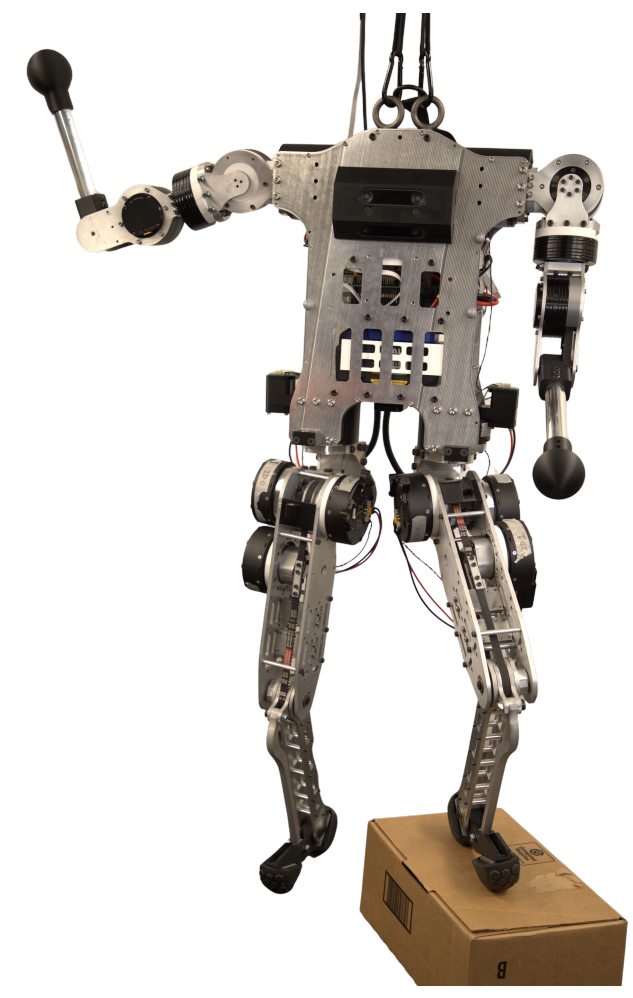


Humanoid Control

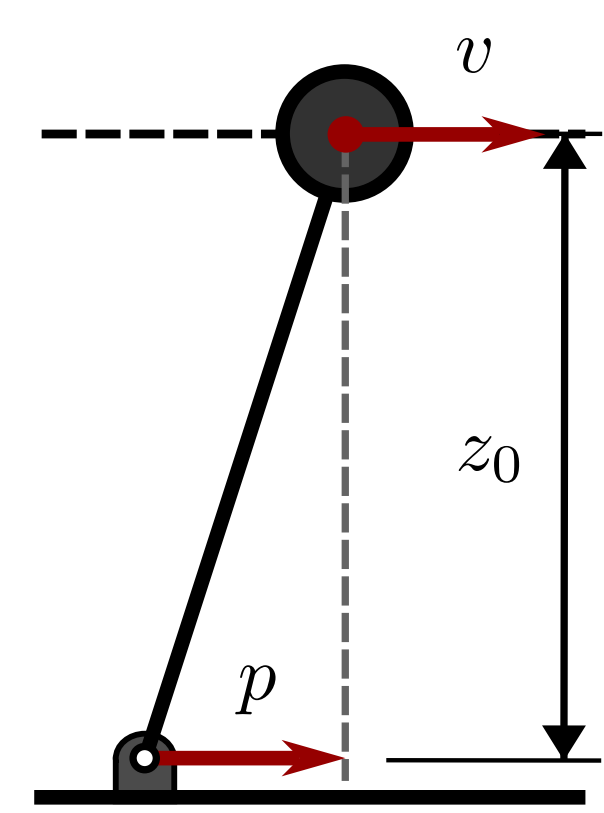
$$\mathbf{D}(\mathbf{q})\dot{\mathbf{v}} + \mathbf{H}(\mathbf{q}, \mathbf{v}) = \mathbf{B}\mathbf{u} + \mathbf{J}_c(\mathbf{q})^\top \boldsymbol{\lambda}(\mathbf{q})$$



