MPC with Learned Reachability Constraints for Bipedal Walking on Broken Terrain

Brian Acosta and Michael Posa

DAIR Laboratory — GRASP Laboratory — University of Pennsylvania

INTRODUCTION

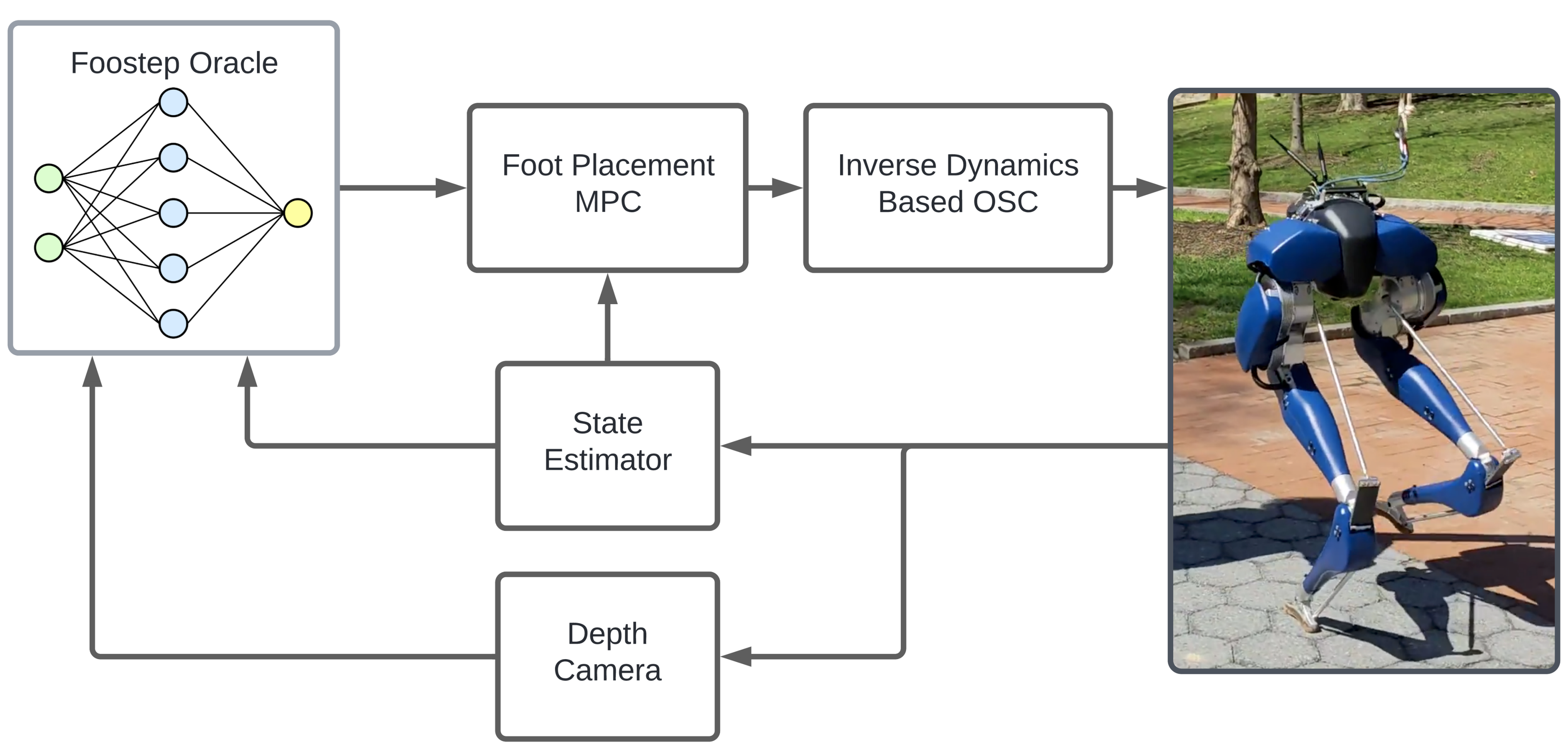
Hiking in unstructured environments breaks key assumptions of current underactuated bipedal walking controllers such as

- Fixed workspace constraints
- Fixed gait timing
- Existence of identifiable convex planar footholds

To address these concerns in a unified framework, we present

- A tractable mixed integer nonlinear program which generalizes LIP based footstep controllers such as [1] to scenarios with stepping stone constraints and variable footstep timing.
- A proposal for sim-to-real supervised learning of stepping stone constraints based on kinematic and dynamic reachability.

