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RSL Robotic Systems Lab

# Planar Bipedal Locomotion with Nonlinear Model Predictive Control: Online Gait Generation using Whole-Body Dynamics

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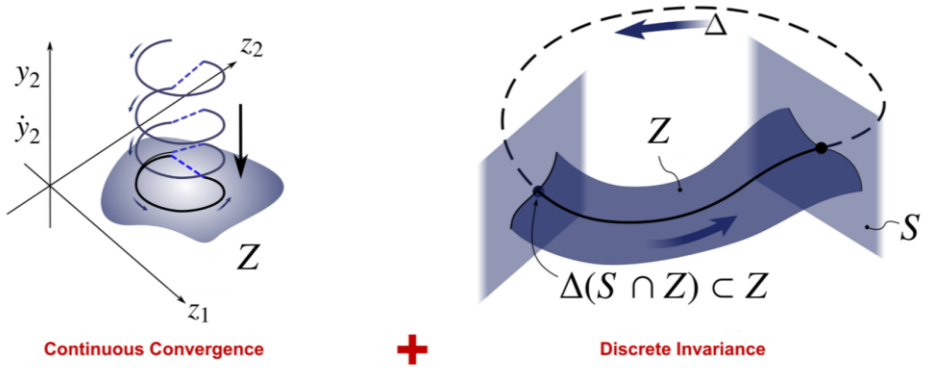
# Related Approaches – Dynamic Locomotion

## Offline Gait Synthesis using Whole-Body Dynamics

Hybrid Zero Dynamics (HZD)

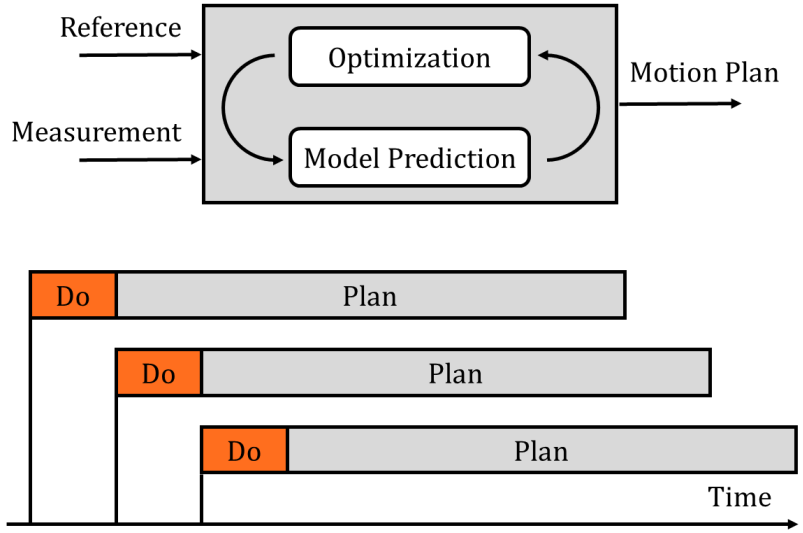



Feedback Control of Dynamic Bipedal Robot Locomotion, Eric R. Westervelt, 2007

- Find periodic trajectory of actuated outputs $\boldsymbol{y_d(q, \alpha)}$ s.t. unactuated DoF exhibit stable periodic behavior

**Precomputed Stable Periodic Trajectories**

## Online Gait Synthesis using MPC




- S-LIP Model, Centroidal Dynamics

A Unified MPC Framework for Whole-Body Dynamic Locomotion and Manipulation, Jean-Pierre Sleiman, 2021

**Simplified/Reduced Model Dynamics**

# Contribution

**Whole-Body Nonlinear MPC**

**Reduced computational cost via HZD  Reference & Terminal**

**Experimental validation on planar biped AMBER-3M**

# MPC Formulation – Reparametrized Whole-Body Dynamics

**Exclude inverse dynamics from MPC prediciton**

- $x = (q_b, q_j, \dot{q}_b, \dot{q}_j)^T$
- $u = (\lambda_c, \ddot{q}_j)$
- $\dot{x} = (\dot{q}_b, \dot{q}_j, \ddot{q}_b, \ddot{q}_j)^T$

