# NRI: FND: COLLAB: Hierarchical, Safe, and Distributed Feedback Control of Multiagent Legged Robots for Cooperative Locomotion and Manipulation

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Virginia Tech **Caltech**

Goals and Scientific Impact

To establish a formal foundation that develops hierarchical, distributed, and robust control algorithms for safe cooperative locomotion and manipulation of quadrupedal robots in complex environments
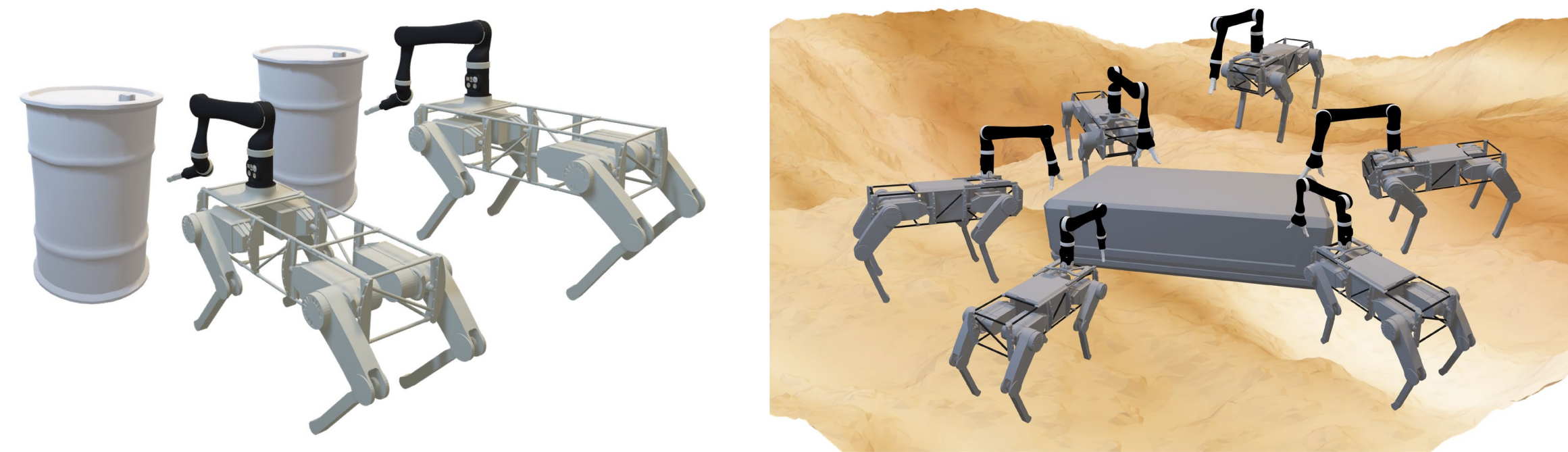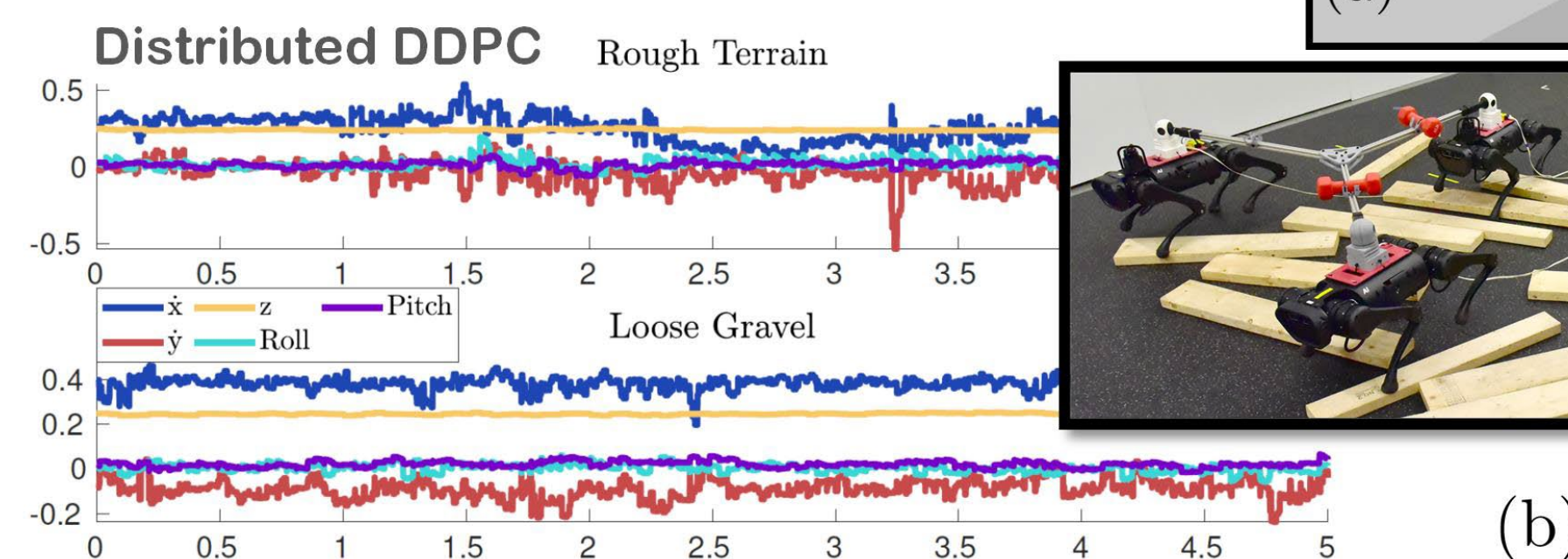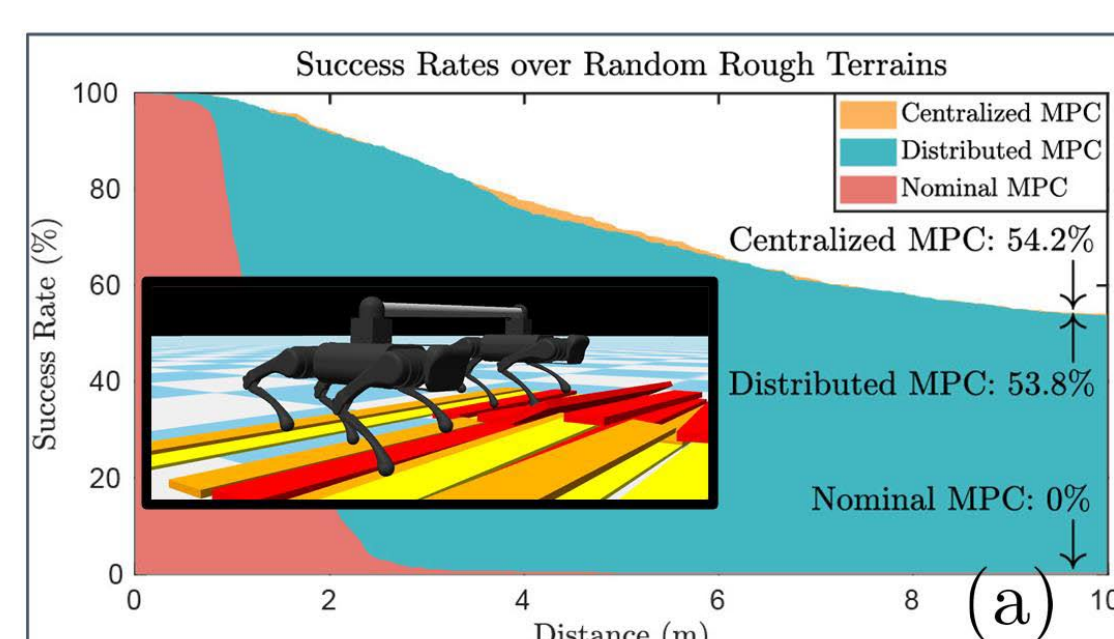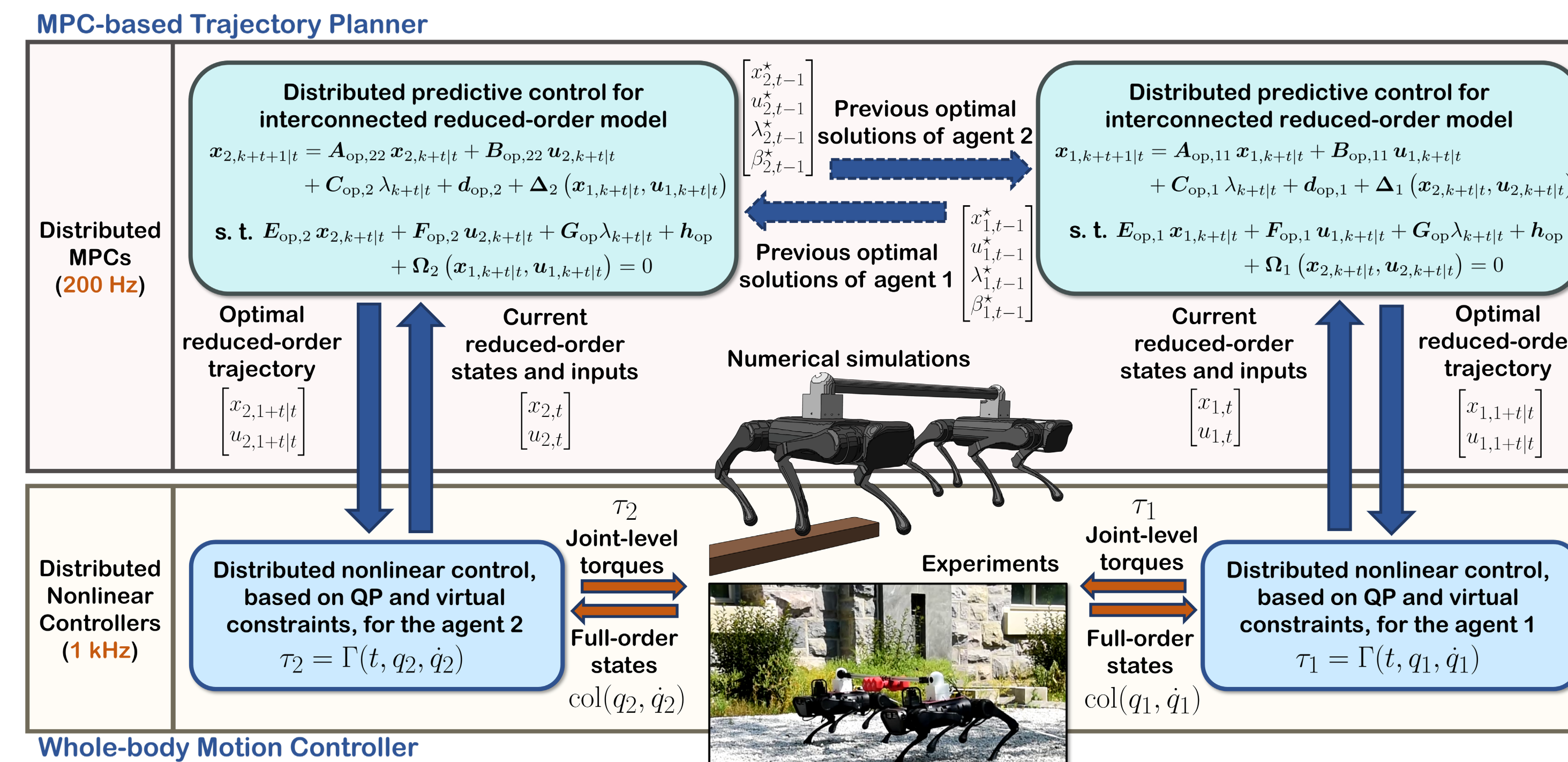
Challenges

