Learning to Walk – Optimal Gait Synthesis and Online Learning for Terrain-Aware Legged Locomotion

Aaron Ames (ME), Daniel Goldman (PHYS), Patricio Vela (ECE), Erik Verriest (ECE)
Georgia Institute of Technology

CPS GOAL: Advance CPS by more explicitly tying sensing, perception, and computing to the optimization and control of physical systems with variable and uncertain properties.

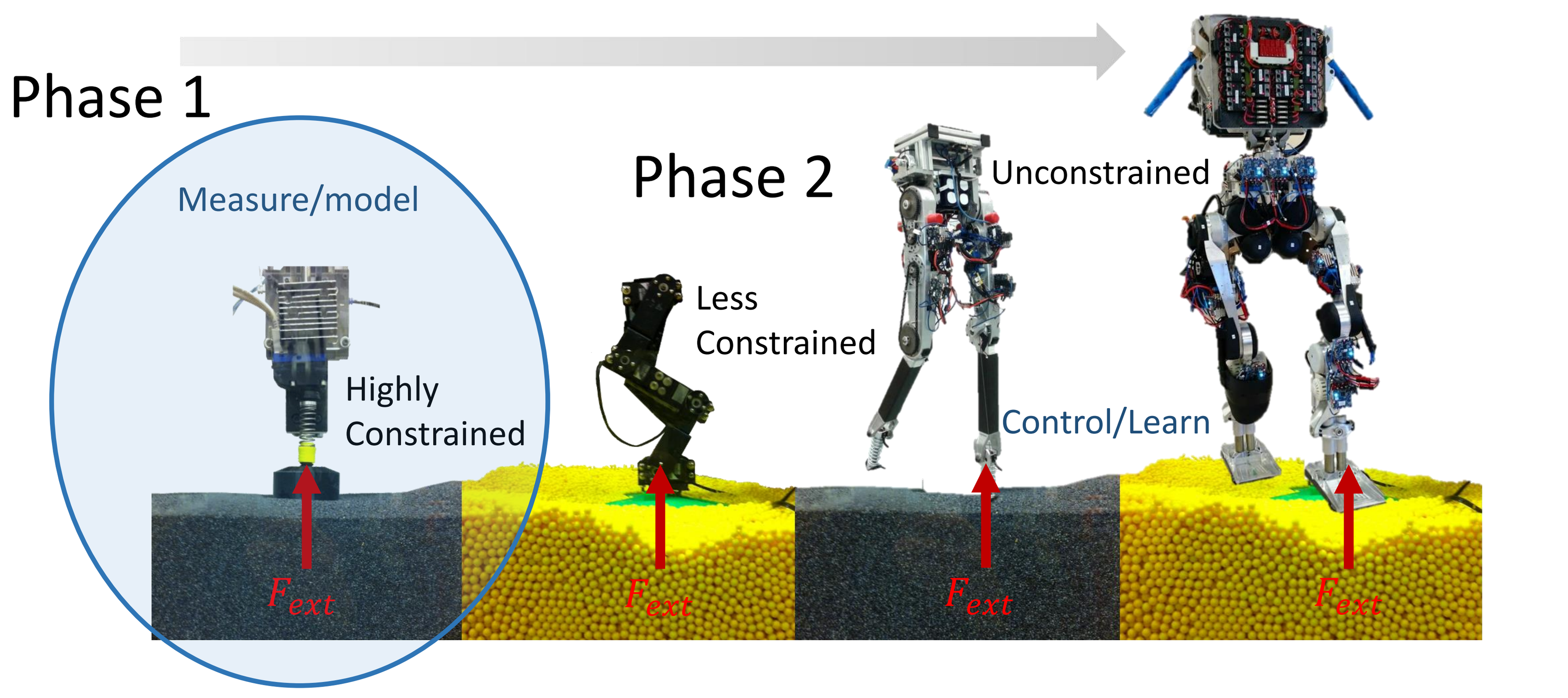
RESEARCH GOAL: Improve the perception and control of legged locomotion over granular media for the express purpose of achieving robust, adaptive, terrain-aware legged locomotion.

OBJECTIVES:
- Validated co-simulation platform for legged robot movement over granular media;
- Terrain-dependent, stabile gait generation and gait transition strategies via optimal control;
- Online, compute-constrained learning of granular interactions for adaptation and terrain classifications; and
- Validated contributions using experimental, granular-media testbeds
- Communicate value of STEM education.

