Multi-legged Locomotion Incorporating Slip

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Abstract

For humans and large animals, slipping while running can be catastrophic and there are many well documented slippage avoidance strategies. However, while there is no obvious critical survival reason for small animals to avoid slipping, computational models of multi-legged locomotion still assume non-slip conditions in stance. We have found non-slip constraints to severely impede the performance of some of our hexapod robots, and therefore set out to test if these non-slip assumptions apply to the animals that inspired their designs. We investigated slipping in *Blaberus discoidalis* cockroaches (N=7, 2.66±0.8 g (mean,sd)) running at 15-77cm/s (51±10 cm/s (mean,sd)). We found that front, mid, and hind legs slipped 21.%, 18.%, 20.% of their total travel distance in the lab frame. We separated video frames into quintiles sorted by turn rate and used Mann-Whitney U tests to compare median turn rate versus slipping distance. We found that median slippage distance was not significantly different in the turning rate bins. Our results suggest that slipping is a routine part of cockroach locomotion, and is independent of turning speeds.

Keywords: slip, locomotion, cockroach

1. Introduction

The most diverse extant (living) group in the animal kingdom is arthropods, encompassing nearly 80% of the known species in the Animalia kingdom [1]. Within arthropods, insects represent a large sub-group. Living in all corners of the globe, insects thrive in a variety of terrains. Rapidly coordinating their leg movement to navigate through complex and unstable terrain, insects' mobility offers potential solutions to unsolved problems in biorobotics and has inspired many studies in both biological and engineering research [2, 3, 4]. In particular, from its locomotor behavior to its biomechanics, the *Blaberus discoidalis* cockroach has been meticulously studied [5, 6, 7]. Thus, the *Blaberus discoidalis* cockroach provides a well-studied natural animal model and a starting point for investigating how to achieve stable locomotion in biologically inspired robotics.

Effective locomotion is an essential component of animal survival and fitness. Animals that maneuver through their environment are subject to numerous environmental demands and stresses. Whether fleeing from a predator or running on a low friction surface, animals must overcome a variety of dynamical challenges to maintain stability. On low-friction or 'slippery' surfaces, animals must propel themselves forwards without the help of static friction to sustain balance. Within biology, slippage avoidance strategies have been well documented. Legged terrestrial animals like guinea fowl employ postural control strategies to avoid slippage [8]. Stick insects emulsify from their foot adhesive pads that prevent slipping on smooth surfaces [9]. Weaver ants have arrays of fine hairs on their legs with different attachments to a substrate to balance themselves while walking [10]. While slippage is

common across animals, in the engineering perspective slippage is a relatively unexplored phenomena.

Identifying the underlying mechanisms used to achieve stability under rapid leg locomotion is difficult due to the complex interplay between biomechanical dynamics and neural control. However, patterns of general behavior can be constructed by considering reduced order simplified models [11]. These models approximate gait, but make simplifications coming to friction. For simplicity, numerous papers in robotics literature assume a no-slip or no-slide surface or, in simulation, there always exists a stationary contact point with the surface [12, 13, 14]. This is perhaps due to the discontinuities of various models of friction.
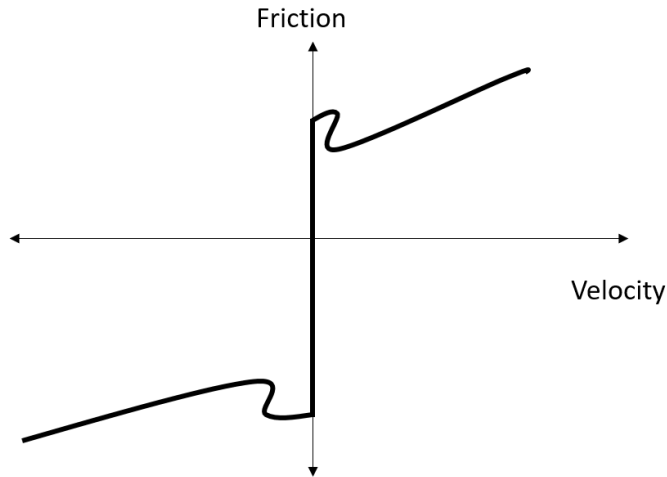

