Roll and height control for legged locomotion on the water surface

[1]Nitish Thatte [1]Mahdi Khoramshahi [2]Auke Ijspeert [1]Metin Sitti

[1]Carnegie Mellon University [2]École Polytechnique Fédérale de Lausanne

Introduction

Motivation

- The Basilisk Lizard can sustain highly dynamic legged locomotion on a range of surfaces from hard-ground to water [1]
- This level of multiterrain locomotion facility is unseen in robotics
- We wish to develop an amphibious legged robotic system
- Gain insight into mobility on other yielding surfaces, such as granular media and mud

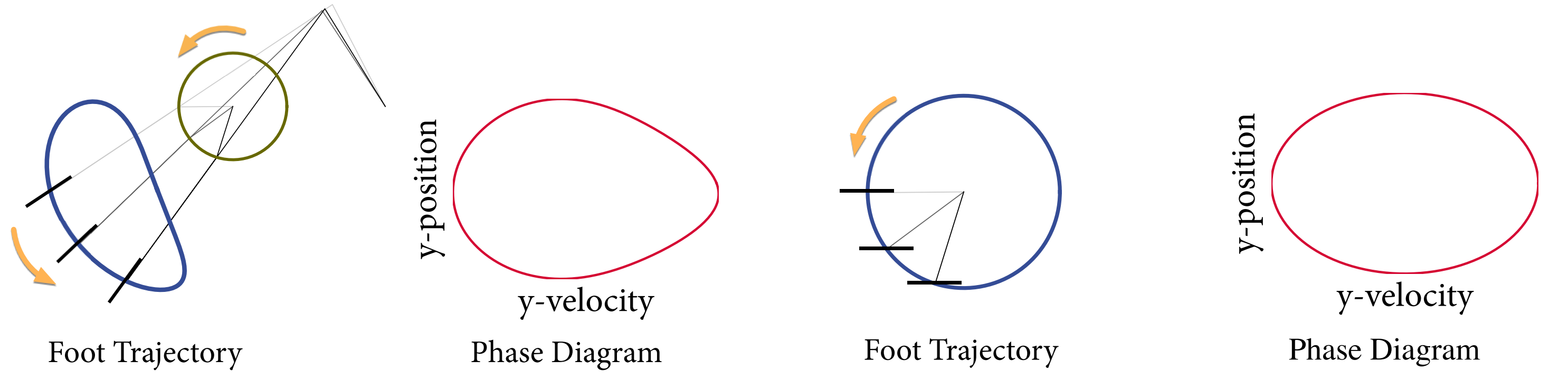
Previous Work and Problem

- Prototype water running robot generates sufficient lift forces
- Unstable in roll and pitch
- Undesired pitching motion was remedied by adding a tail [2]
- No proposed method for controlling roll or height

Objective

- Design a controller to regulate roll and height
- Develop a tractable model of the system to improve controller effectiveness
- Controller must simultaneously maintain a trot gait to minimize torques on the body

System Modeling



(a) Robot foot locus and phase portrait (b) Simplified foot locus and phase portrait

Figure 1: Real and simplified leg trajectories (blue) and phase portraits (red).

Leg Model

- Only considers time-averaged vertical forces generated in one cycle of a simplified trajectory
- Assumes velocity of legs $\gg$ velocity of body oscillations
- Allows for different foot velocties during the downwards and upwards phases of the trajectory
- We integrate the following force equation [3] over the simplified trajectory

$$F(t) = -C_D^* \left[\frac{1}{2} S\rho \dot{y}_f(t)|\dot{y}_f(t)| + S\rho g y_f(t)\right] \tag{1}$$

C_D^* drag coefficient, S area of foot, ρ water density, y_f position of foot, g acceleration of gravity

Robot Model

We linearize the result of integrating equation 1 and write the height and roll dynamics of the robot in the form

$$M\ddot{\vec{y}} = A\vec{y} + G + B\vec{\omega} \tag{2}$$

$\vec{y} = [y, \theta]^T =$ height and roll
$\vec{\omega} = [\omega_l^-, \omega_l^+, \omega_r^-, \omega_r^+]^T =$ plunge and retract leg frequencies for left and right sides of robot

Controller Design

Central Pattern Generator (CPG)

