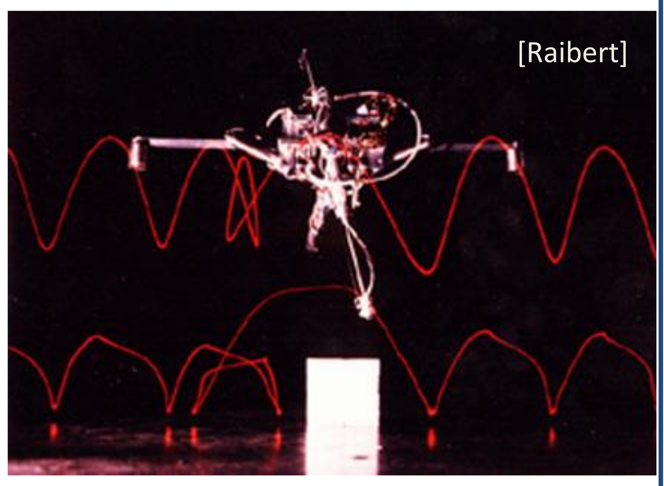
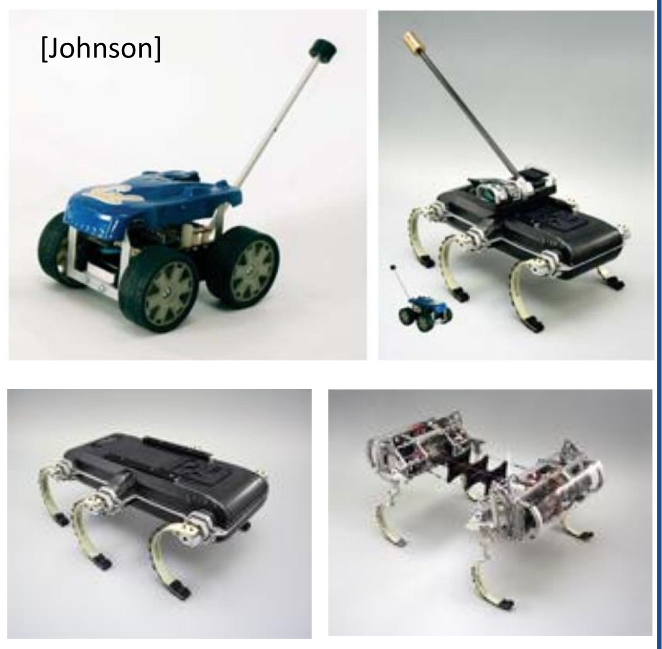
Planar Hopping with a Leg and a Tail

Avik De Aaron M. Johnson Daniel E. Koditschek
Electrical and Systems Engineering, University of Pennsylvania

Inspiration from previous robots

We aim for
- dynamic behaviors; high specific power
- more appendages (but not more actuators)
- robust, compositional control [1]
- morphology promoting energy transfer from battery to body





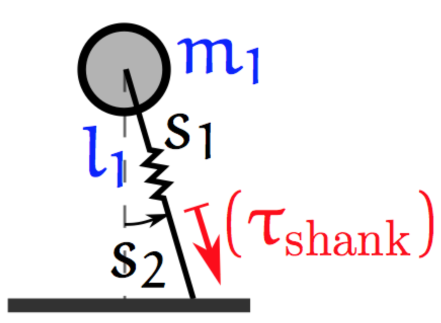
Inspiration from Biology

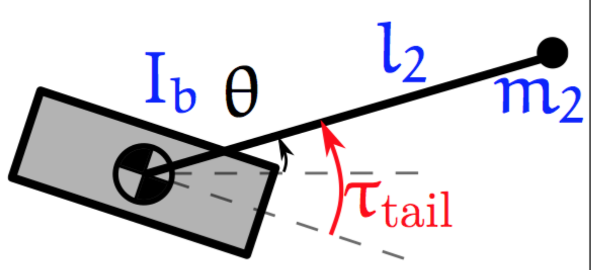
Tails are used for various purposes:
- Inertial reorientation [3]
- Turning
- Counter-act leg inertia in swing phase
- Static balance
- Quasistatic balance

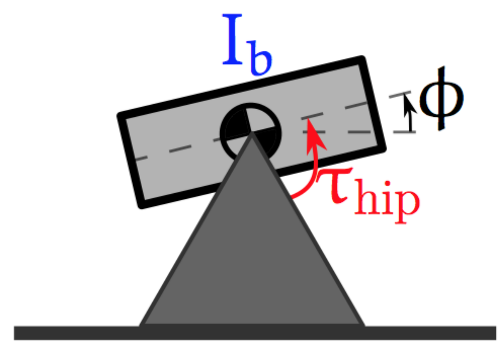
Can we use a tail as the primary energizer?