Task2: Derive dynamics and gait controller,

$$\dot{x} = f\big(x(t), u(t)\big) + g_{ext}(x(t))\, F_{ext}$$

for multiple terrain types and for gait transitions.



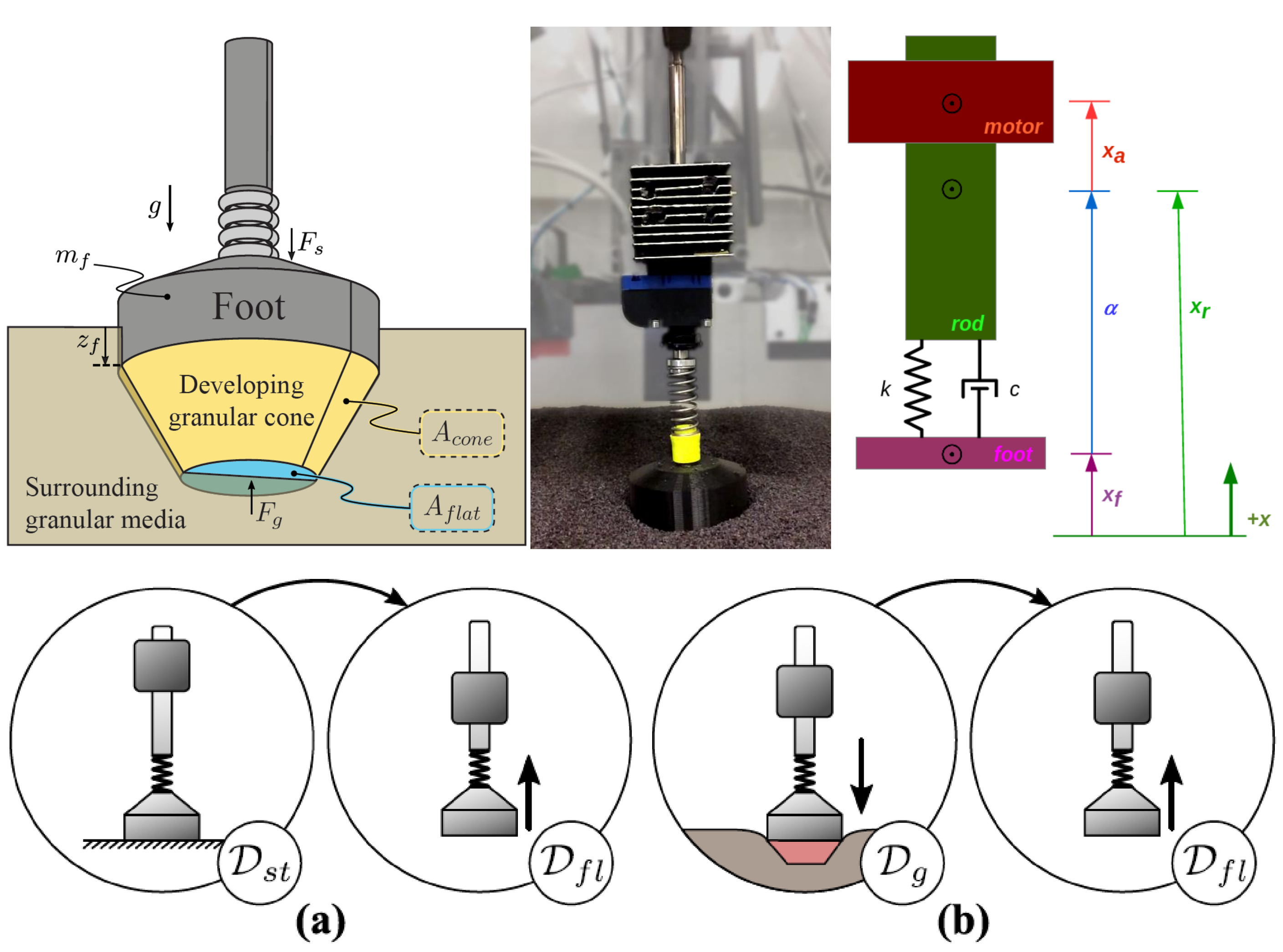
Task 1: Experimentally derive granular force laws for modeling F_{ext} through controlled experiments

Task 3: Learn terrain models (F_{ext}) online. Classify terrain based on experienced models.