Figure 1: Generalized Stribeck curve of frictional force

Classical friction models often model friction as discontinuous, complicating kinematic models that attempt to incorporate the effects of friction. In the generalized Coulomb model of frictional force, there exists a discontinuity

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when attempting to break from static friction. To overcome static friction, a large enough force must be applied to free the contact from the surface. This is a piecewise continuous function, where after breaking from static friction, the frictional force is of constant magnitude. Given the combined Coulomb and Viscous friction model, after breaking from static friction, frictional force becomes proportional to velocity. These models are well known and simple, but fail to account for friction at low velocity. In the Stribeck curve of frictional force, a frictional model that describes low velocity friction phenomena, slipping can occur anytime after the velocity becomes nonzero. However, as velocity increases there exists a nonlinearity that makes it difficult to maintain speed stability: at near zero velocities, the frictional force decreases as a function of velocity and at higher velocities friction increases as a function of velocity. As multiple legs are added to a robot, further nonlinearities must be considered.

In our frictional model, all locomotion happens in a friction-dominated kinematic regime, thereby allowing for some simplification by removing the considerations placed by static friction. We assume a linear frictional model for simulation and verify this model by running experimental trials on cockroaches and measuring their foot placements. If our linearized model consistently recreates footholds from our cockroach's physical foot placements from our animal experiments, we have a reasonable approximation for turning behavior in the gait planning space.

2. Materials and Methods

2.1. Animals

We performed experiments on adult male and female death-head cockroaches *Blaberus discoidalis* with a mass of 2.66±0.8 g (mean,sd., N=7) that were commercially available (Backyard Brains). Animals were kept at room temperature (22-24°C) and under a 12h:12h light:dark cycle. Cockroaches were housed in plastic containers with a supply of dog food and water. When cockroaches reached their final molt, cockroaches were chilled to clip their wings.

2.2. Experimental setting

We performed our experiments at room temperature (20-24°C) and under high light conditions. Cockroaches ran on a testing arena enclosure that was constructed by foam core and melting adhesive. Light was illuminated onto a testing arena by two custom light sources with a panel of infrared LEDs (100W operational power). We recorded trials by two high speed FasTec video cameras (FasTec Imaging USA, San Diego, CA, USA), separated into a main view (1088 × 932 × 250 fps) and side view (1280x1024x114fps). The trial videos were saved on disk frame by frame into .bmp files with HiSpec Control Software (FasTec Imaging USA, San Diego, CA, USA).

2.3. Experimental protocol

Before beginning each trial, we inspected cockroaches to see if tarsals (tips of the feet) were intact. We then induced cockroach movement by placing cockroaches under a plastic cup and then rapidly exposing them to light. Using a host computer, we manually triggered trials to end when
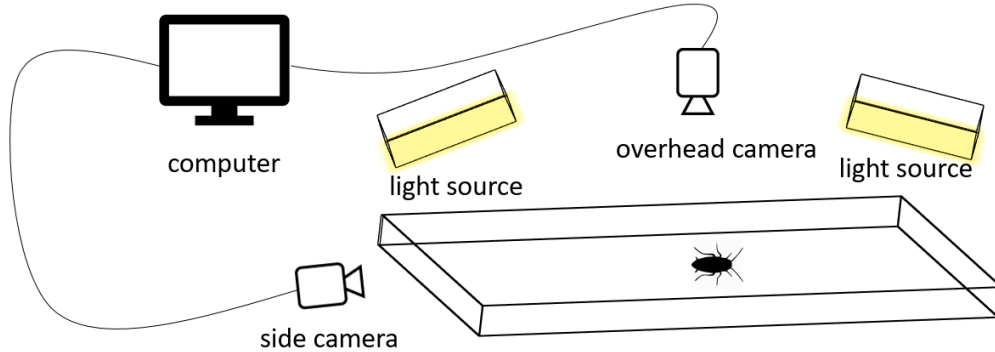
Figure 2: Experimental Setup

the cockroach moved out of frame of the overhead camera. Our selection criteria was for cockroaches to make 5 full strides within the frame of the main overhead camera and not contact the walls of the enclosure either with their body, feet, or antenna. Video trials were shorted to meet this criteria. Animals were used for multiple trials. While downloading the video on disk, cockroaches were covered by a plastic cup.