Control as a parallel composition of templates

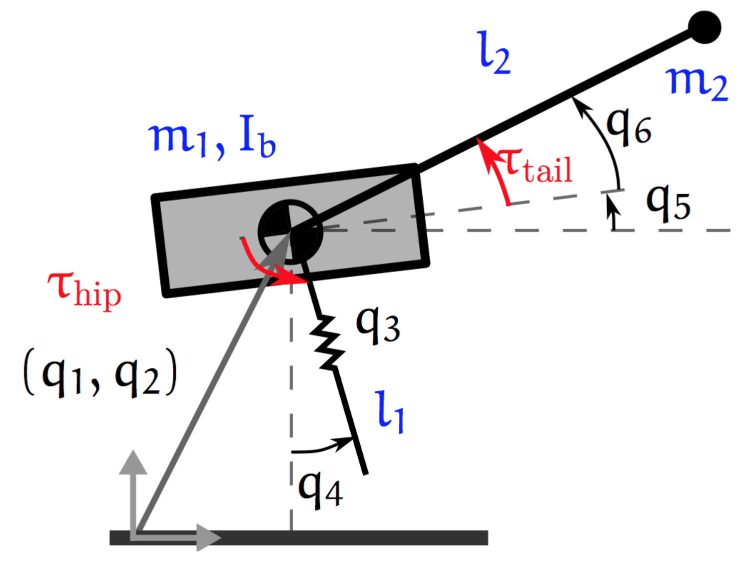
	Templates			
	Vertical hopping (VH)	Fore-aft (FA)	Shape	Pitch
Mode				
Flight		Toe placement	Tail torque	
Stance	Tail "wag"			Hip torque