- Dynamics Formulation via Euler Lagrange

$$D(q)\,\ddot{q} + C(q,\dot{q})\,\dot{q} = B\,\tau + J_c^T(q)\,\lambda_c$$

$$\begin{pmatrix} D_{bb} & D_{bj} \\ D_{jb} & D_{jj} \end{pmatrix} \begin{pmatrix} \ddot{q}_b \\ \ddot{q}_j \end{pmatrix} + \begin{pmatrix} C_b \\ C_j \end{pmatrix} \dot{q} = \begin{pmatrix} 0 \\ I \end{pmatrix} \tau + \begin{pmatrix} J_{cb} \\ J_{cj} \end{pmatrix} \lambda_c$$

$$\ddot{q}_b = D_{bb}^{-1}(-D_{bj}\,\ddot{q}_j - C_b\,\dot{q} + J_{cb}\,\lambda_c)$$

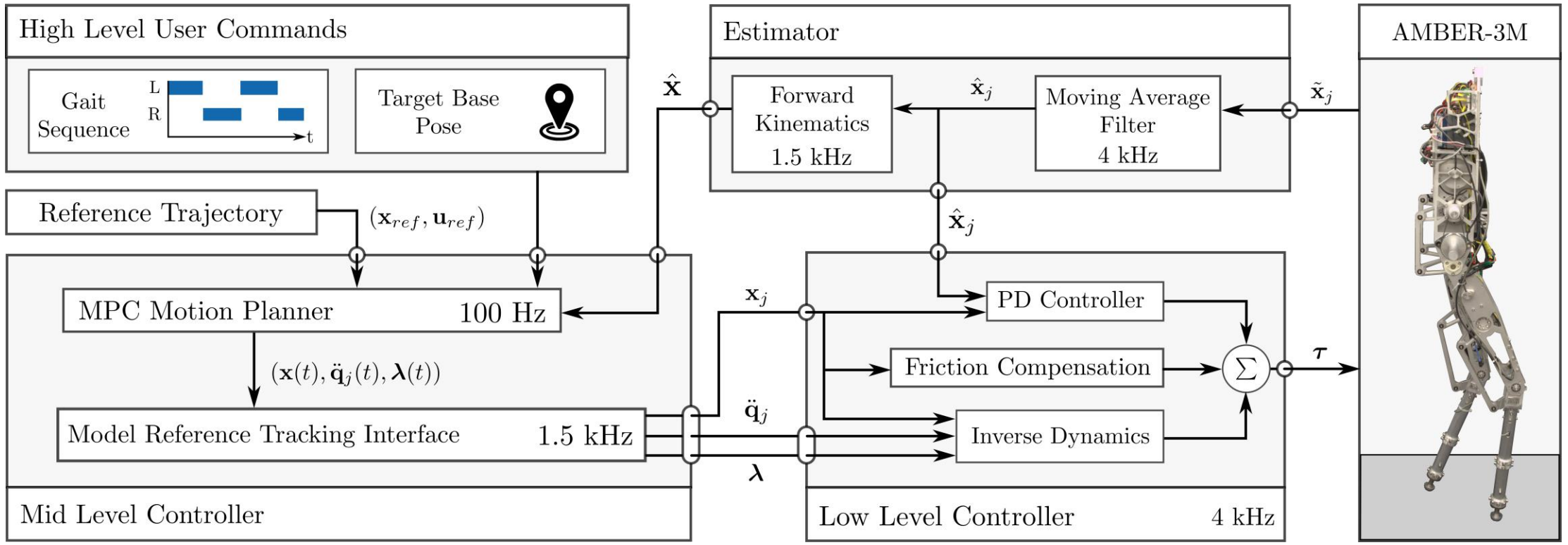
- **Recover torques via inverse dynamics**