- High Dimensional, $\mathbf{x} \in \mathbb{R}^{48}$
- Unactuated base and feet
- Hybrid Dynamics, 2^{n_c} Contact Modes

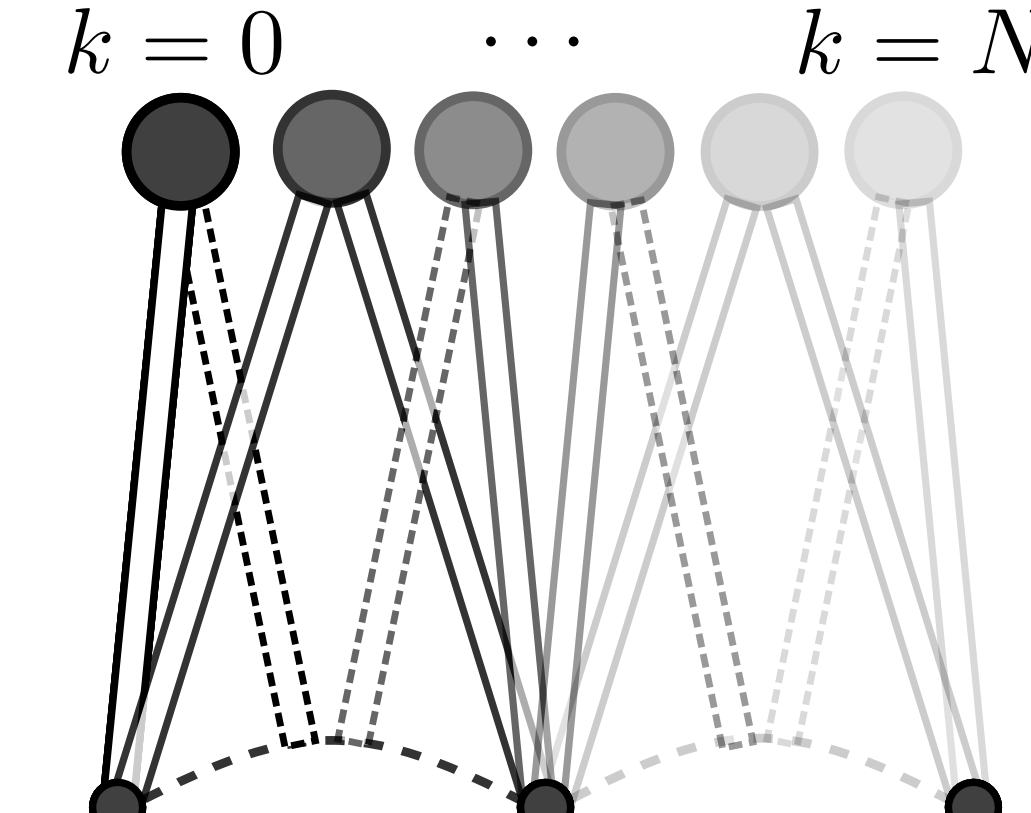