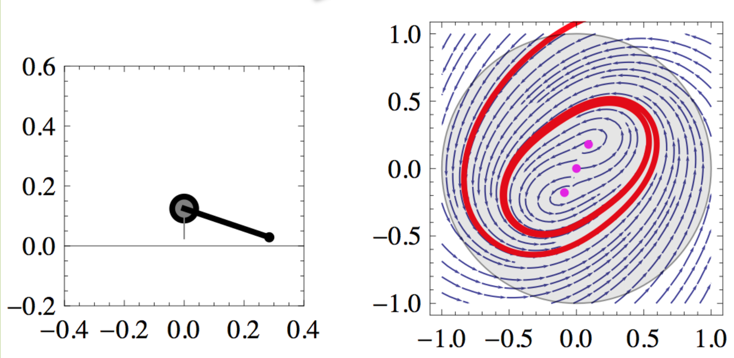






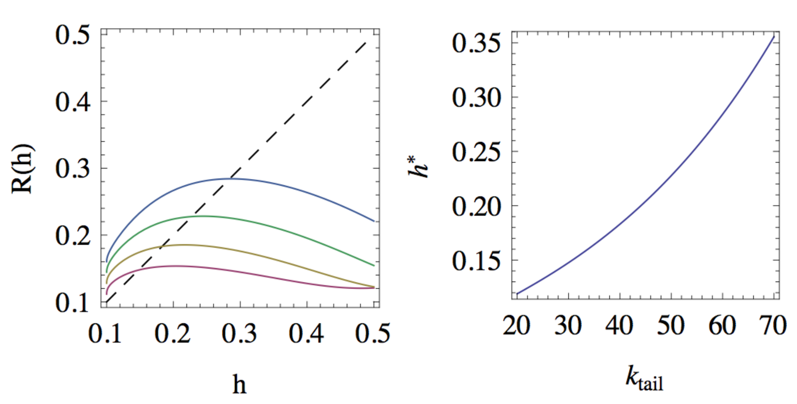
=

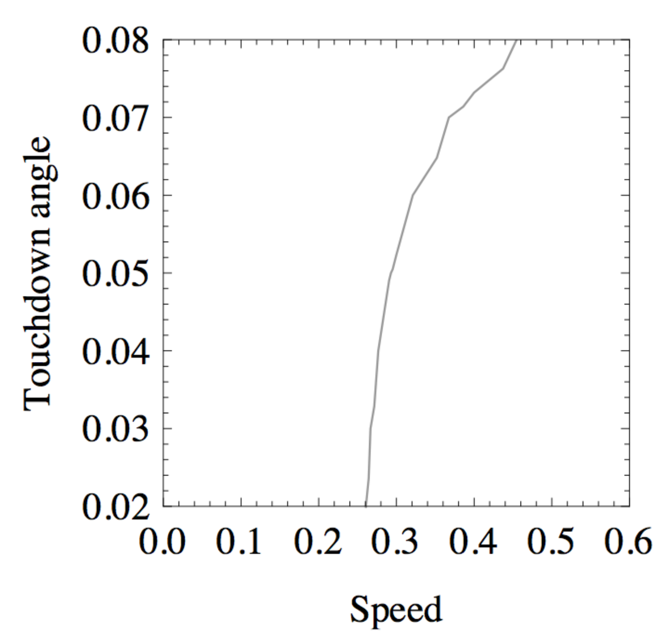




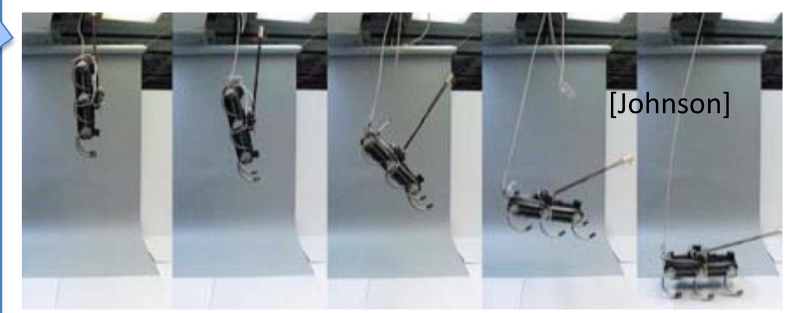
Simulation return map shows that the tail-energization is stable and can control hopping height for a range of tail gains.

Model for tail-energized 1-DOF vertical hopping; limit cycle and analytically-found trapping region (as in [2]).





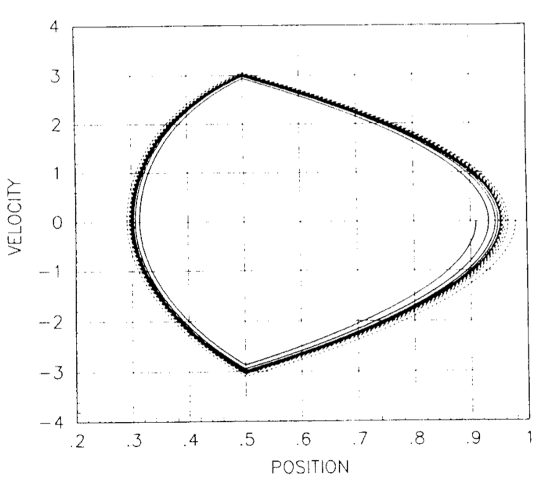
The fore-aft "acceleration" through stance shows the same monotonicity leveraged in [1]. (Simulation data)



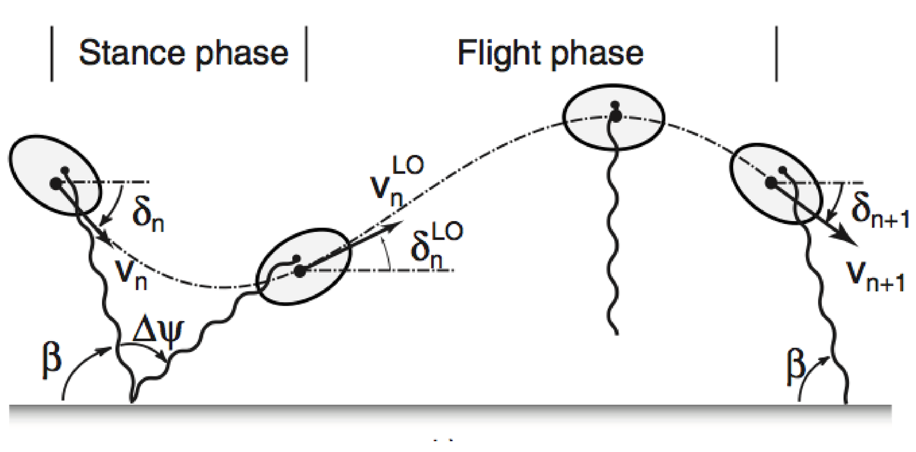
We borrow the idea of inertial reorientation in freefall from [3] and implement a simple PD servo with the tail torque that is available in flight.

