body motion are highly variable and difficult to track, quantify, and control systematically, we developed and used a robotic physical model (Figure 2A) to understand physical principles and test hypotheses. Our robot had a head, two wings, and a laterally swinging leg. By deliberately controlling wing and leg actuation, our robot achieved qualitatively similar strenuous behavior as the animal. When the robot opened and pushed its wings against the ground, it first pitched forward, but was trapped in a metastable mode (Figure 2A), from which it eventually escaped after multiple failed attempts (Figure 2D, black). Successful self-righting always occurred by rolling sideways (Figure 2D, red).

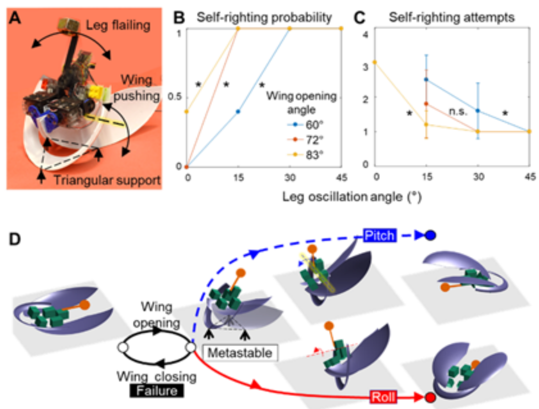

Figure 2: Robotic physical modelling (A) Robot, shown in metastable mode. (B) Robot's self-righting probability and (C) total number of self-righting attempts at different wing opening angles, as a function of leg oscillation angle. (D) Snapshots illustrating the robot's metastable (black), pitch (blue), and roll (red) modes during self-righting.

When used together, wings and legs facilitated the robot's self-righting. As both wing opening and leg oscillation amplitude increased, self-righting probability increased (Figure 2B) and approached one and the number of attempts required for self-righting decreased (Figure 2C). Similar to the animal, the robot's body pitch, body roll, and center of mass height were stereotyped during both successful and failed self-righting attempts, but with trial-to-trial variations (Figures 2D, 3A).

3 Potential energy landscape modeling

Because self-righting involves change in body orientation

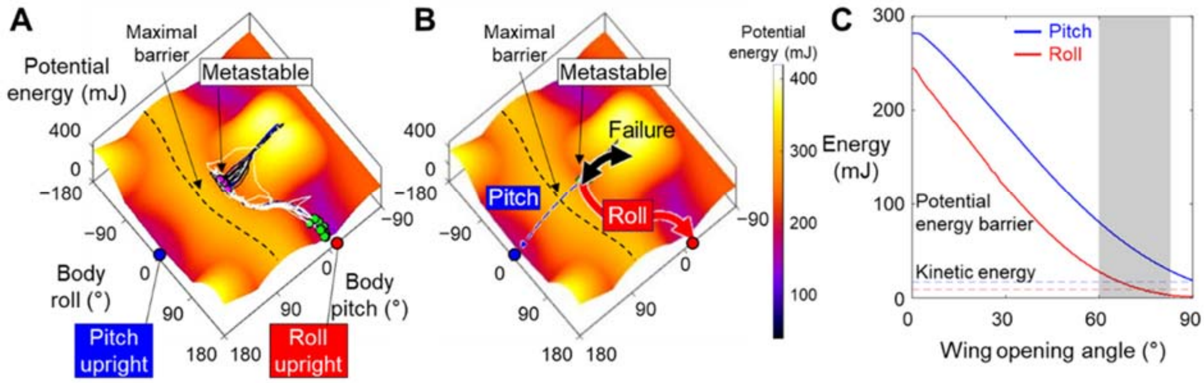

Figure 3: Potential energy landscape of self-righting. (A, B) Robot's stochastic yet stereotyped state trajectories for failed (black curve and pink dots) and successful (white curve with green dots) self-righting attempts on the potential energy landscape over its body pitch-roll space. (B) Possible locomotor modes and transitions and illustrative trajectories. (C) Potential energy barrier to self-right by pitch (blue) and roll (red) modes as a function of wing opening angle. Blue and red dashed lines show pitch and roll kinetic energy fluctuation, respectively. Gray band shows range of wing openings tested.

(Figures 1A, 2D) to overcome a potential energy, we modelled the robot's self-righting as a barrier-crossing transition on a potential energy landscape [3] over its body pitch-roll space (Figure 3). The gravitational potential energy *E* of the robot is

$$E = mgz_{\mathrm{com}} \tag{1}$$

where, m is the robot mass, g is the gravitational acceleration, z_{com} is the center of mass height of the robot. We constrained the robot body's lowest point to be always in contract with the ground. We used the measured body roll and pitch of the robot to observe how its state behaved on the energy landscape (Figure 3A).

Initially, when flipped over and horizontal, the robot's system state was trapped in an upside-down energy basin on the landscape. As the robot opened its wings its body shape changed. On the landscape, this was reflected as the upside-down basin evolving into a metastable basin (Figure 3A), which strongly attracted and trapped the system state over the multiple failed wings opening attempts (Figure 3A, black curves). When an attempt eventually succeeded and the robot rolled sideways, system state escaped from metastable basin by overcoming an energy barrier and was attracted towards a roll-upright basin (Figure 3A, white curves).

We then measured the potential energy barriers for escaping metastable basin via roll and pitch modes and compared them to the robot's pitch and roll kinetic energy fluctuation (Figure 3C). As wings opened more, the escape barrier decreased for both roll and pitch modes but was always higher for pitch mode. Without leg flailing, the pitch kinetic energy generated by wings pushing against the ground was insufficient to overcome the high barrier to escape by pitching. Similarly, without wing opening, the roll kinetic energy fluctuation from leg flailing was insufficient to overcome the low barrier for rolling (Figure 3C). However, when used together, wing opening further lowered the roll barrier and enabled the kinetic energy fluctuation from leg perturbation to probabilistically induce barrier-crossing and self-right.

4 Discussion

The strong attraction of the system state to landscape basins, which led to the emergence of stereotyped system state trajectories, demonstrated that stereotyped self-righting behavior is strongly constrained by physical interaction with the environment. Given this constraint, for both animal and robot, inherent and added randomness produces variation in wing opening and leg flailing, and as a result, the robot's motion. This variation leads to stochastic outcomes and is beneficial when locomotor behavior is separated into distinct modes as it can induce stochastic transition between modes.

Our landscape modeling revealed that propelling (wings) and perturbing (legs) appendages together facilitated self-righting on the ground. More broadly, the animal's self-righting also involves other complex body and appendage motions, such as abdomen flexion and twisting, passive wing deformation under load, occasional leg pushing against the ground. We expect that some or all of these motions can further increase rolling perturbation and reduce potential energy barrier and facilitate self-righting.

5 Acknowledgements

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