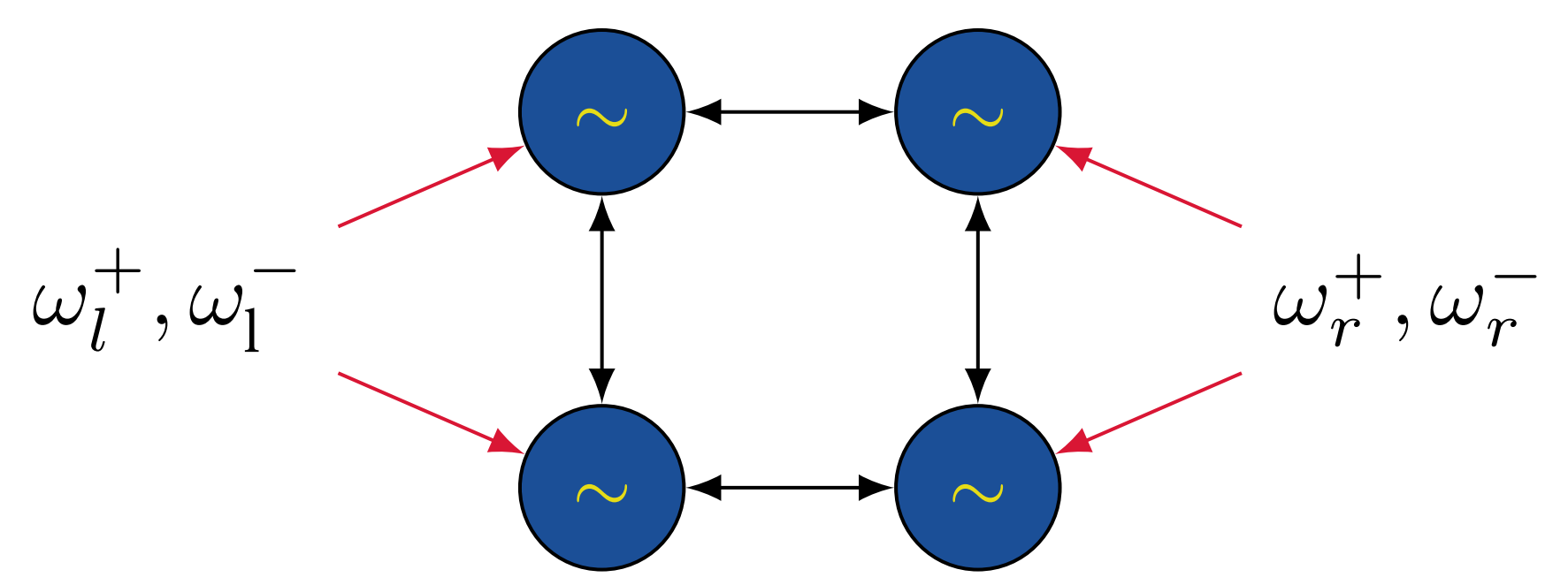


Figure 2: The CPG helps maintain a trot gait. Blue circles represent leg oscillators, black arrows represent phase couplings, and red arrows represent external forcing signals [4].