Intriguing theoretical questions

- Subsystems analyzed in isolation in the past, but there is no analytical result guaranteeing success of parallel composition



Vertical hopping [2]

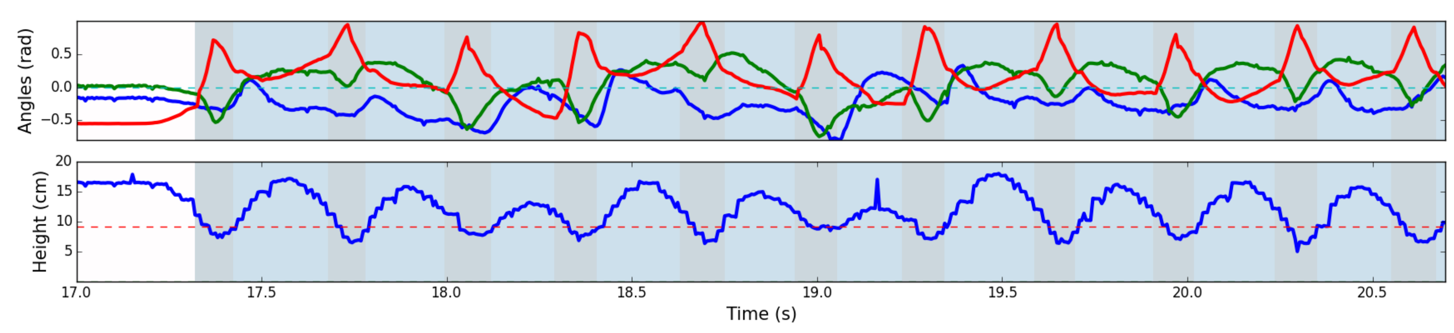


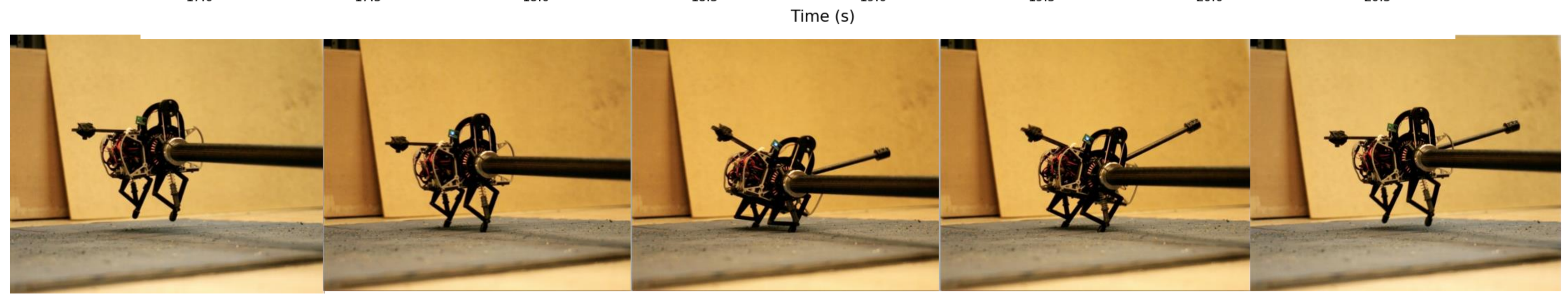
Passive fore-aft SLIP stability [4]

Under what conditions does parallel composition of these decoupled controllers work?

Empirical demonstration on physical platform

- Preliminary prototype on a planarizing boom
- 2 Kg platform, 180 W/Kg (peak output power)
- Implemented experiments with varying degrees of coupling
- Plots below are for the fully coupled system (4-DOF)





[1] M. Raibert, *Legged Robots that Balance*. Artificial Intelligence, MIT Press, 1986.
[2] D. E. Koditschek and M. Buehler, "Analysis of a simplified hopping robot," *The International Journal of Robotics Research*, vol. 10, pp. 587–605, Dec. 1991.
[3] A. M. Johnson, E. Chang-Siu, T. Libby, M. Tomizuka, R. J. Full, and D. E. Koditschek, "Tail assisted dynamic self righting," in *Proceedings of the Intl. Conf. on Climbing and Walking Robots*, 2012.
[4] R. M. Ghigliazza, R. Altendorfer, P. Holmes, and D. Koditschek, "A simply stabilized running model," SIAM Journal on Applied Dynamical Systems, vol. 2, no. 2, pp. 187–218, 2003.