2.4. Data Analysis

Movements were tracked using MATLAB (Version 9.1, The MathWorks, Inc., Natick, MA, USA) using custom-written scripts (written by Dr. Shai Revzen, EECS, University of Michigan, Ann Arbor). The scripts tracked the bodies of the cockroaches and obtained the body position and orientation over time. These images were rotated to a registered position and orientation. We then tracked the positions of the animals' feet using an additional custom tool. This resultant data gave the center of mass and direction of heading of the cockroaches in the world frame and the foot tip trajectory in the body
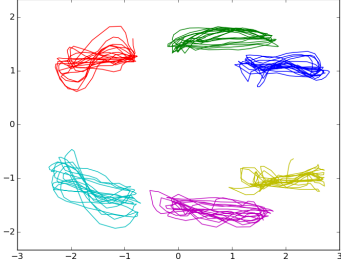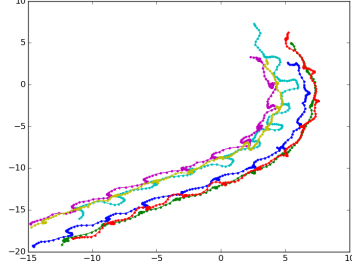
Figure 3: Foot locations in body frame

Figure 4: Foot locations in world frame

frame. Given we know the body frame with respect to world frame, we apply transformation to see the foot locations with respect to the world frame.

$$\begin{bmatrix} x \\ y \end{bmatrix}_{world} = \begin{bmatrix} cos(\Theta) & -sin(\Theta) \\ sin(\Theta) & cos(\Theta) \end{bmatrix} \cdot \begin{bmatrix} x \\ y \end{bmatrix}_{body} + \begin{bmatrix} x \\ y \end{bmatrix}_{COM} \tag{1}$$

We then calculated when legs 'slip'. Since cockroaches do not move their legs backwards in air, slipping only occurs when legs are on the ground and have a negative velocity. Finding these frames and computing their distance compared to the total travel distance, we found that front, mid, and hind legs slipped 21.%, 18.%, 20.% of their total travel distance in the lab frame. We used bootstrapping to achieve our confidence intervals. We then investigated the influence that slipping has on turning speeds. We found cockroaches ran at 15-77cm/s (51±10 cm/s (mean,sd)). We separated video frames into quintiles sorted by turn rate and used Mann-Whitney U tests to compare median turn rate versus slipping distance. We found that median slippage distance was not significantly different in the turning rate bins.

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2.5. Theoretical Model

This model was created largely in part by Professor Shai Revzen with Ph.D. student Brian Bittner. In this paper, we assume a linear relationship between changes in the systems shape and changes in its position

$$\xi = A(r)\dot{r} \tag{2}$$

where r is the cockroaches' shape, $\dot{r}$ is the shape velocity, and ξ is the body velocity of the cockroach. $A(r)$ is a mapping with nonlinear dependence on (r) that maps shape velocities to body velocities. Recent work has determined a way to estimate the mechanical connection, $A(r)$, locally about gaits for friction-dominated regimes [15]. Thus, we believe we can evaluate its performance by locally estimating its connection matrix $A(r)$. We created a quzi-static mode, lumped element model. The parameters we fit are the stiffness of the 3 pairs of legs. Our current model can successfully predict cockroach turning direction, but the turning radius is imprecise.

3. Future Work

Most legged locomotion occurs while animals are contacting the ground with multiple legs at a time, posing difficulties for modeling due to uncertainty about inter-leg force distribution and foot slipping outcomes. We present such a model, but are still in our validation stage from using data from running *Blaberus discoidalis* cockroaches. Currently, we need further work on our theoretical model to improve the predicted turning radius.

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