Reduced-Order Model References

① Hybrid LIP



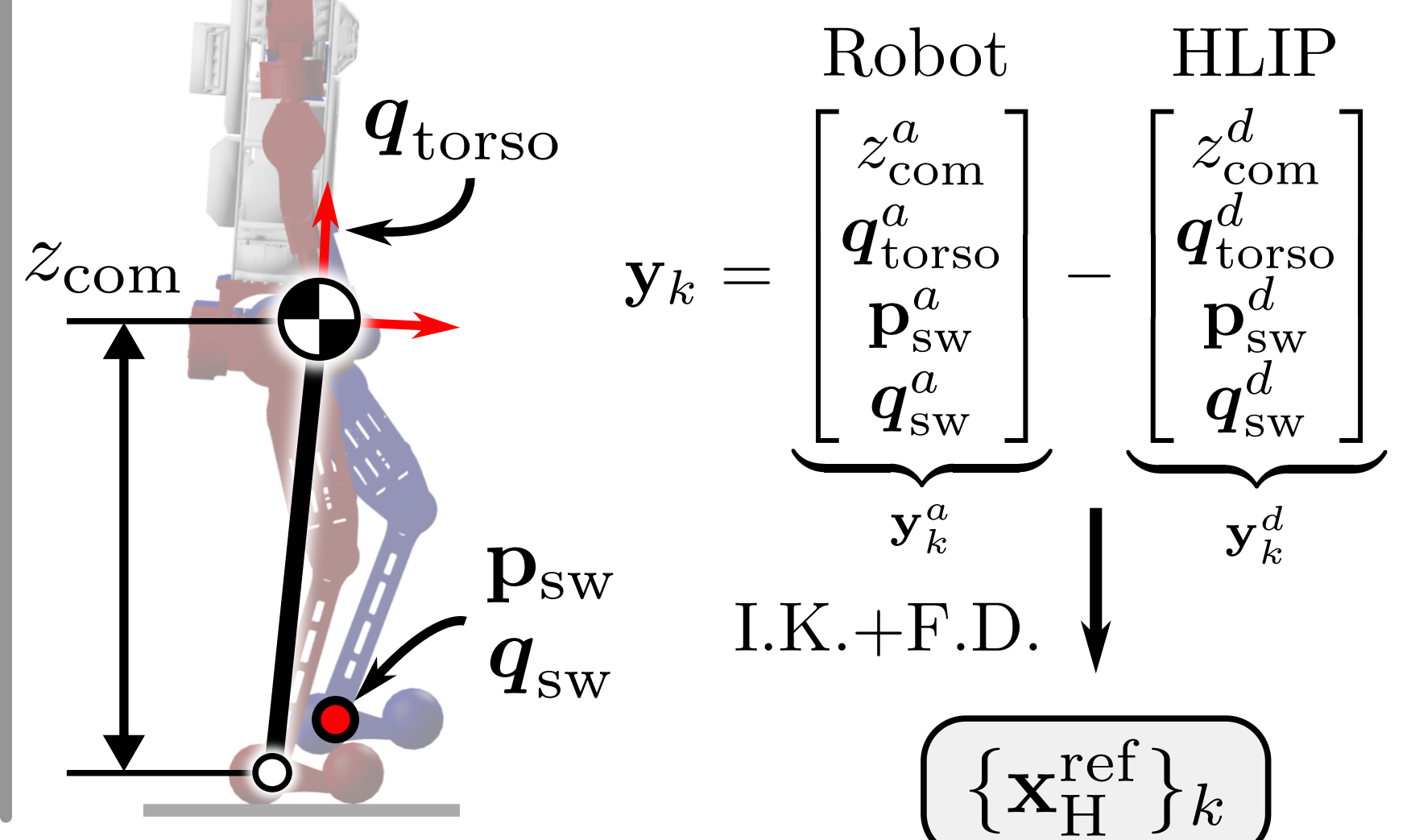
$$\mathbf{x}^H = (\mathbf{p}, \mathbf{v}) \in \mathbb{R}^4$$

