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.

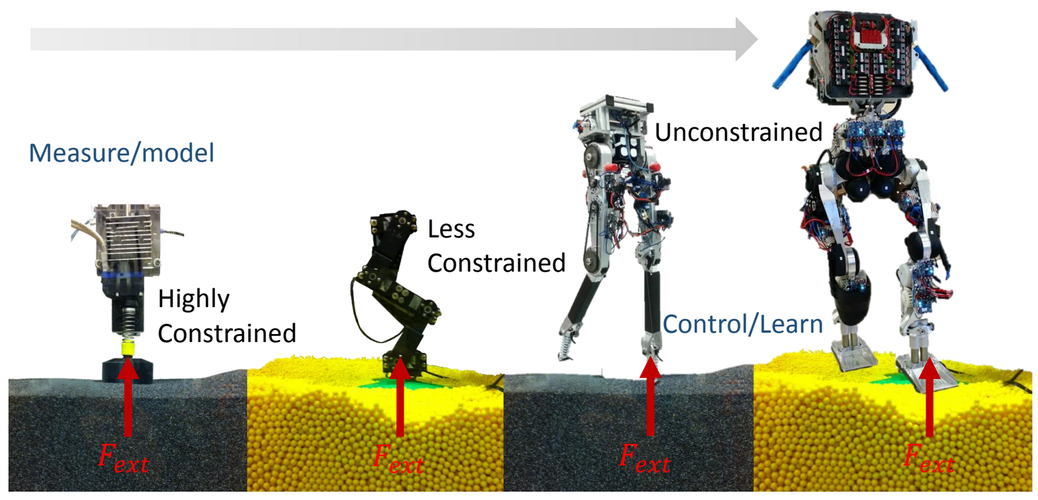
OBJECTIVES:

- 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.



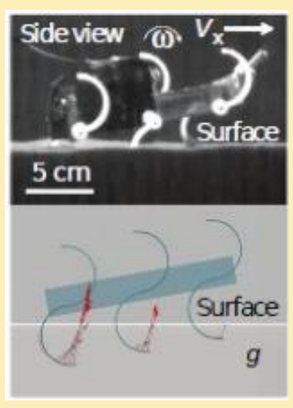
Task 1: Experimentally derive granular force laws for modeling F_{ext} through controlled experiments

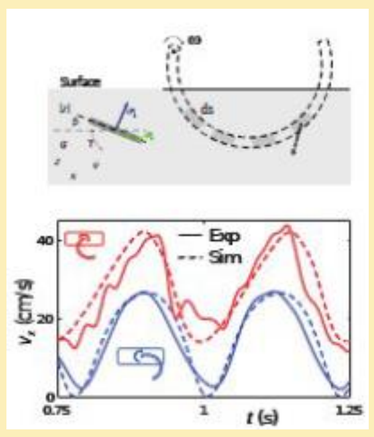
Task 3: Learn terrain models (F_{ext}) online. Classify terrain based on experienced models.

Task 4: Integrate and validate research contributions.

Modeling Locomotion over Granular Media

- Controlled experiments to identify interaction models
- Simulation tools at varying fidelity levels
- Diversified and highly controlled experimental testbeds



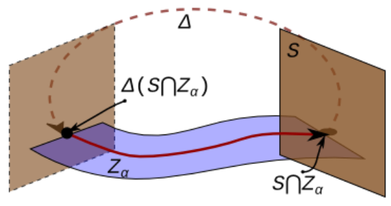


MOTIVATION/ISSUES:

- Unlike solid ground, granular ground substrates do not provide a hard constraint.
- Reaction forces have variable properties.
- Yielding ground destabilizes bipedal legged locomotion.