Task 4: Integrate and validate research contributions.

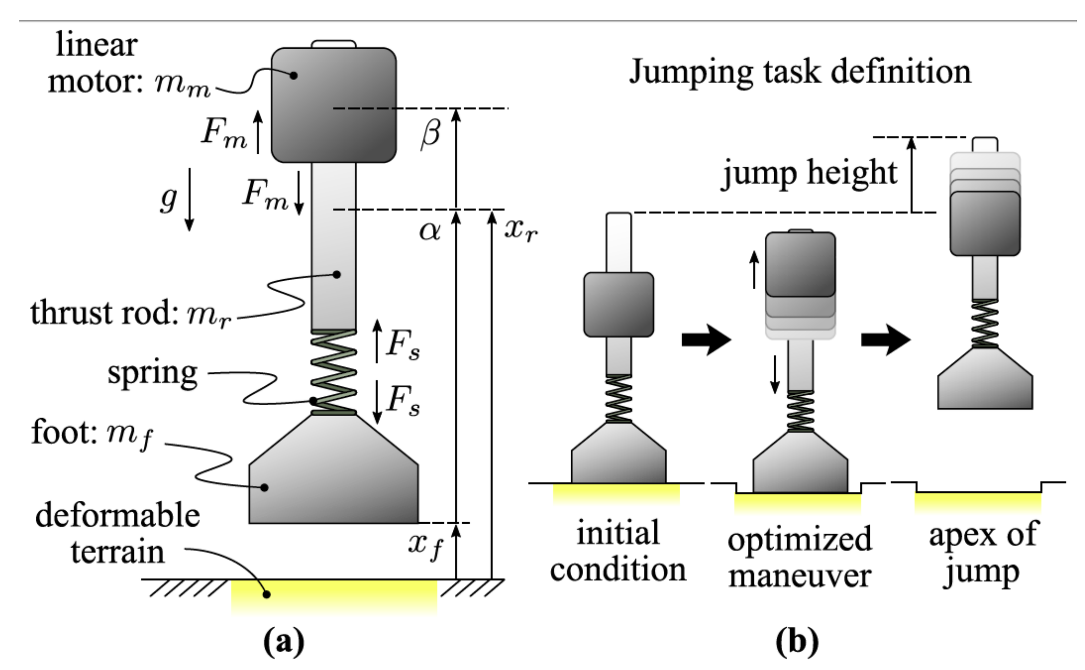
Modeling Hopping over Granular Media

MOTIVATION/ISSUES:
- Unlike solid ground, granular ground substrates do not provide a hard constraint.
- Reaction forces have variable properties.
- Yielding ground reduces control effectiveness.