$$\tau = J_c^T\,F_c - D\,\ddot{q} - C\,\dot{q} - G$$

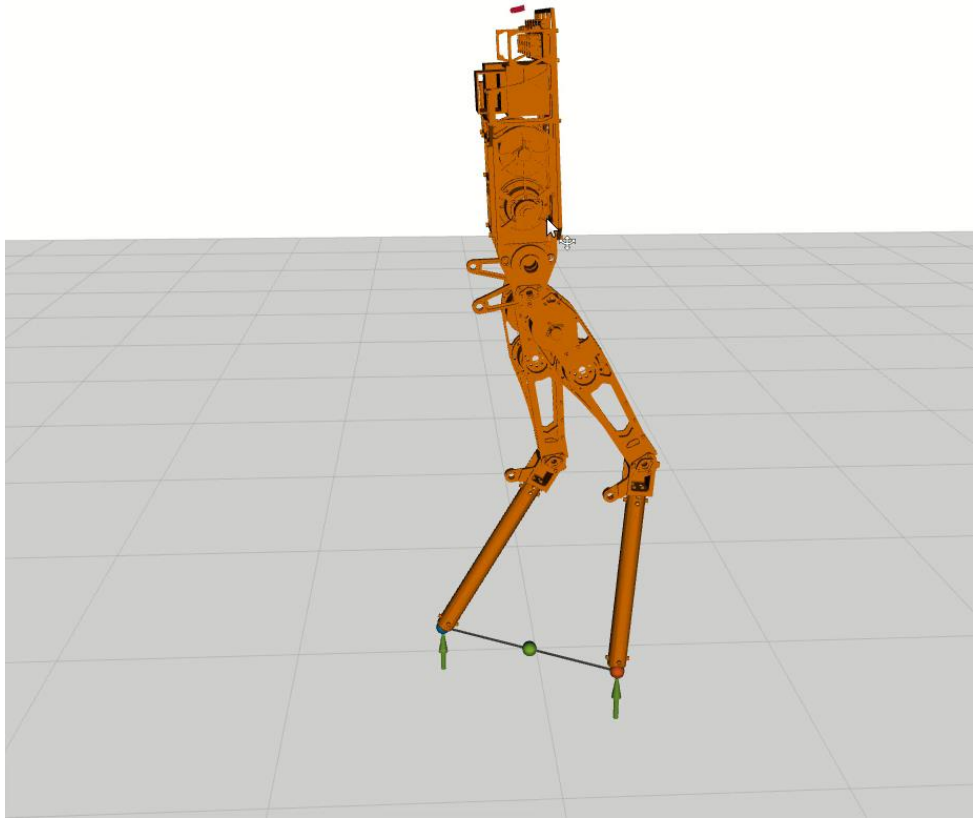
→ **Focus computation on unactuated DoF**