Inverse Dynamics

- We use an inverse dynamics approach to reject disturbances

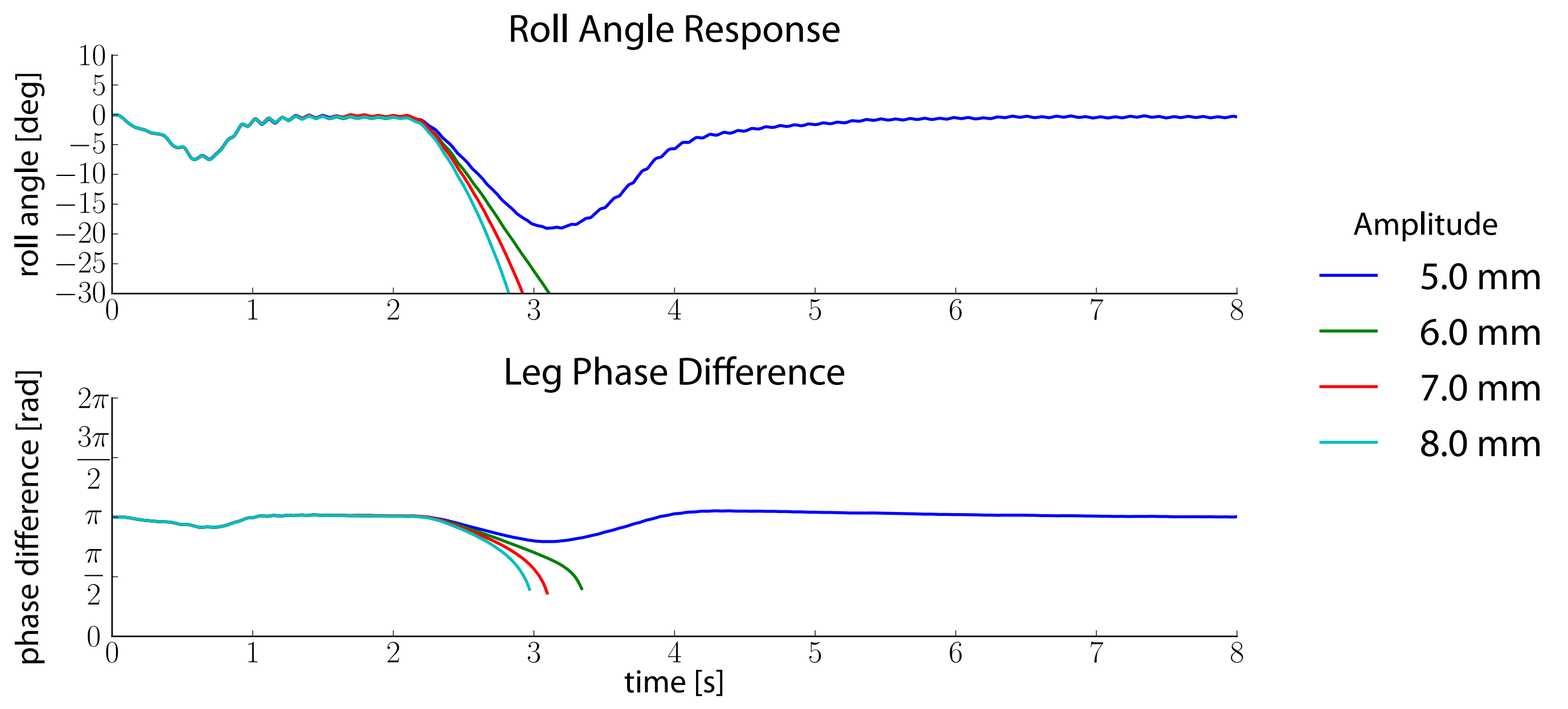
$$\vec{\omega} = B^\dagger \left[M\mathrm{PID}(\vec{y}_d - \vec{y}) - A\vec{y} - G\right] + (\mathbb{1} - B^\dagger B)\vec{\omega}_0 \tag{3}$$

- A heuristic is used to set $\vec{\omega}_0$ at each time step so that the nullspace is used to find control inputs that help the system converge to a trot gait