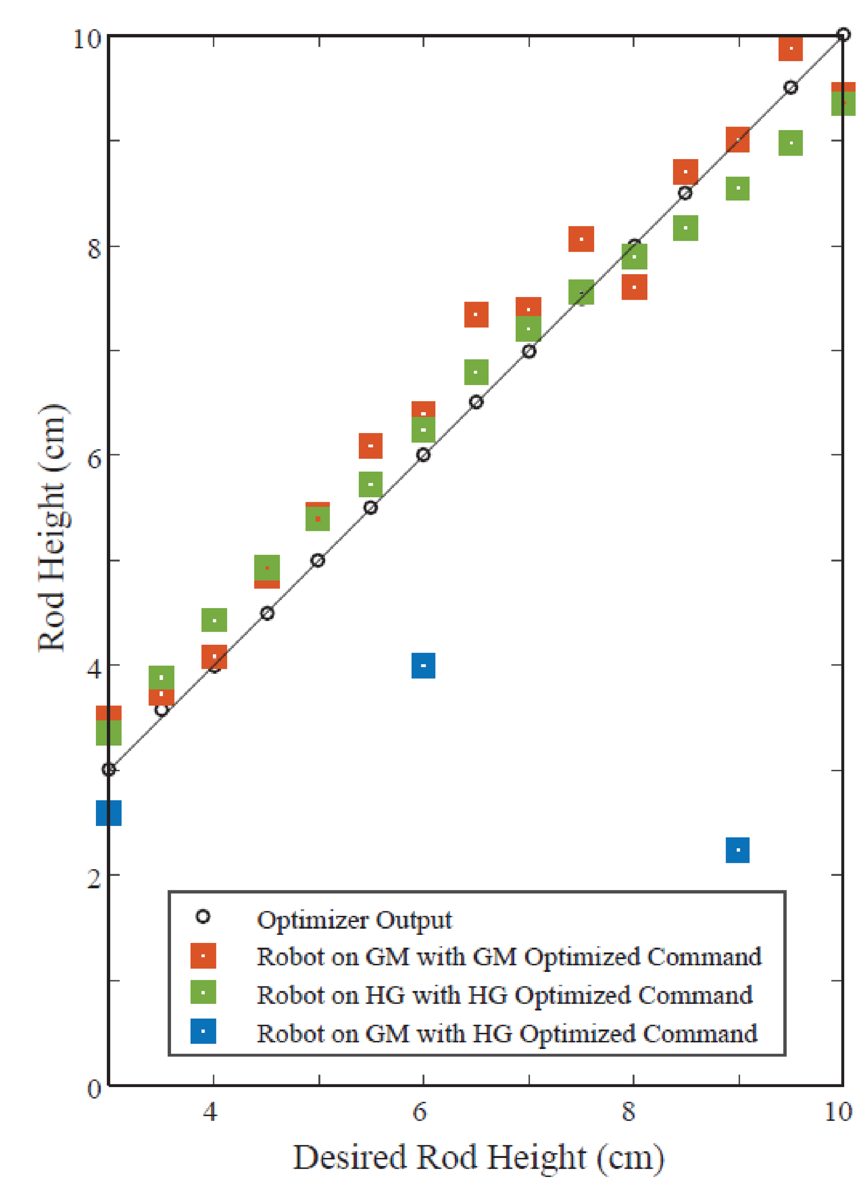


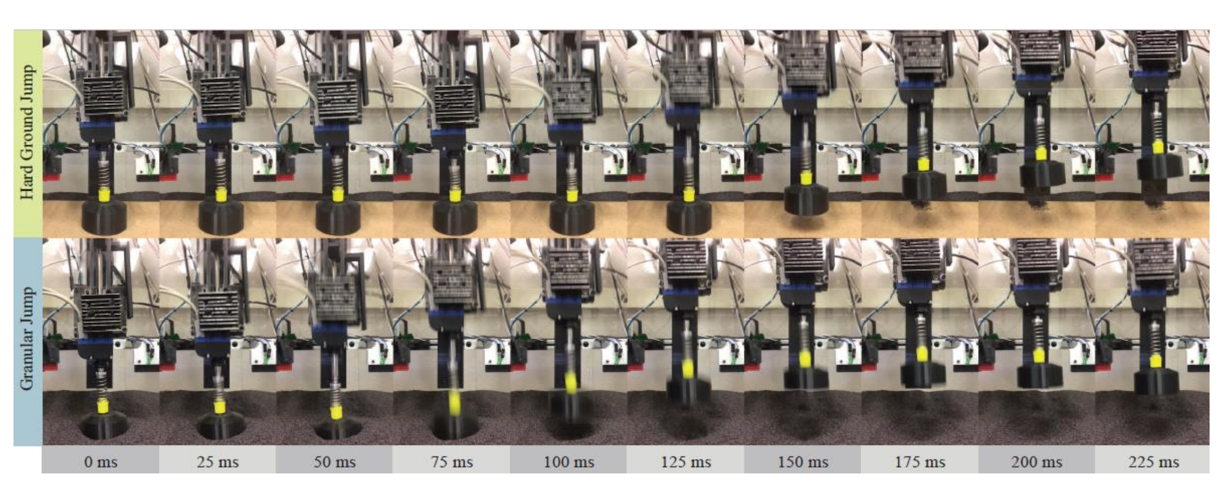
- Controlled experiments identify terrain interaction models
- Simulation created to replicate actual behavior