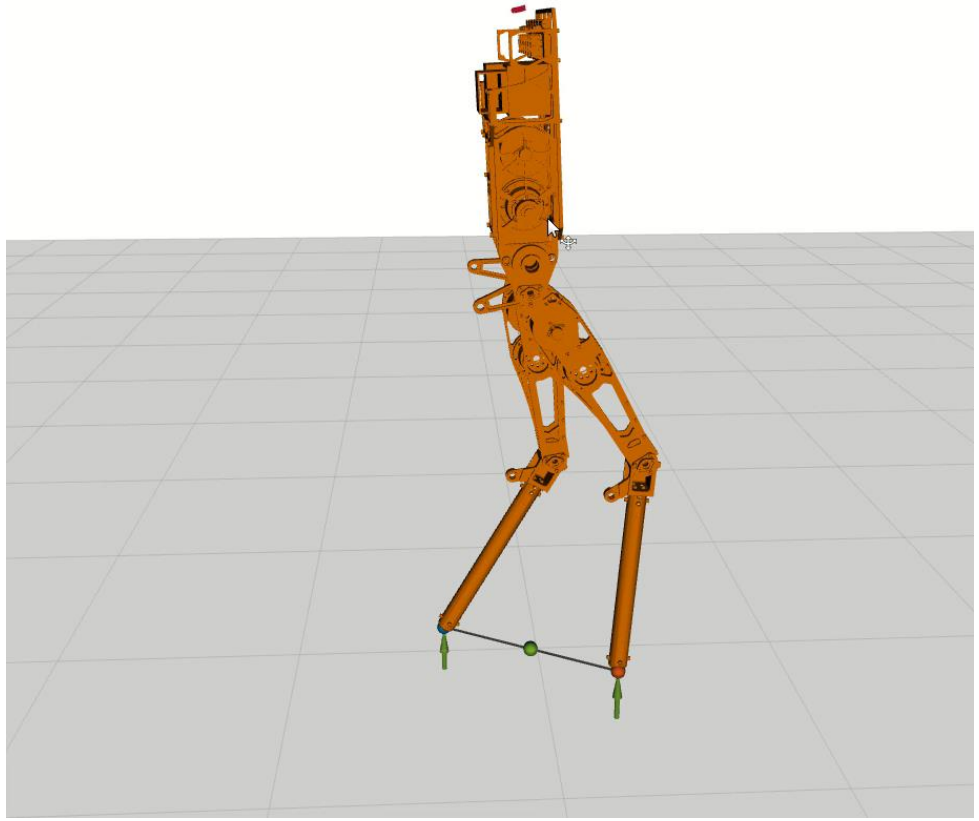
→ **Whole-Body nonlinear dynamics/constraints**