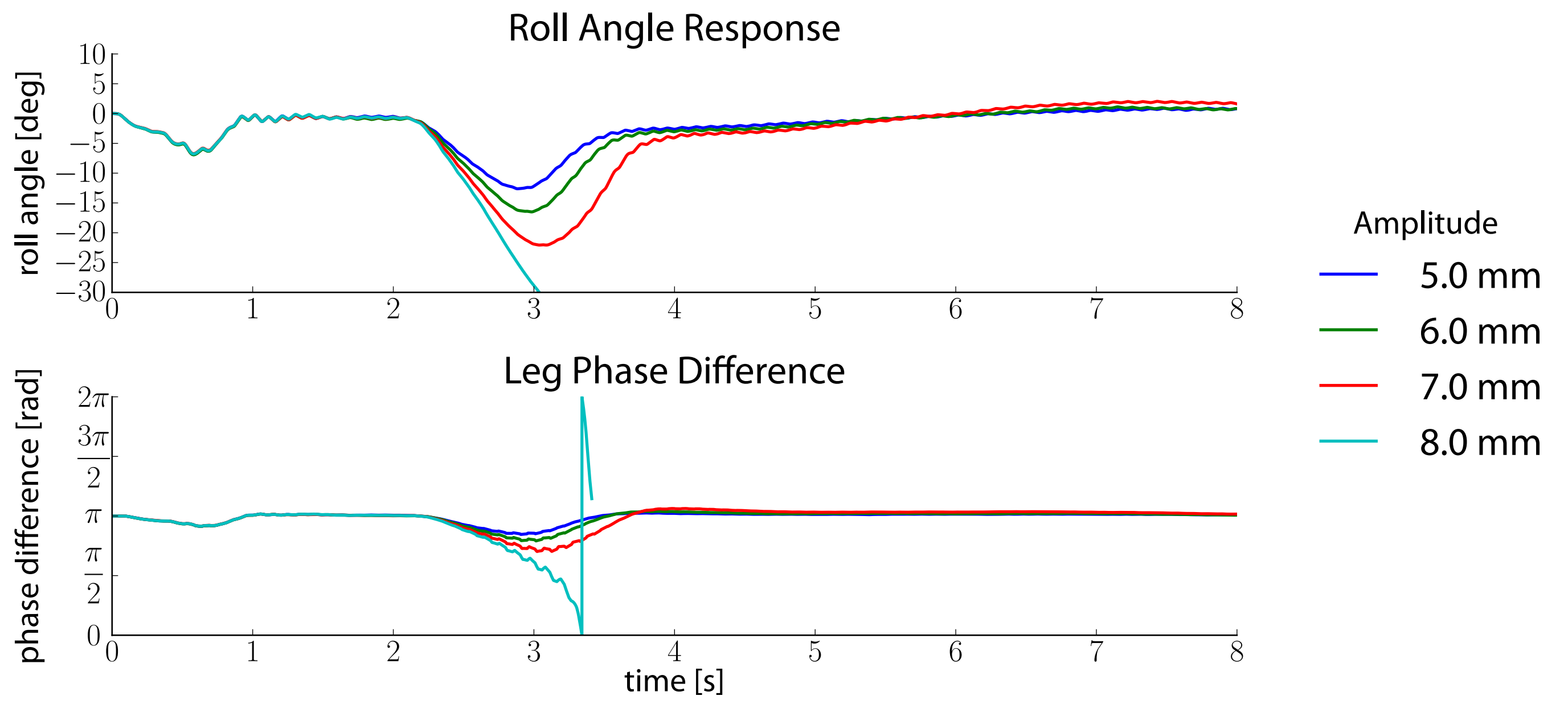
$$\vec{\omega}_0^{t+1} = \underbrace{\frac{1}{2}\begin{bmatrix} \omega_l^{-t} + \omega_l^{+t} \\ \omega_l^{-t} + \omega_l^{+t} \\ \omega_r^{-t} + \omega_r^{+t} \\ \omega_r^{-t} + \omega_r^{+t} \end{bmatrix}}_{\text{term 1}} + \underbrace{k \begin{bmatrix} \sin(\phi_r^t - \phi_l^t - \pi) \\ \sin(\phi_r^t - \phi_l^t - \pi) \\ \sin(\phi_l^t - \phi_r^t + \pi) \\ \sin(\phi_l^t - \phi_r^t + \pi) \end{bmatrix}}_{\text{term 2}} \tag{4}$$

- Term 1: leg speeds at the next timestep are close to those at the last time step
- Term 2: leg speeds that help bring the robot back to a trot gait

Simulation Results



(a) Result with $k = 0$ in term 2 of equation 4



(b) Result with $k = 10$ in term 2 of equation 4

Figure 3: Response of roll angle and leg phase difference when the robot's right side feet are exposed to half sine wave changes in water level of varying amplitude at $t = 2$ s.