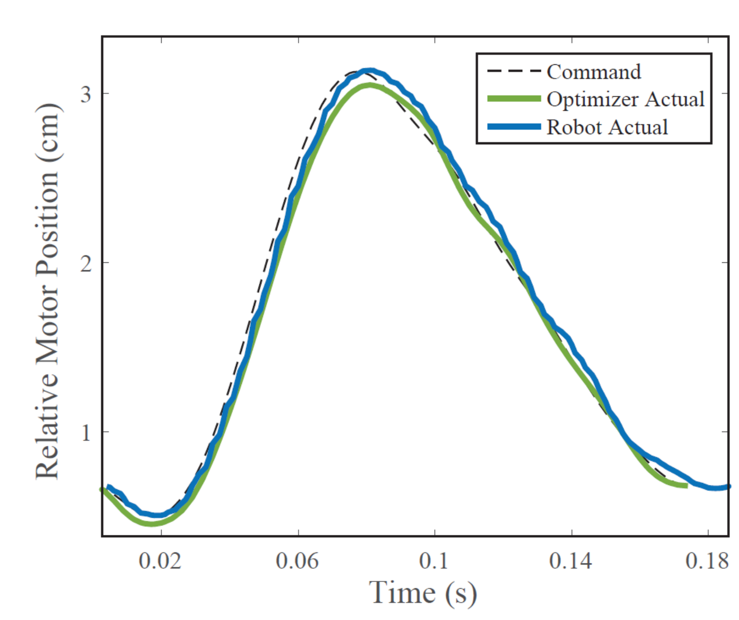
Optimal Control of Hopping Height over Granular Media



- Optimal control formulation created with terrain interaction model.
- Objective: Meet target hopping height while minimizing control effort.
- Optimal control outcomes matched between experiment and simulation.
- Able to meet same hopping height with terrain as with hard ground, when model included.



