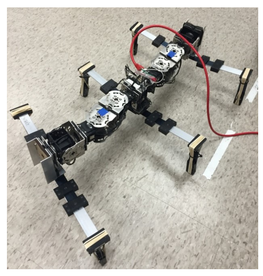
Slip Matters in Hexapedal Steering

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Introduction



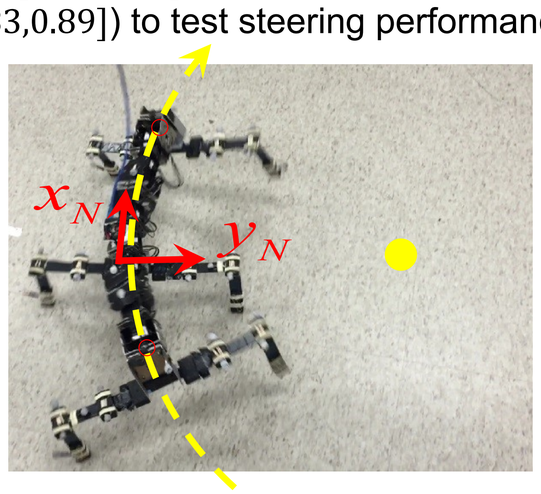
Commonly, models of legged locomotion assume a non-slip contact with substrate. In our research into hexapedal "steering" (gaits that allow heading change while moving forward), we found foot slipping to be crucial for understanding these gaits in our robot. The robot even shows better steering performance with more slip.

In our preliminary analysis of cockroach running, we see that cockroaches do slip while running and feet slip an even longer distance while steering, quite similar to the robot steering observations. We are developing a multi-legged locomotion model that accommodates slipping to be used in planning and design for our robots, and could potentially be applied to animals as well.

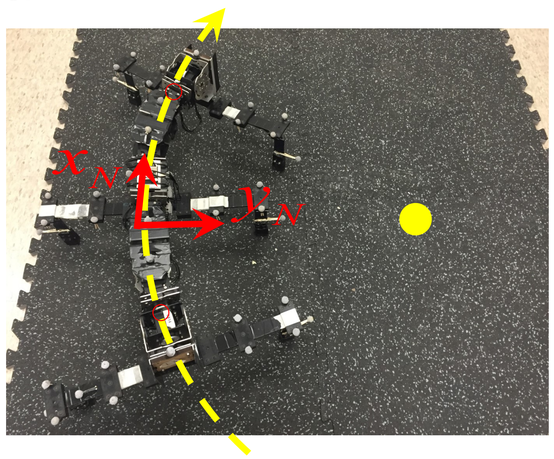
Robot Steering

1. Steering on surfaces with different friction

We ran our hexapedal robot on a low friction rigid surface(linoleum floor, $\mu_l \in [0.33,0.34]$) and a high friction compliant surface(C9 fitness mat, $\mu_h \in [0.83,0.89]$) to test steering performance.



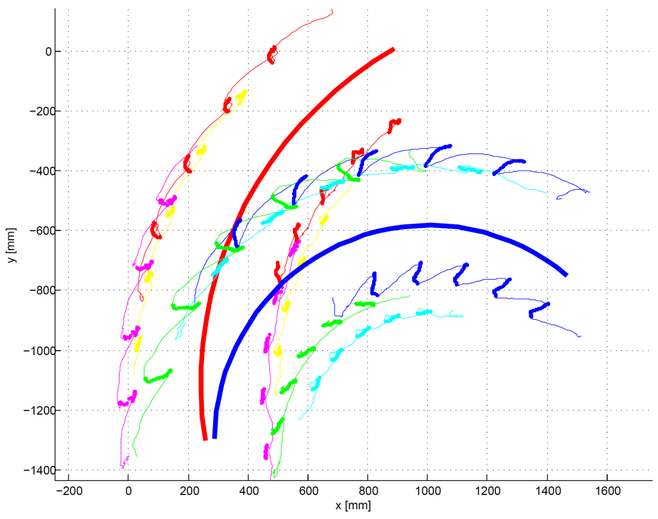
Low friction surface



High friction surface

2. Steering performance compare

We recorded 3 trials each on each surface. These parameters were chosen based on previous work seeking optimal turning rates. One trial of foot trajectories is shown in following figure.



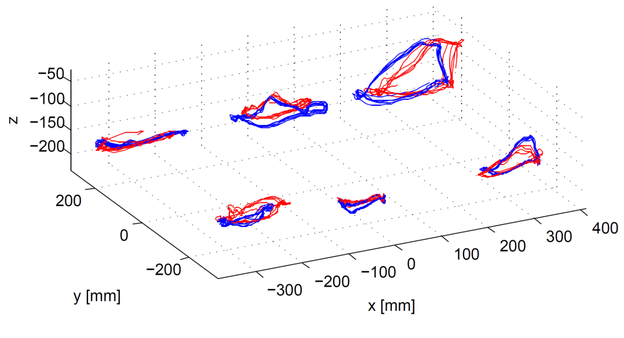
Foot trajectories in world frame

Steering on low friction (cold colors) and high friction (warm colors). Foot motions shown with slipping highlighted (thicker lines). We used least squares to fit circular arcs (thick red, blue) to find turn radii: 121cm in low friction and 70cm in high friction.

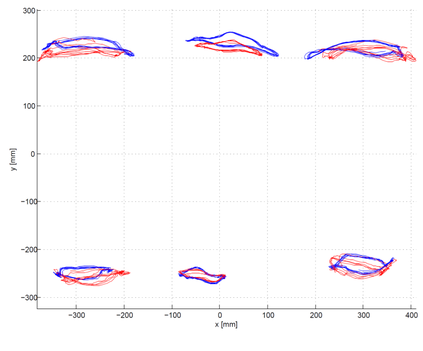
Turning radii nearly halve and non-dimensional turning rates (deg/cycle) grow by 50% as the distance feet slip is doubled. Thus, it can be concluded that low friction surface makes it easier to steer our robot with the gait adopted.