# AMBER Implementation – Control Overview

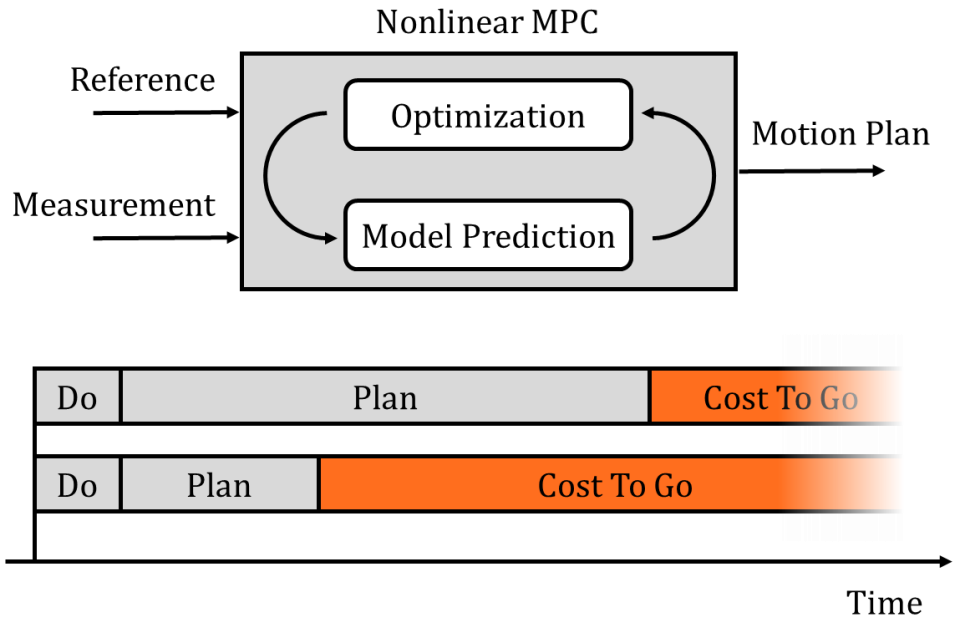


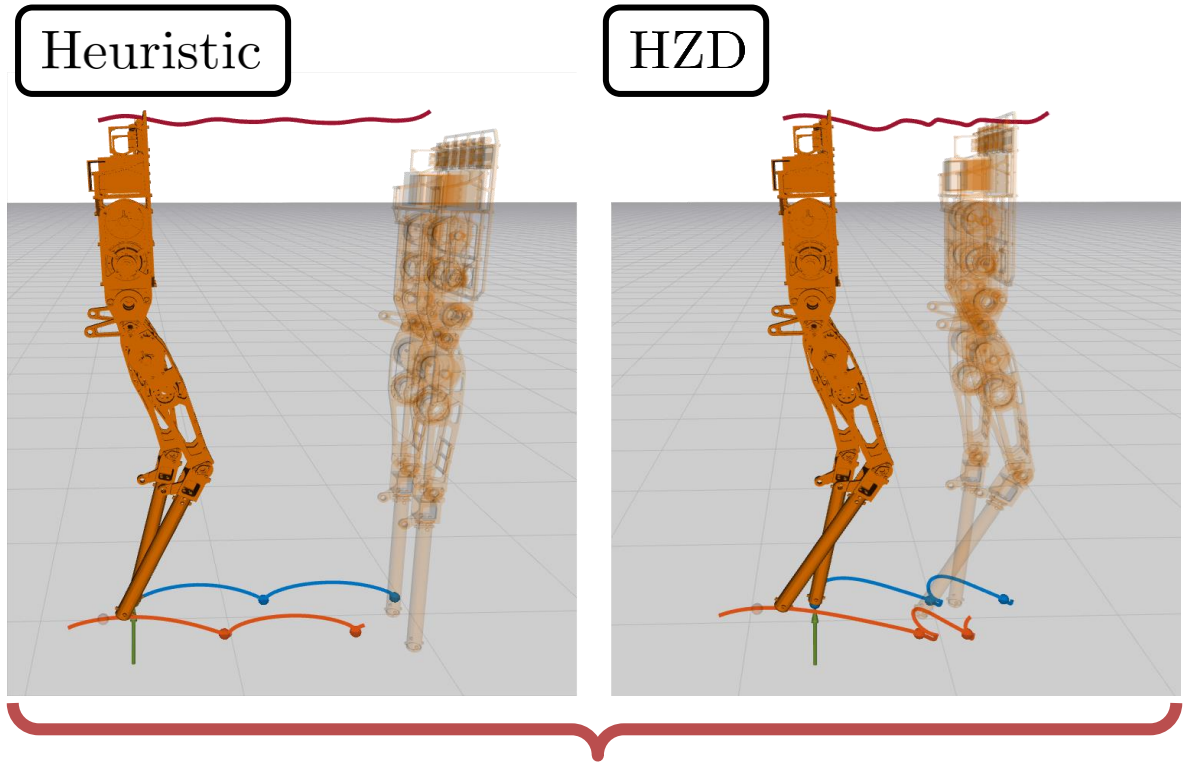
# Results - Simulation





# Reduce Computational Cost via Horizon Shortening

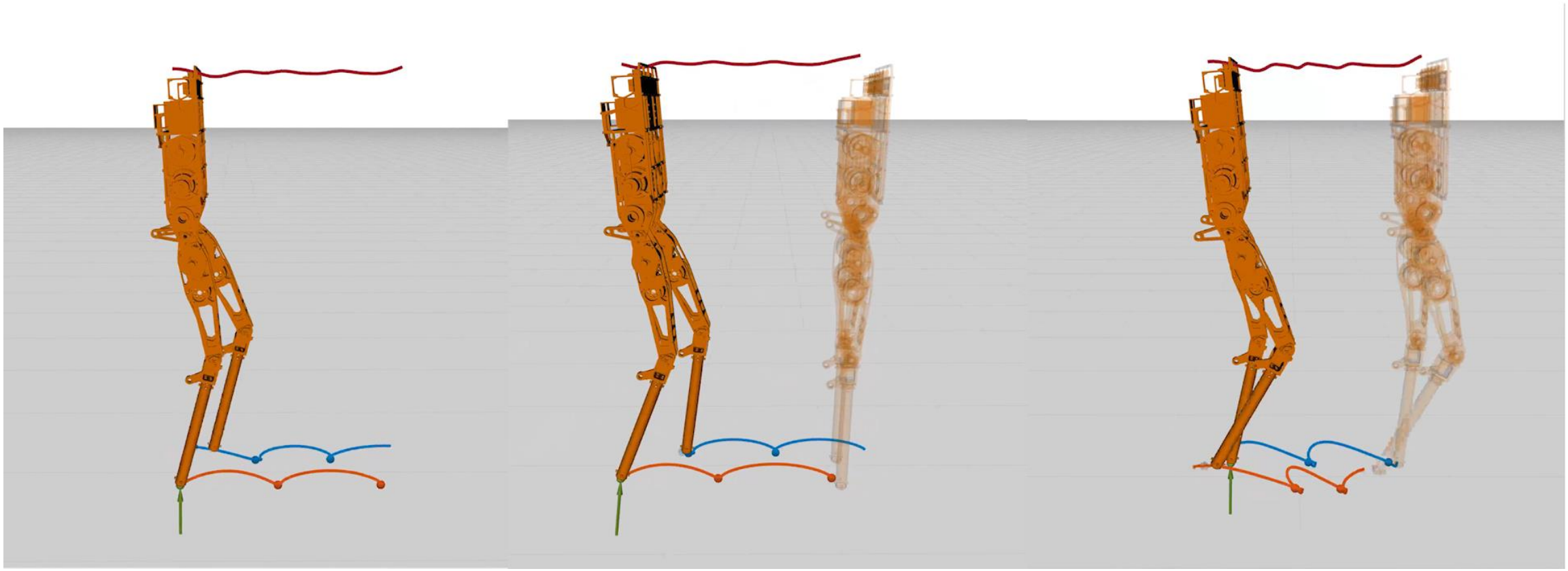



$$\underset{\mathbf{u}(\cdot)}{\text{minimize}} \qquad \phi(\mathbf{x}(t_H)) + \int_0^{t_H} l(\mathbf{x}(t), \mathbf{u}(t), t)\mathrm{d}t$$

# MPC Terminal Cost Visualization 2s Horizon

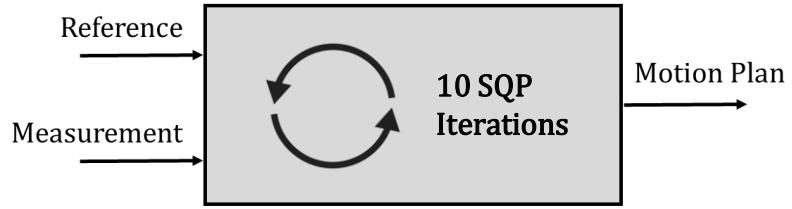
No Terminal | Heuristic Terminal | HZD Terminal