② Solution Trajectory



$$\chi(\mathbf{x}_0^H) = (\Lambda, I, C)$$

③ Lower Body Trajectory



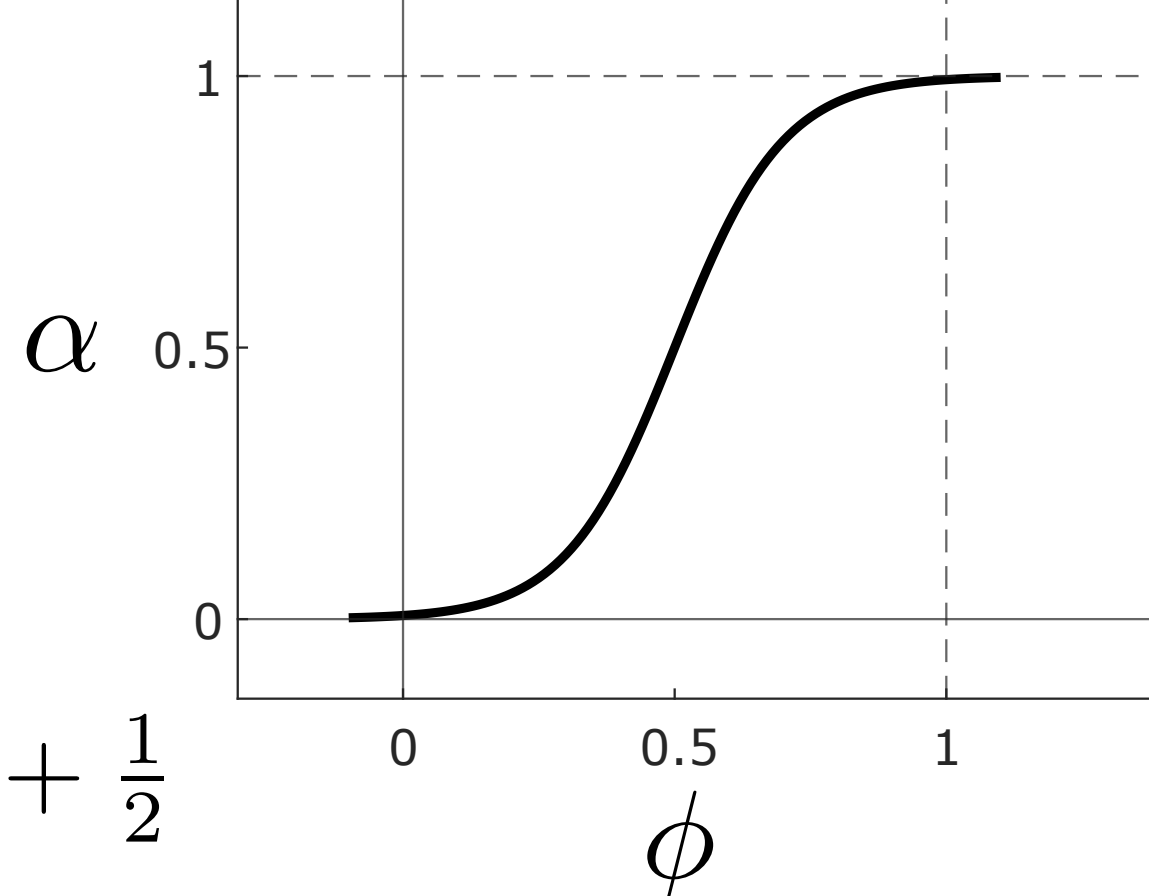
Trajectory Combination

Velocity Magnitude

$$\phi = \left\| \begin{bmatrix} \mathbf{c}^\top & \mathbf{v}^\top \end{bmatrix} \right\|_{\mathbf{P}}^2$$