	Low friction	High friction
Slip[mm±1]	70,71,74	41,39,42
Turning Radius[cm±1]	78,70,68	130,126,121
Turning Rate[º/cycle±1]	14,15,15	10,9,10

Slipping amount and steering performance



Foot trajectories in body frame 3D



Foot trajectories in body frame 2D projection

Foot trajectories in body frame on low (blue) and high (red) friction surfaces are shown in above figures. Despite the large change of robot motion in world frame, foot trajectories in the body frame hardly changed with substrate, which indicates the robot adopted the same cycle of postures on different surfaces.

3. A simple model of steering

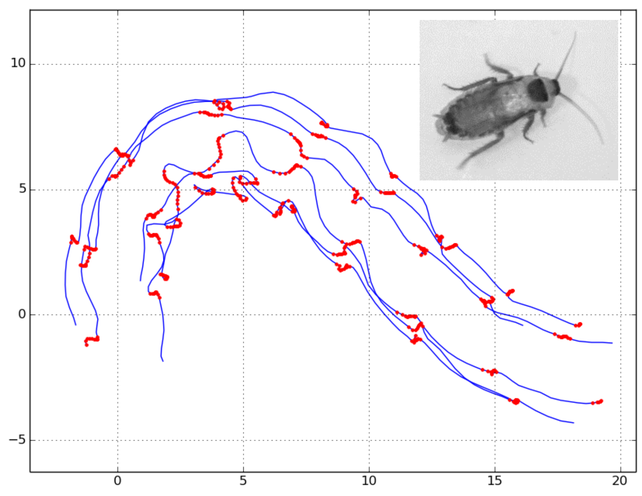
A simple model is carried out to verify the steering performance given the knowledge of sipping amount. In this model, a gait cycle is divided into two steps based on which tripod is supporting, the left tripod step and the right tripod step. Within each step, the effective step strokes are calculated by subtracting the slip distance from body frame step stokes. Then differential steering assumption is applied to calculate the turning angle during that step.

		Low friction	High friction
Model results	Turning Radius[cm±1]	64,75,76	96,92,100
	Turning Rate[º/cycle±1]	16,14,14	11,12,11
Experiment results	Turning Radius[cm±1]	78,70,68	130,126,121
	Turning Rate[º/cycle±1]	14,15,15	10,9,10

Model results compared to experiment results

Cockroach Steering

We have found non-slip constraints 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±0.8g (mean±sd)) running at 15-77cm/s (51±10 cm/s (mean±sd)).

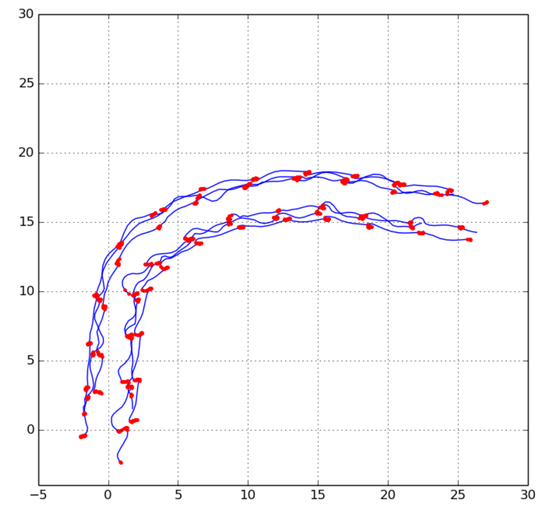


Foot trajectories in world frame

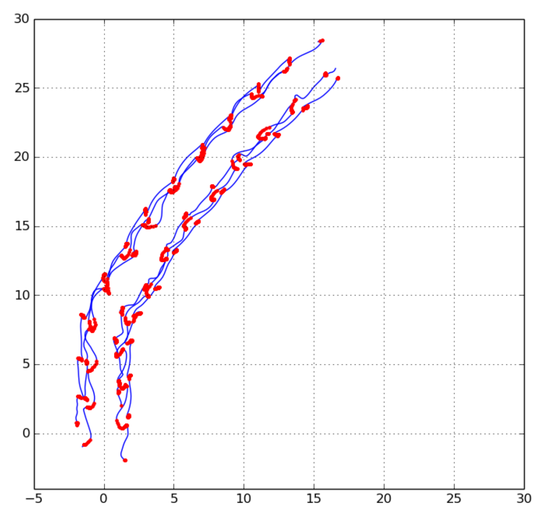
One trial of cockroach steering. Foot slipping is highlighted by red thicker lines. The ratio of slip distance during steering vs straight forward is 1.2. During steering, the inner leg slips 28% more than outer leg.

We found that front, mid, and hind legs slipped 21%, 18%, 20% of their total travel distance in the lab frame. During steering, the inner legs slip more than outer legs. Our results suggest that slipping is a routine part of cockroach locomotion.

Applying the model that we built for our robots to cockroach data, the results are like figures below. It takes leg trajectory in body frame as inputs and calculates slipping distance, then generates leg and COM trajectories in world frame. This simulation can predict turning directions correctly, while the turning radii prediction still needs better parameter fitting for cockroach.



Experiment result



Simulation result

Conclusion

From the above experiment and simulation results, we conclude that better understanding of slipping is essential for realistic modeling of multilegged locomotion of both robots and animals.