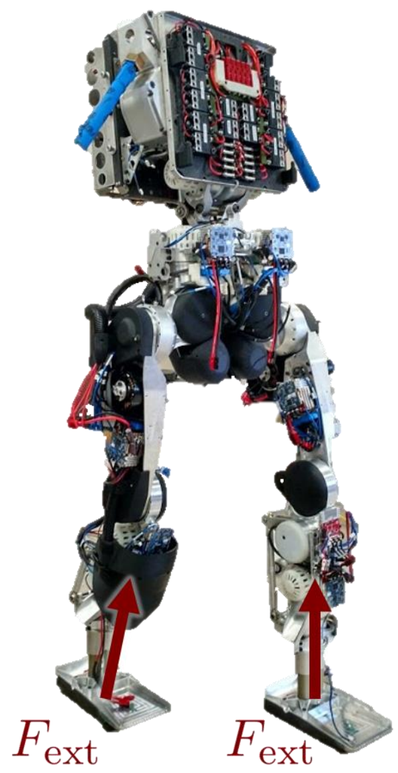
Hybrid Zero Dynamics and Modeling of Foot-Terrain Interaction

$$\dot{x} = f(x,z) + g(x,z)u + g_{ext}(x,z)F_{ext}$$
$$\dot{z} = q(x,z)$$



Zero dynamics surface: $\boldsymbol{Z_\alpha} = \{x \in \mathbb{R}^n \mid y_\alpha(x) = 0 \text{ and } \dot{y}_\alpha = 0\}$

Optimal Gait Transition based on (Gluskabi) Raccordation



Signal defined by:

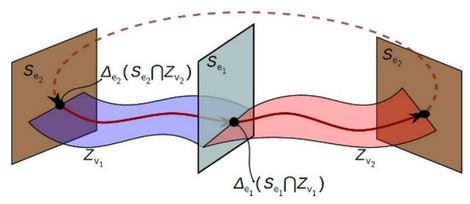
$$T = \{x \in B_0 \mid \mathbf{Op}\, x = 0\}$$

Gluskabi extension defined by:

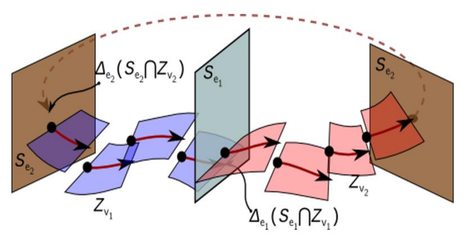
$$G = \{x \in B_0 \mid \mathbf{Op}^* Q \mathbf{Op}\, x = 0\}$$

Gluskabi raccordation results from optimization:

$$\arg\min_x \|\mathbf{Op}\, x\|_Q \text{ s.t.} \begin{cases} x = x^0 & t \le 0 \\ x = x^1 & t \ge 0 \end{cases}$$



(Task 2.2) Hybrid Zero Dynamic Representation for a Given Terrain Type



(Task 2.3) Gait Transitions for Variable Terrain

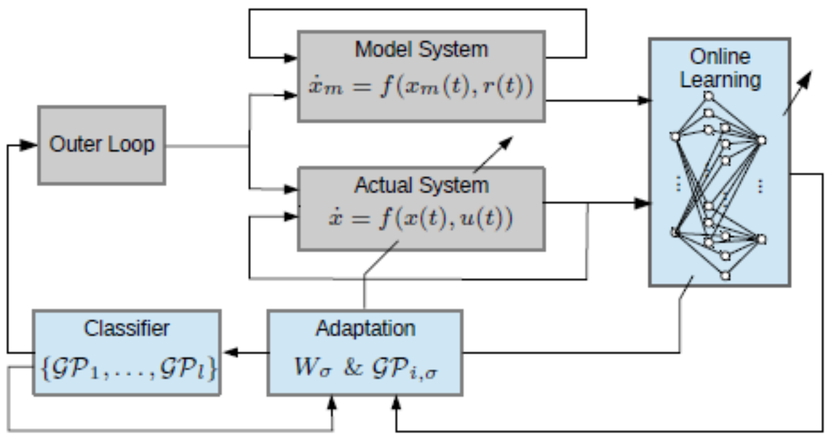
Defines transverse control u_{trans} to switch from one gait to another:

$$\dot{x} = f(x,z) + g(x,z)(u_g + u_{trans}) + g_{ext}(x,z)F_{ext}$$

STEM Education and Outreach

- Informal dissemination through web and media outlets
- Presentation of research results to public and visitors
- Integration of research through VIP.

Online Learning and Terrain Classification



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

Learn: unmodeled dynamics and state/gait-dependent uncertain external forces using Gaussian processes.

Classify: terrain type based on function approximation for ground reaction force.