Activation

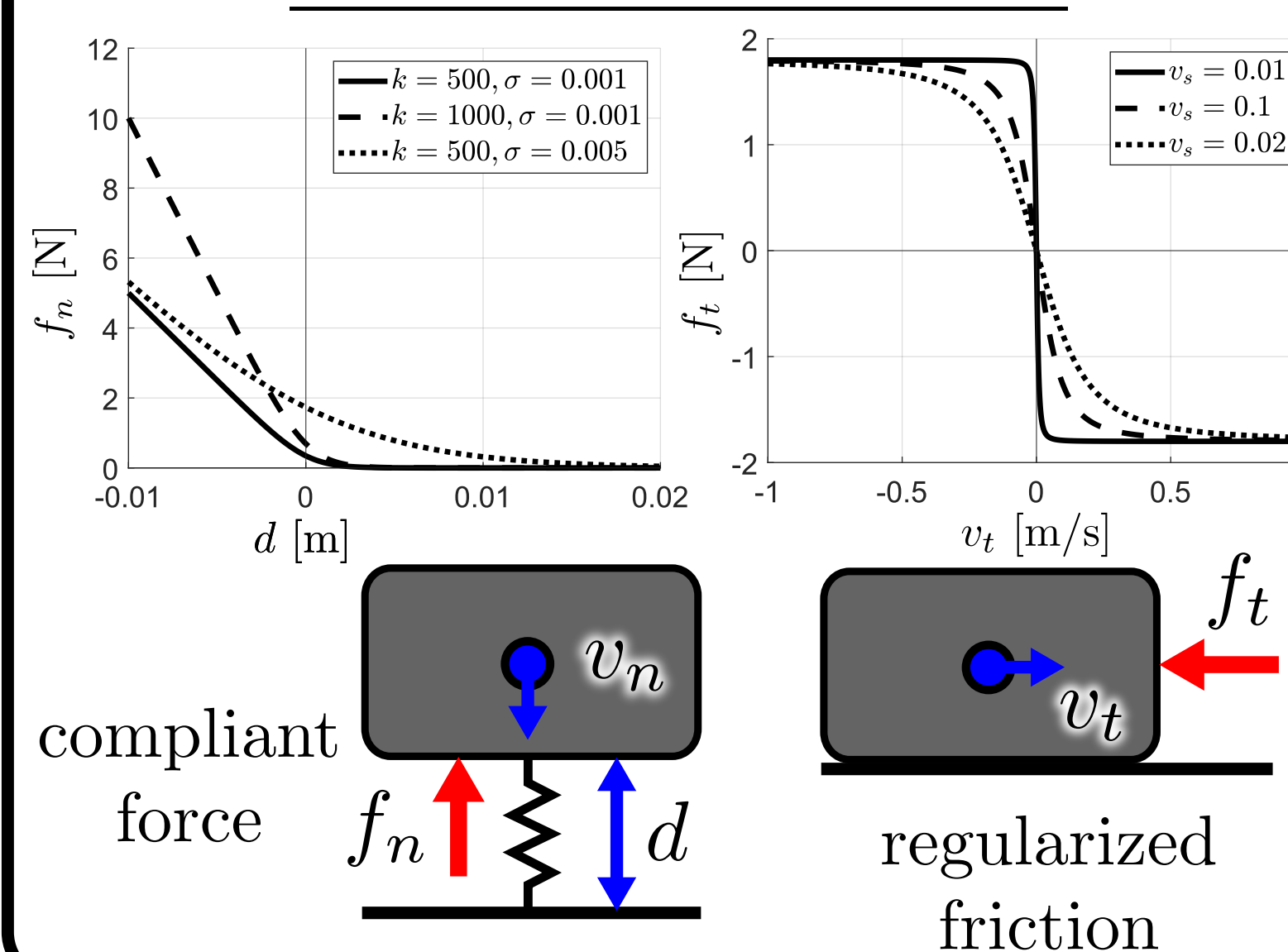
$$\alpha(\phi) = \frac{1}{2} \tanh(\rho_1(\phi - \rho_2)) + \frac{1}{2}$$



$$\{\mathbf{x}_{\text{ref}}\}_k = \alpha \{\mathbf{x}_H\}_k + (1 - \alpha) \{\mathbf{x}_S\}_k$$

Contact-Implicit MPC

Contact Modeling



Trajectory Optimization

$$l(\mathbf{x}, \mathbf{u}, t) = \|\mathbf{x} - \mathbf{x}_{\text{ref}}(t)\|_{\mathbf{Q}}^2 + \|\mathbf{u}\|_{\mathbf{R}}^2 \quad l_f(\mathbf{x}) = \|\mathbf{x} - \mathbf{x}_{\text{ref}}(T)\|_{\mathbf{V}}^2$$