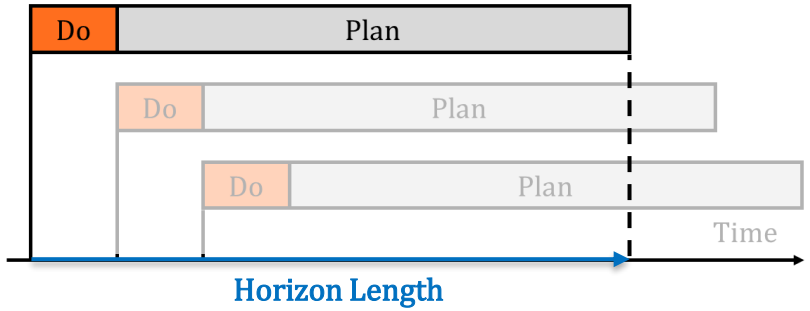


# Results - Metrics

Ryzen 9 5950x at 10 SQP Iterations

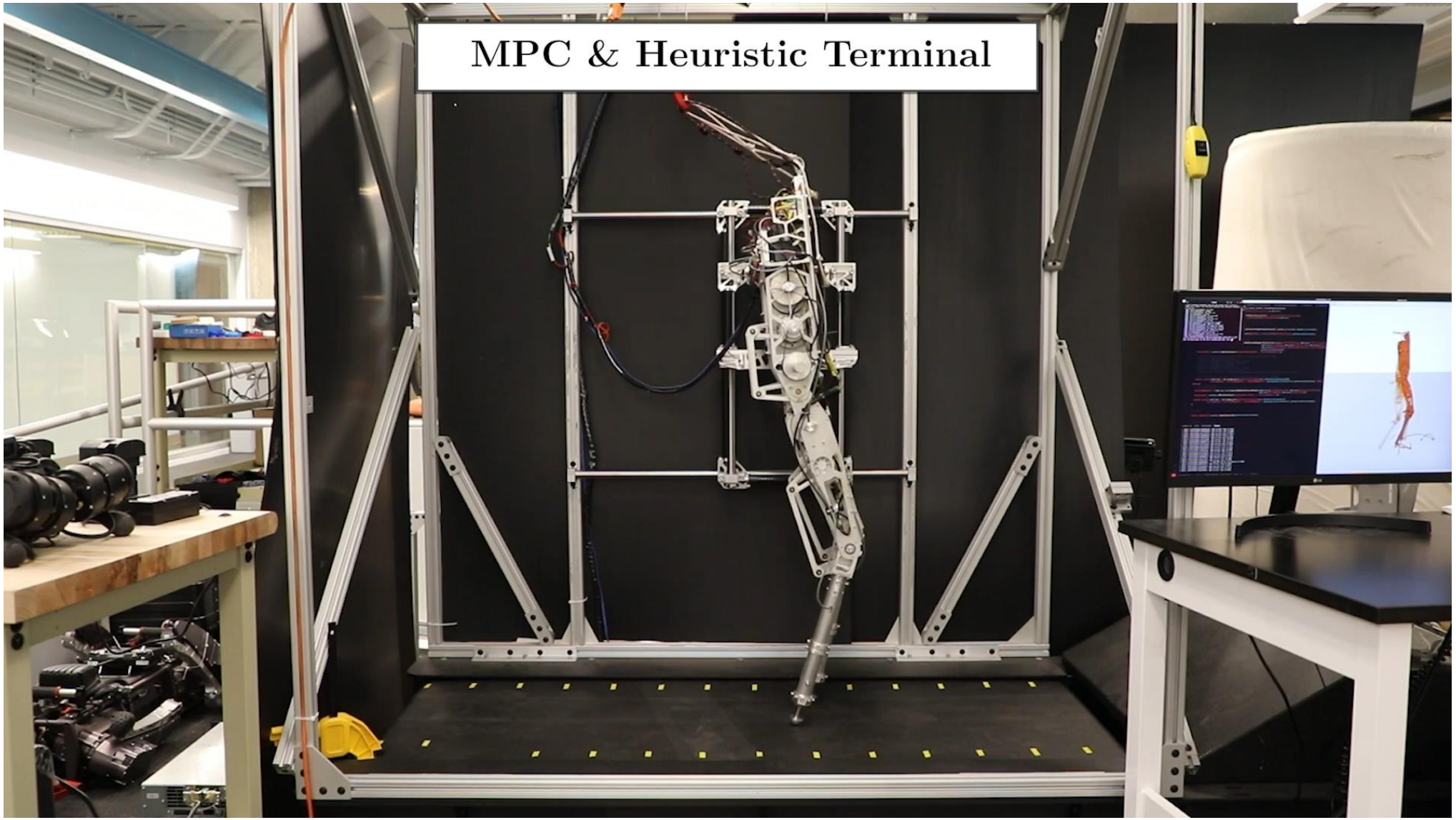
| Horizon Length [s] | 2.0 | 1.0 | 0.5 | 0.2 |
|---|---|---|---|---|
| MPC Frequency [Hz] | 270 | 480 | 670 | 850 |