High-dimensional and inherently unstable hybrid models for cooperative locomotion
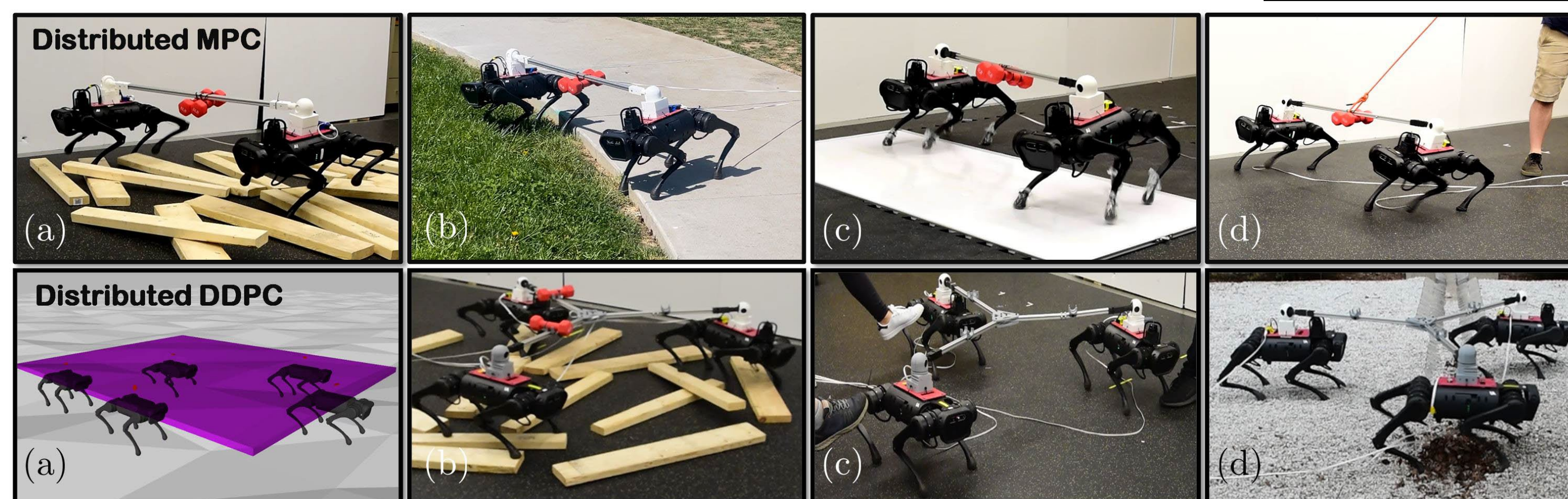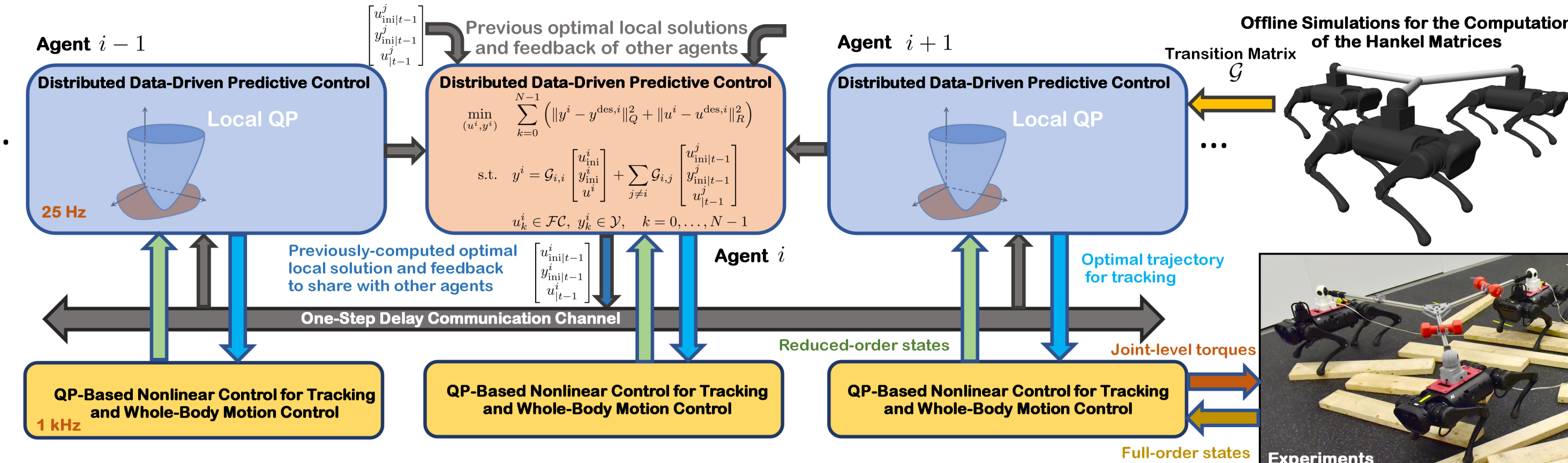
Technical Approach and Innovations