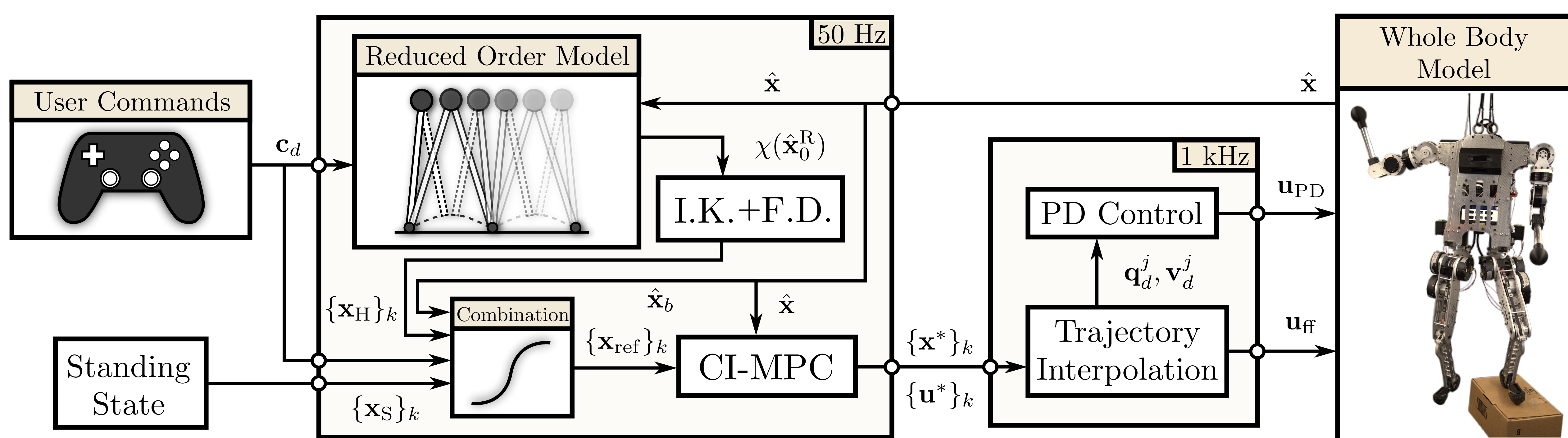
ROM Ref. ROM Ref.

$$\begin{aligned} \min_{\mathbf{u}(t)} \quad & \int_0^T l(\mathbf{x}(t), \mathbf{u}(t), t) dt + l_f(\mathbf{x}(T)) \\ \text{s.t.} \quad & \mathbf{D}(\mathbf{q})\dot{\mathbf{v}} + \mathbf{H}(\mathbf{q}, \mathbf{v}) = \mathbf{B}\mathbf{u} + \mathbf{J}_c(\mathbf{q})^\top \boldsymbol{\lambda}(\mathbf{q}, \mathbf{v}) \\ & \mathbf{x}(0) = \mathbf{x}_0 \end{aligned}$$