CONTROL FRAMEWORK



MPC FORMULATION

We jointly optimize over the state, x, input u, mode duration t, footstep location p, and stepping stone selection μ using the hybrid MPC formulation

$$\min_{x,u,t,p,\mu} \quad \left(\sum_{n=0}^{N} \sum_{k=0}^{K} \tilde{x}_{n,k}^T Q \tilde{x}_{n,k} + u_{n,k}^T R u_{n,k} \right) + \tilde{x}_{N,K}^T Q_f \tilde{x}_{N,K} \qquad (1)$$

$$\text{s.t.} \quad x_{n,k+1} = f(x_{n,k}, u_{n,k}, t_n) \qquad (2)$$

$$x_{n+1,0} = g(x_{n,K}, p_n, p_{n+1}) \qquad (3)$$

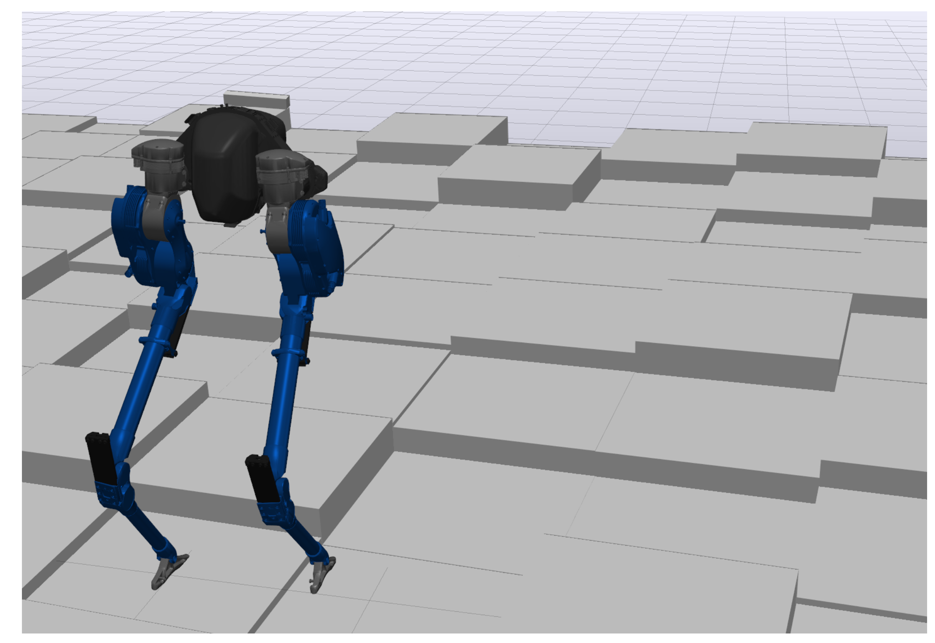
$$[p_{n+1}, t_n]^T \in \mathcal{P}_{\mu_n} \qquad (4)$$

$$\mu_n \in \mathcal{I}_n \qquad (5)$$

where $\mathcal{I}_n$ indexes the available stepping stones for the n^{th} footstep.

[1] Grant Gibson, Oluwami Dosunmu-Ogunbi, Yukai Gong, and Jessy Grizzle. Terrain-adaptive, alip-based bipedal locomotion controller via model predictive control and virtual constraints, 2021.

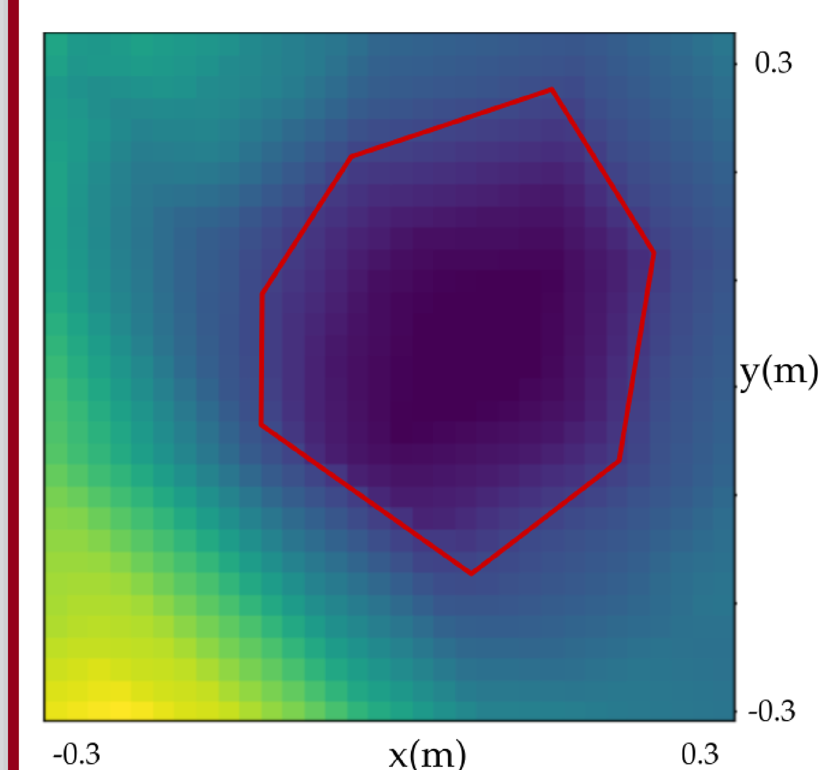
ORACLE TRAINING ENVIRONMENT



To collect data for oracle training, we simulate Cassie on rough terrain, replacing the MPC with fixed footstep targets.