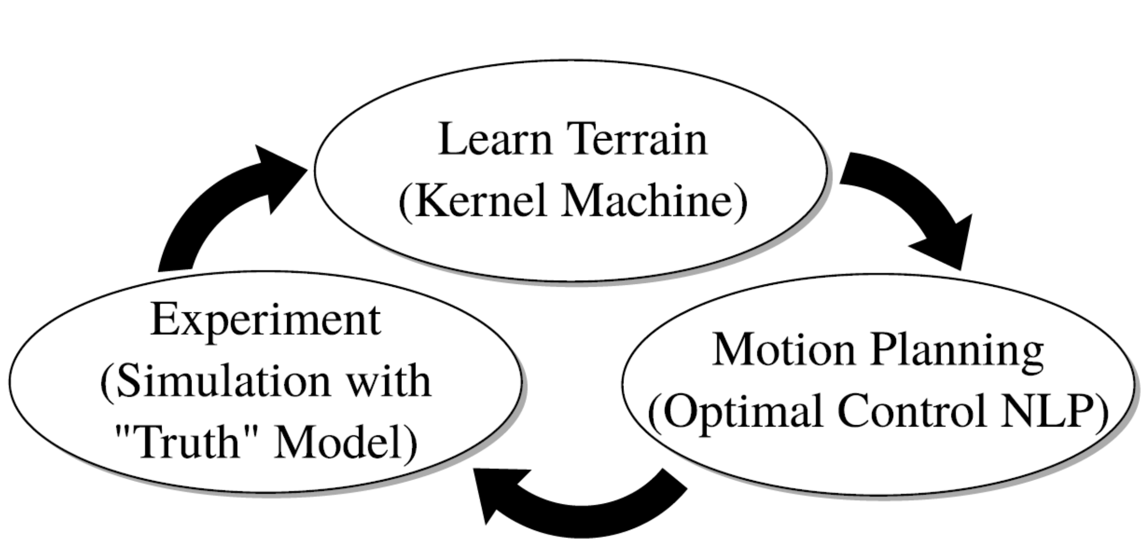


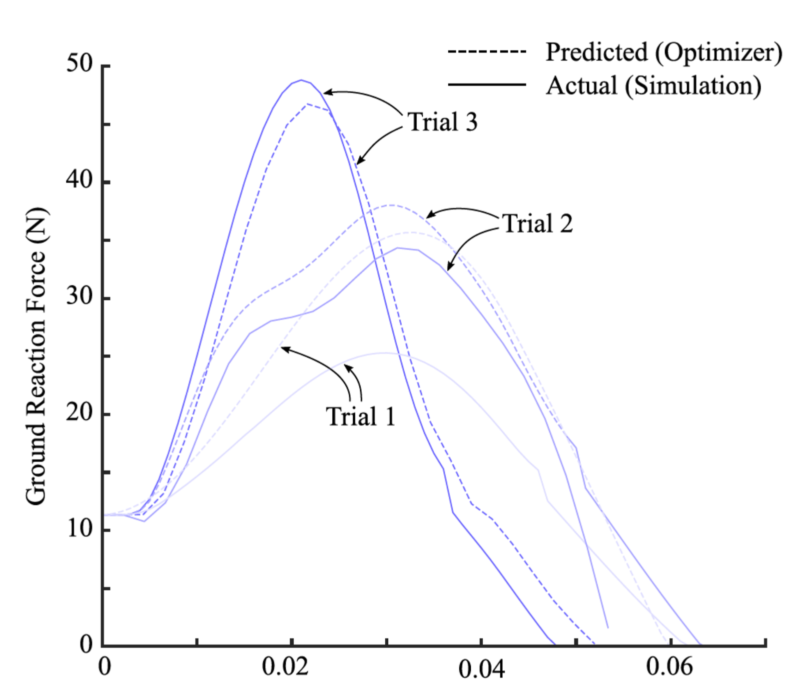


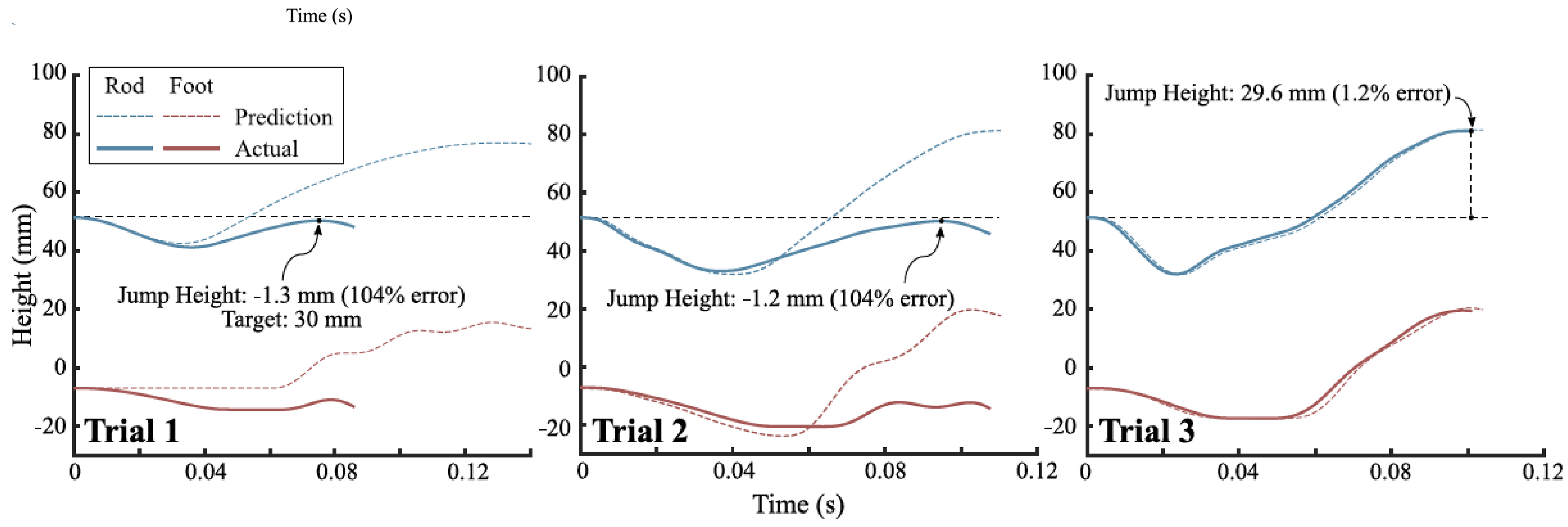
Online Learning of Terrain Forces

- Repeat optimal control experiment with no knowledge of terrain force model.
- Assume hard ground, then let measured outcomes inform revised model.
- Defect-based system of equations plus measured dynamics provide data to Guassian process model.
- Quickly learn terrain force model in simulations.

$$\dot{x} = f(x, u^*) + \hat{g}_{ext}(x)[\hat{F}_{ext} + \Delta_F(x)]$$







Ongoing Work and Next Steps

- Verifying outcome of overall process on actual hopper.
- Extend current results to planar, bipedal walking.
- Develop force defect equations for bipedal system.
- Achieve alignment between simulation and experiment for planar bipedal system.