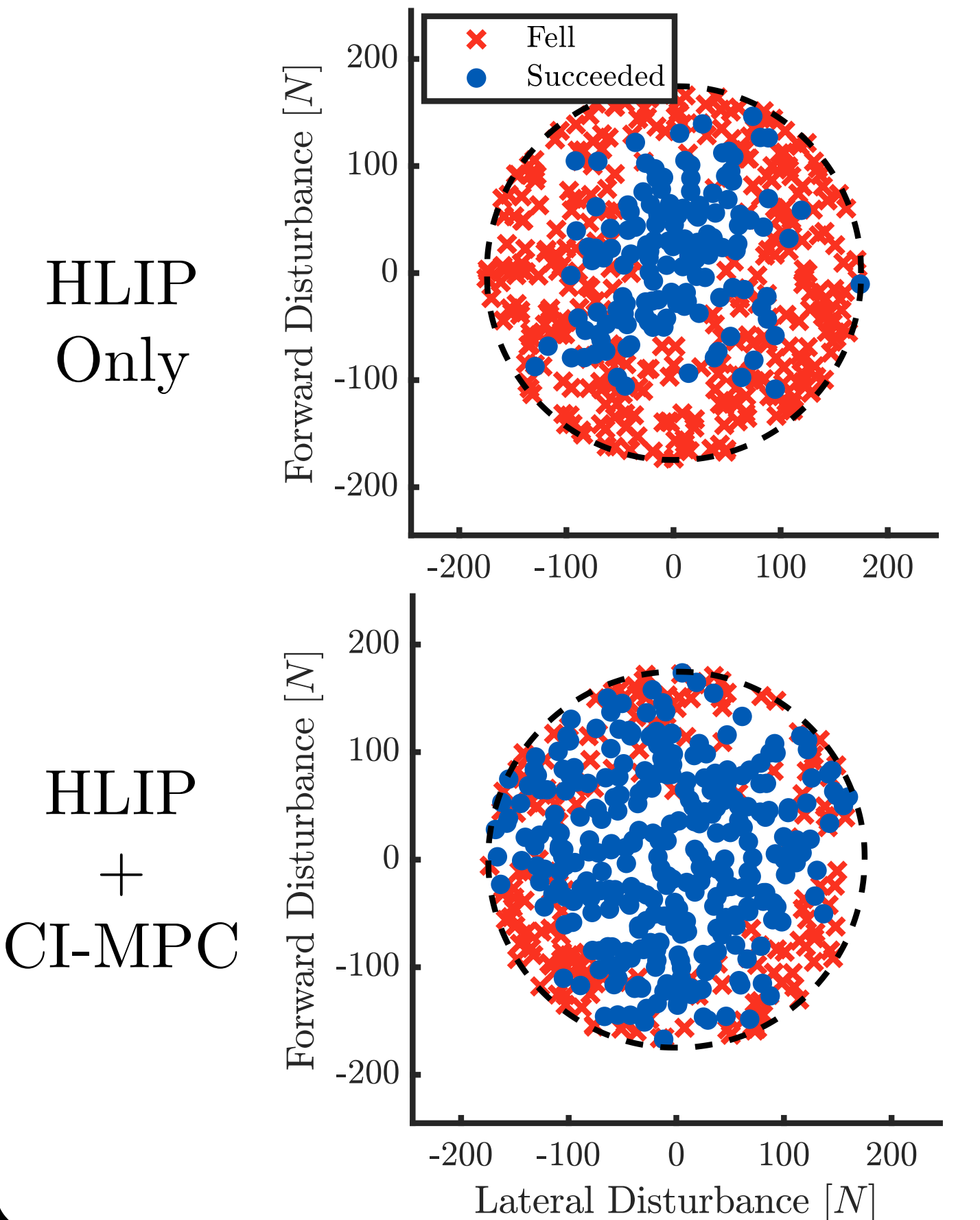
Contact

$$\text{Opt. Solution: } (\{\mathbf{x}^*\}_k, \{\mathbf{u}^*\}_k)$$

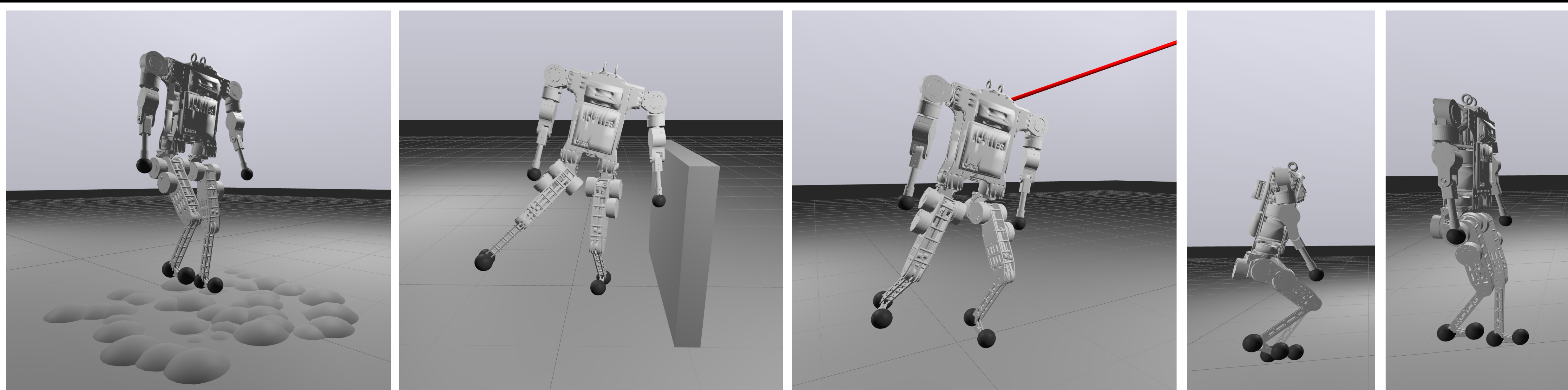
Control Architecture



Robustness



ROM Guided CI-MPC Behaviors

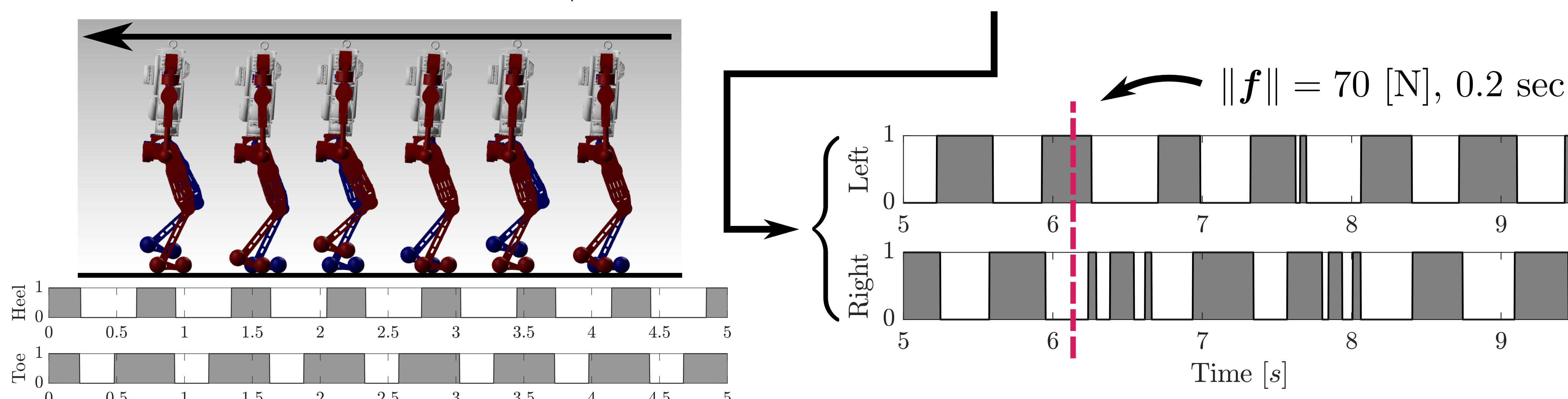


Robust Walking

Contact w/ Environment

Disturbance Recovery

Walking at Various Heights



Implementation