We use simulated depth images for extracting feasible footholds and identifying target foothold height.

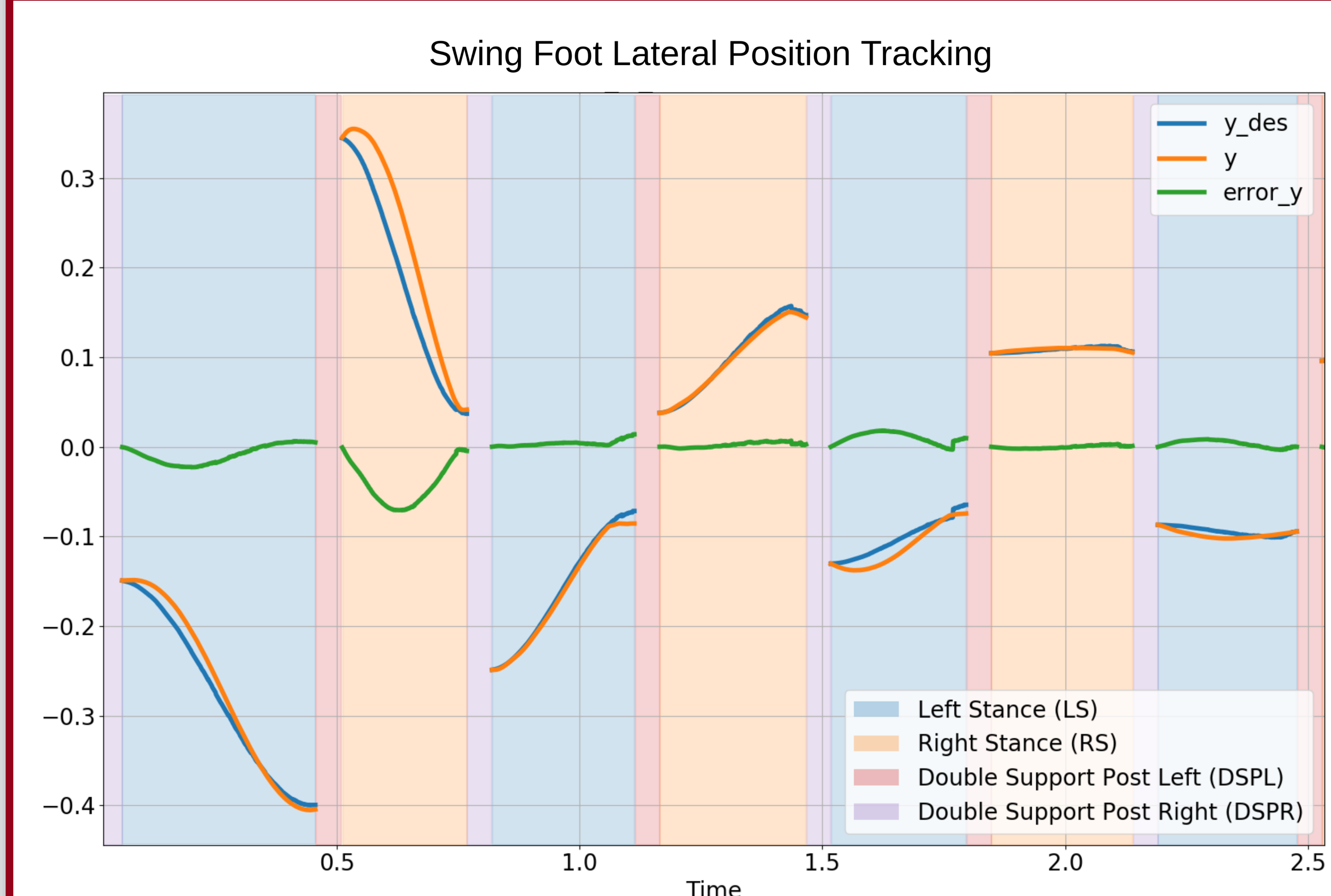
FOOTHOLD EXTRACTION



We train a MLP to predict the swing foot position tracking error at touchdown for a given robot state and footstep location.

To construct footholds, we propose sampling the oracle network and approximating the α sublevel set as a convex polytope for a chosen threshold, α.

TIMING ADAPTATION ON FLAT GROUND



Online optimization of the mode timings can be useful for disturbance recovery in addition to traversing stepping stones.

{bjacosta,posa}@seas.upenn.edu