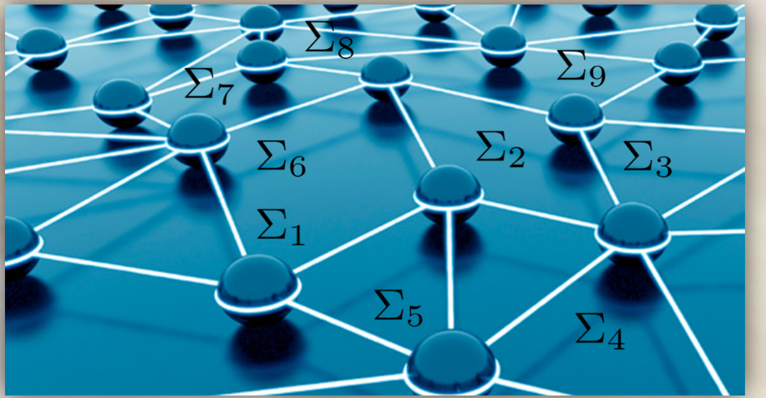
NRI: Decentralized Feedback Control Design for Cooperative Robotic Walking with Application to Powered Prosthetic Legs

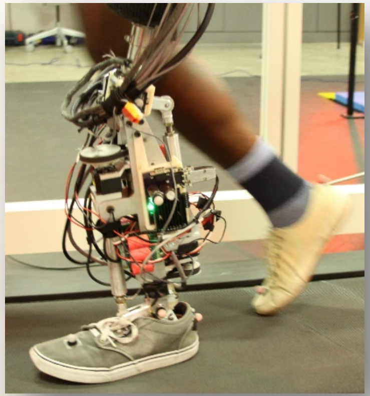
PI: Kaveh Akbari Hamed

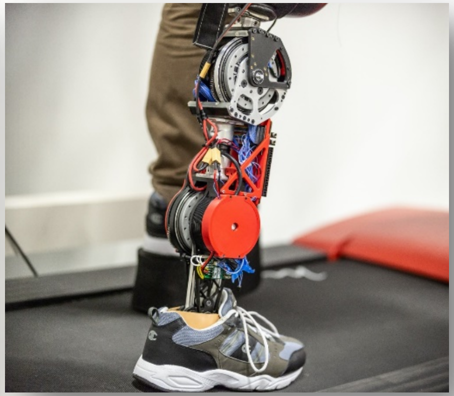
Assistant Professor
Hybrid Dynamic Systems and Robot Locomotion Laboratory
Department of Mechanical Engineering
Virginia Tech

Co-PI: Robert D. Gregg

Assistant Professor
Locomotor Control Systems Laboratory
Department of Mechanical Engineering
The University of Texas at Dallas