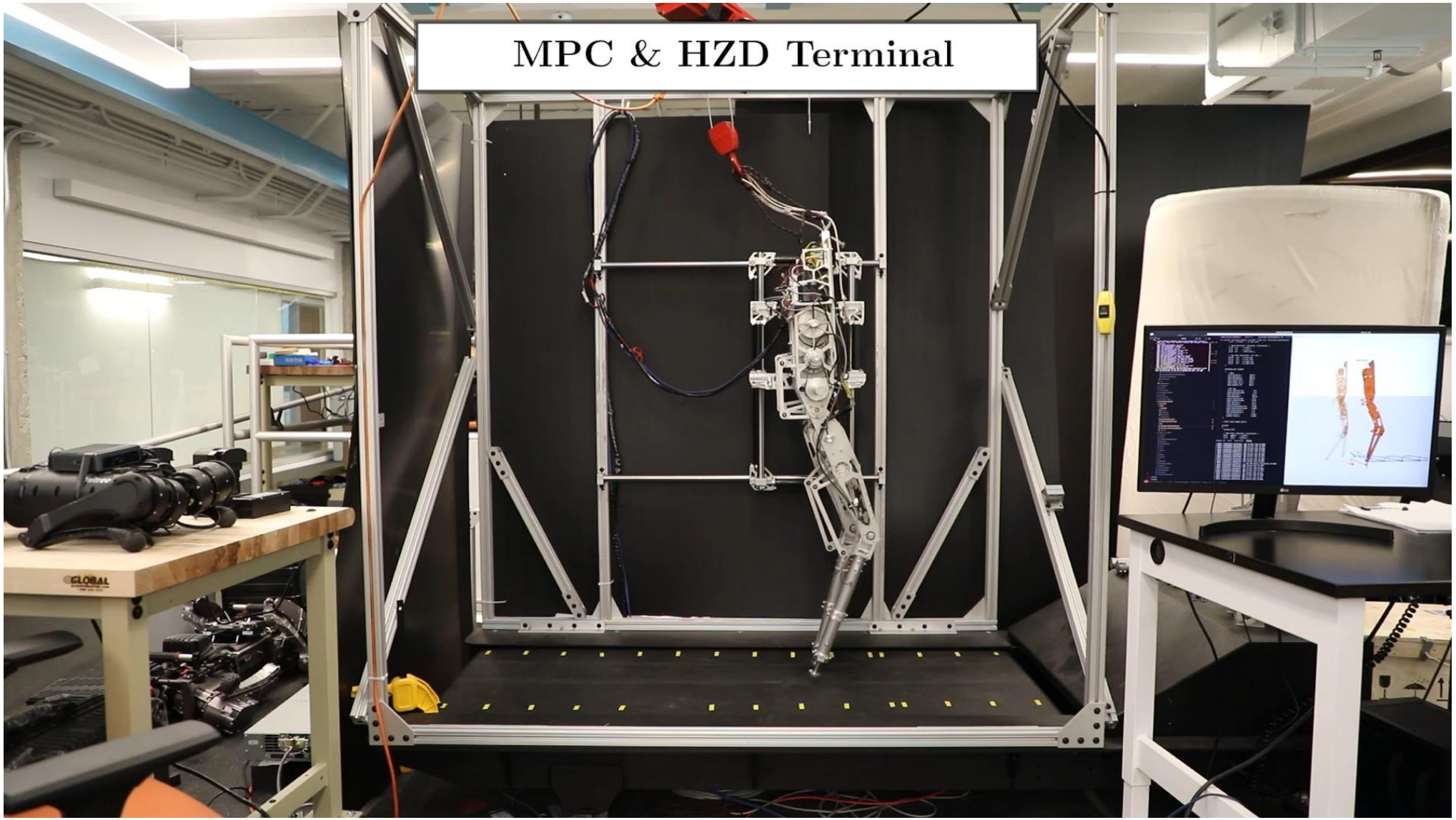




**Reduce computational complexity through terminal**

# Results



# Results – MPC & HZD Terminal



# Conclusion

**Reparametrized Whole-Body NMPC Formulation**

**Significant Horizon shortening through HZD Terminal**

**Hardware Demonstration of Whole-Body Online Planning**

# Thank you for your Attention!

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