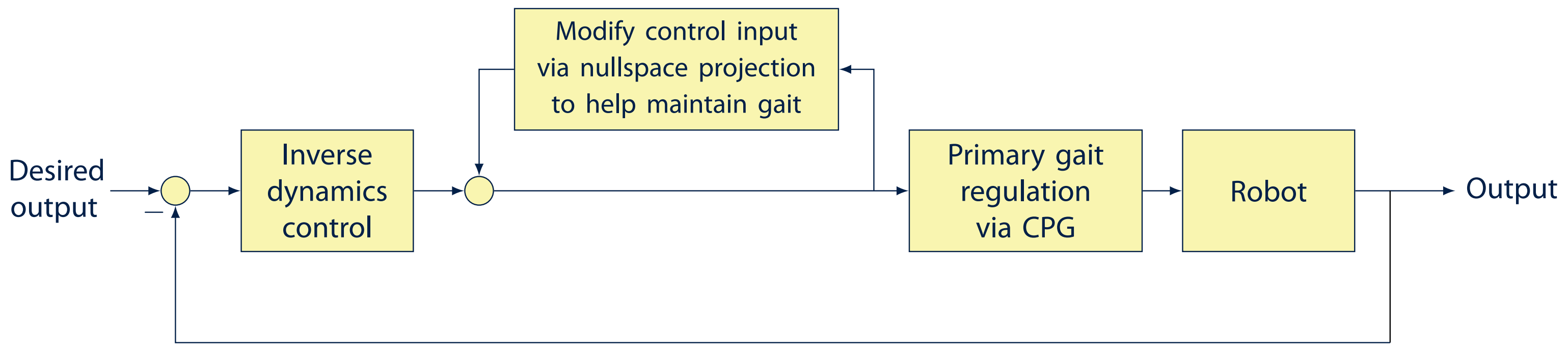


Figure 4: Schematic of control system

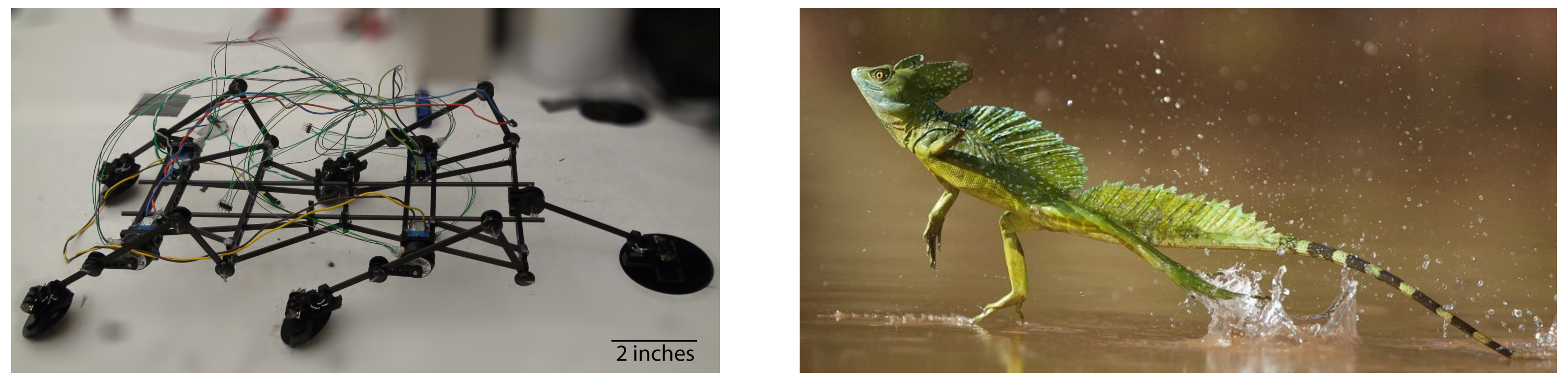
Conclusion

Findings

- Using only first term of heuristic (Figure 3a):
  - the robot easily leaves a trot gait when disturbed
  - departure from a trot gait reduces the stability of the system
  - the robot becomes unstable at higher amplitude disturbances
- Using both terms of the heuristic (Figure 3b):
  - $\sim$ 50% increase in maximum disturbance amplitude over a controller that only uses term 1
  - $\sim$ 100% increase in maximum disturbance amplitude over the open loop response
  - projecting $\vec{\omega}_0$ into nullspace forces the robot to utilize differing plunge and retract rates
  - this helps maintain a trot gait
  - system can still be forced to leave a trot gait if the disturbance is large enough

Future Work

- We should test other possible heuristics for guiding the system back to a trot gait
- Test the controller on a real robot to verify its robustness given:
  - motor dynamics
  - waves produced by feet
  - sensor noise



(a) Current Robot Hardware (b) Real Basilisk Lizard

Figure 5: The current robot design compared to a real Basilisk Lizard. A rotating boom setup will allow us to test the robot as it runs in a circle in a small pool.

Acknowledgement

This material is based upon work supported by the National Science Foundation Graduate Research Fellowship under Grant No. (0946825).

References

[1] J. Glasheen and T. McMahon, "A hydrodynamic model of locomotion in the basilisk lizard," *Nature*, vol. 380, no. 6572, pp. 340–341, 1996.

[2] H. S. Park, S. Floyd, and M. Sitti, "Roll and pitch motion analysis of a biologically inspired quadruped water runner robot," *The International Journal of Robotics Research*, vol. 29, no. 10, p. 1281, 2010.

[3] J. Glasheen and T. McMahon, "Vertical water entry of disks at low froude numbers," *Physics of Fluids*, vol. 8, p. 2078, 1996.

[4] A. Crespi and A. J. Ijspeert, "Amphibot ii: An amphibious snake robot that crawls and swims using a central pattern generator," in *Proceedings of the 9th international conference on climbing and walking robots (CLAWAR 2006)*, vol. 11, no. 7-8. Citeseer, 2006, pp. 19–27.

nitisht@andrew.cmu.edu, khoramsh@andrew.cmu.edu, auke.ijspeert@epfl.ch, sitti@cmu.edu