1) Creation of distributed predictive control algorithms for motion planning of cooperative locomotion

2) Creation of whole-body motion control (WBMC) algorithms based on convex optimization and nonlinear control

3) Extensive numerical and experimental validation on a team of quadrupedal robots

Distributed MPC + WBMC

MPC-based Trajectory Planner

Distributed MPCs (200 Hz)

Distributed predictive control for interconnected reduced-order model
$$x_{2,k+1+1|t} = A_{op,22}\, x_{2,k+t|t} + B_{op,22}\, u_{2,k+t|t} + C_{op,2}\, \lambda_{k+t|t} + d_{op,2} + \Delta_2\left(x_{1,k+t|t}, u_{1,k+t|t}\right)$$
s. t. $E_{op,2}\, x_{2,k+t|t} + F_{op,2}\, u_{2,k+t|t} + G_{op,2}\, \lambda_{k+t|t} + h_{op} + \Omega_2\left(x_{1,k+t|t}, u_{1,k+t|t}\right) = 0$

Previous optimal solutions of agent 2
$\begin{bmatrix} x^\star_{2,t-1} \\ u^\star_{2,t-1} \\ \lambda^\star_{k+t-1} \\ \beta^\star_{2,t-1} \end{bmatrix}$

Distributed predictive control for interconnected reduced-order model
$$x_{1,k+t+1|t} = A_{op,11}\, x_{1,k+t|t} + B_{op,11}\, u_{1,k+t|t} + C_{op,1}\, \lambda_{k+t|t} + d_{op,1} + \Delta_1\left(x_{2,k+t|t}, u_{2,k+t|t}\right)$$
s. t. $E_{op,1}\, x_{1,k+t|t} + F_{op,1}\, u_{1,k+t|t} + G_{op,1}\, \lambda_{k+t|t} + h_{op} + \Omega_1\left(x_{2,k+t|t}, u_{2,k+t|t}\right) = 0$

Previous optimal solutions of agent 1
$\begin{bmatrix} x^\star_{1,t-1} \\ u^\star_{1,t-1} \\ \lambda^\star_{1,t-1} \\ \beta^\star_{1,t-1} \end{bmatrix}$

Optimal reduced-order trajectory $\begin{bmatrix} x_{2,1+t|t} \\ u_{2,1+t|t} \end{bmatrix}$

Current reduced-order states and inputs $\begin{bmatrix} x_{2,t} \\ u_{2,t} \end{bmatrix}$

Numerical simulations

Current reduced-order states and inputs $\begin{bmatrix} x_{1,t} \\ u_{1,t} \end{bmatrix}$

Optimal reduced-order trajectory $\begin{bmatrix} x_{1,1+t|t} \\ u_{1,1+t|t} \end{bmatrix}$

Distributed Nonlinear Controllers (1 kHz)

Distributed nonlinear control, based on QP and virtual constraints, for the agent 2
$\tau_2 = \Gamma(t, q_2, \dot{q}_2)$

τ_2 Joint-level torques
Full-order states $\mathrm{col}(q_2, \dot{q}_2)$

Experiments

τ_1 Joint-level torques
Full-order states $\mathrm{col}(q_1, \dot{q}_1)$

Distributed nonlinear control, based on QP and virtual constraints, for the agent 1
$\tau_1 = \Gamma(t, q_1, \dot{q}_1)$

Whole-body Motion Controller

Distributed DDPC + WBMC

Agent $i-1$
Distributed Data-Driven Predictive Control — Local QP — 25 Hz

Previous optimal local solutions and feedback of other agents
$\begin{bmatrix} u^i_{init,t-1} \\ y^i_{init,t-1} \\ u^i_{t-1} \end{bmatrix}$

Distributed Data-Driven Predictive Control — Local QP
$$\min_{(u^i, y^i)} \sum_{k=0}^{N-1} \left(\|y^i - y^{des,i}\|^2_Q + \|u^i - u^{des,i}\|^2_R \right)$$
s. t. $y^i = \mathcal{G}_{i,i}\begin{bmatrix} u^i_{init} \\ y^i_{init} \\ u^i \end{bmatrix} + \sum_{j\neq i} \mathcal{G}_{i,j}\begin{bmatrix} u^j_{init} \\ y^j_{init} \\ u^j_{t-1} \end{bmatrix}$
$u^i_k \in \mathcal{FC}, \; y^i_k \in \mathcal{Y}, \quad k = 0, \ldots, N-1$

Agent $i+1$
Distributed Data-Driven Predictive Control — Local QP

Agent i
Previously-computed optimal local solution and feedback to share with other agents $\begin{bmatrix} u^i_{init,t-1} \\ y^i_{init,t-1} \\ u^i_{t-1} \end{bmatrix}$

Offline Simulations for the Computation of the Hankel Matrices
Transition Matrix $\mathcal{G}$

One-Step Delay Communication Channel

QP-Based Nonlinear Control for Tracking and Whole-Body Motion Control — 1 kHz

QP-Based Nonlinear Control for Tracking and Whole-Body Motion Control

QP-Based Nonlinear Control for Tracking and Whole-Body Motion Control

Reduced-order states | Joint-level torques
Optimal trajectory for tracking
Full-order states | Experiments