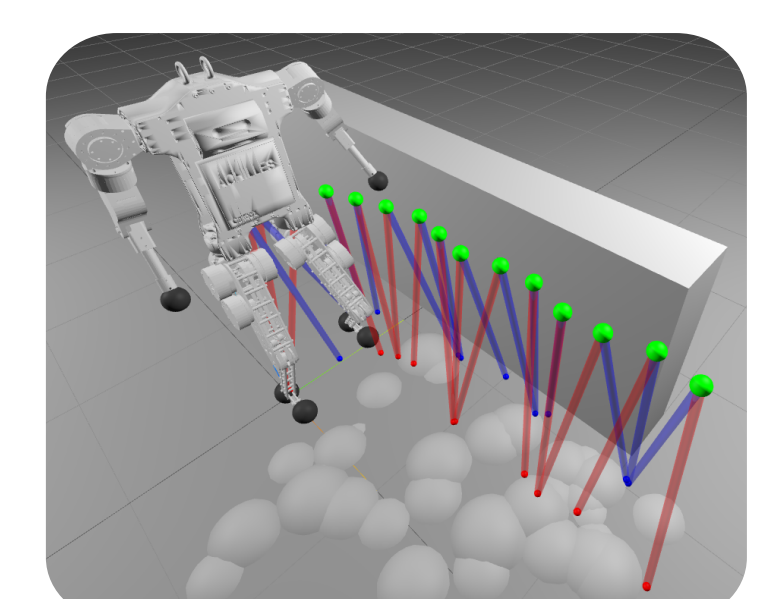
HLIP & MPC Params:

HLIP			CI-MPC		
T_{ssp} [s]	z_0 [m]	Δt [s]	N	Freq. [Hz]	Iters.
0.35	0.62	0.05	25	50	3

Key Takeaways

- Layered architectures enable modularity which can be leveraged.
- Contact relaxation enables discovery of diverse behaviors.
- Gradient-based methods for contact planning does not scale well.

Project Page



rom-cimpc.github.io