Distributed MPC (a) (b) (c) (d)

Distributed DDPC (a) (b) (c) (d)

Experimental and Numerical Validation

Success Rates over Random Rough Terrains
Centralized MPC
Distributed MPC
Nominal MPC
Success Rate (%)
Centralized MPC: 54.2%
Distributed MPC: 53.8%
Nominal MPC: 0%
Distance (m)
(a)

Distributed DDPC
Rough Terrain
$\dot{x}$, z, $\dot{y}$, Roll, Pitch
Loose Gravel
(b)

Broader Impacts

The broader impacts include deploying ubiquitous collaborative legged robots in different aspects of human society, designing an innovative curriculum on robot locomotion at the VT site, and sustaining a STEM-based outreach initiative for K-12 students and teachers at VT and Caltech sites.

See More for Experiments
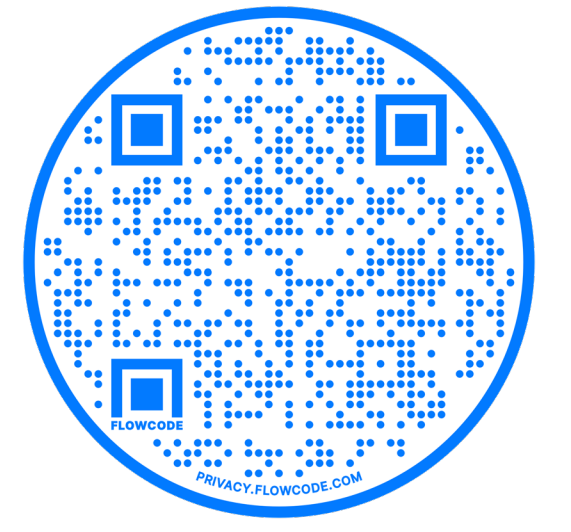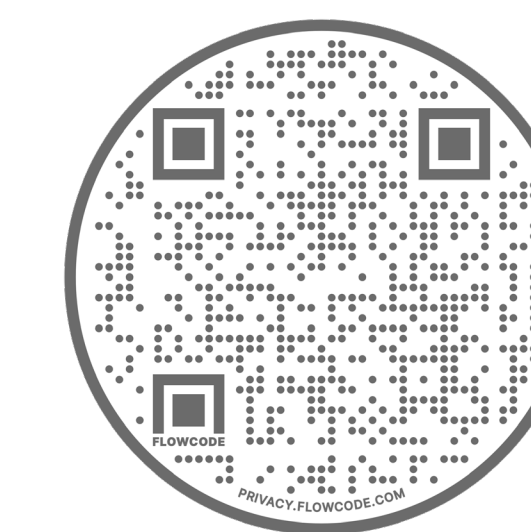
Publications

- J. Kim, R. T. Fawcett, V. R. Kamidi, **A. D. Ames**, and **K. Akbari Hamed**, "Layered control for cooperative locomotion of two quadrupedal robots: Centralized and distributed approaches," *IEEE Transactions on Robotics*, Under review, Revised on March 2023 (arXiv:2211.06913)

- R. T. Fawcett, L. Amanzadeh, J. Kim, **A. D. Ames**, and **K. Akbari Hamed**, "Distributed data-driven predictive control for multi-agent collaborative legged locomotion," *IEEE International Conference on Robotics and Automation (ICRA)*, Accepted to Appear, January 2023 (arXiv:2211.06917)

- J. Kim and **K. Akbari Hamed**, "Cooperative locomotion via supervisory predictive control and distributed nonlinear controllers," *ASME Journal of Dynamic Systems, Measurement, and Control*, 144(3), 031005, December 2021

- R. T. Fawcett, K. Afsari, **A. D. Ames**, and **K. Akbari Hamed**, "Toward a data-driven template model for quadrupedal locomotion," *IEEE Robotics and Automation Letters*, vol. 7, issue 3, pp. 7636-7643, July 2022

- A. Pandala, R. T. Fawcett, U. Rosolia, **A. D. Ames**, and **K. Akbari Hamed**, "Robust predictive control for quadrupedal locomotion: Learning to close the gap between reduced- and full-order models," *IEEE Robotics and Automation Letters*, vol. 7, issue 3, pp. 6622-6629, July 2022