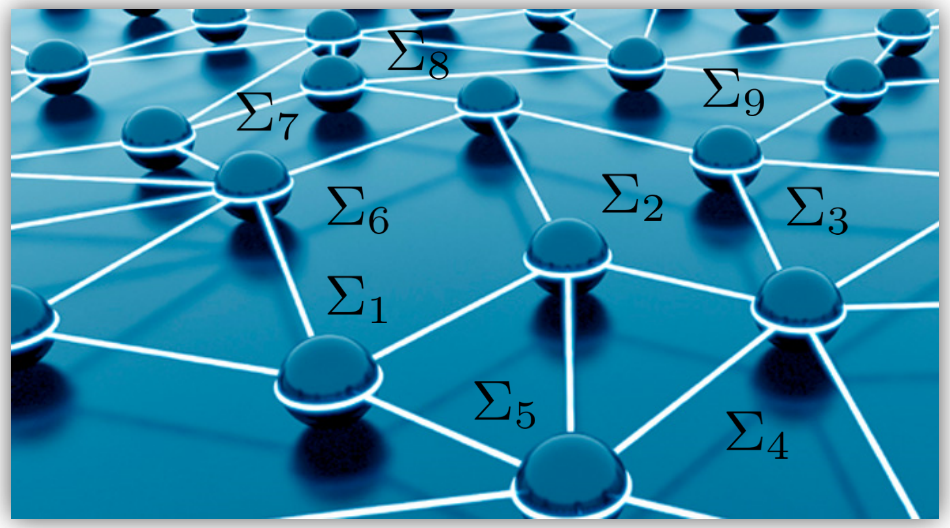


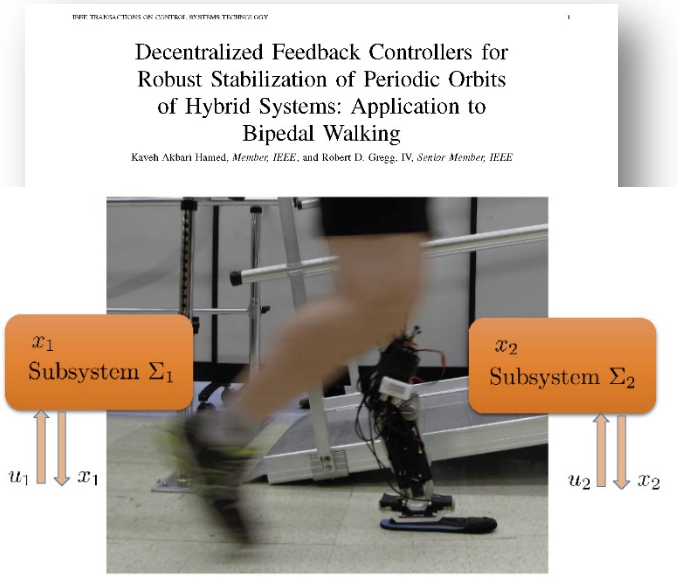


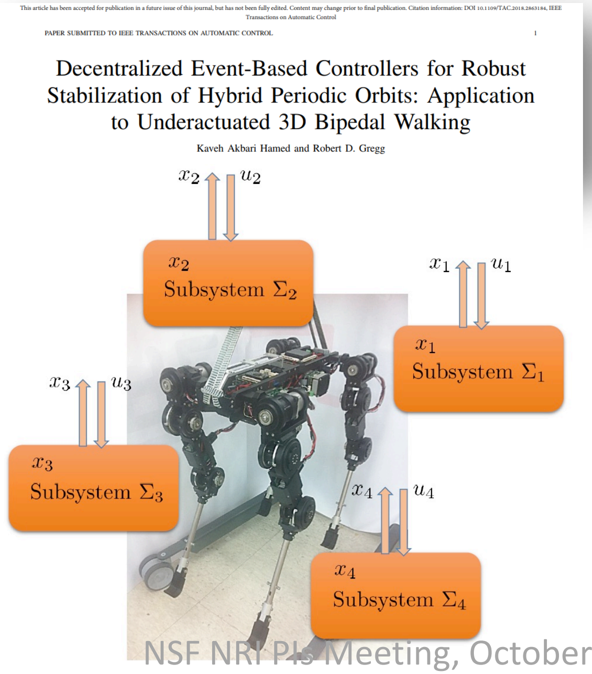
Research Goals

*The **overarching goal** of this project is to create a **potentially transformative** decentralized feedback control framework to robustly stabilize walking trajectories of legged robots through cooperative subsystems.*

1) *To create systematic algorithms that synthesize decentralized feedback controllers to robustly stabilize periodic orbits of hybrid dynamical systems;*
2) *To experimentally realize decentralized feedback control architectures on a 3D quadruped robot and a powered prosthetic leg.*

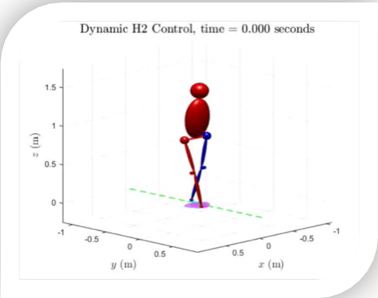


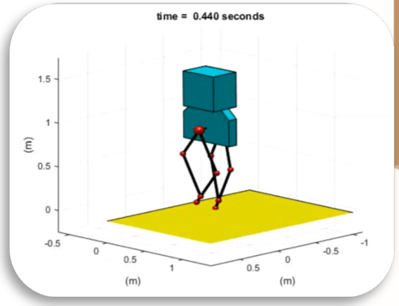


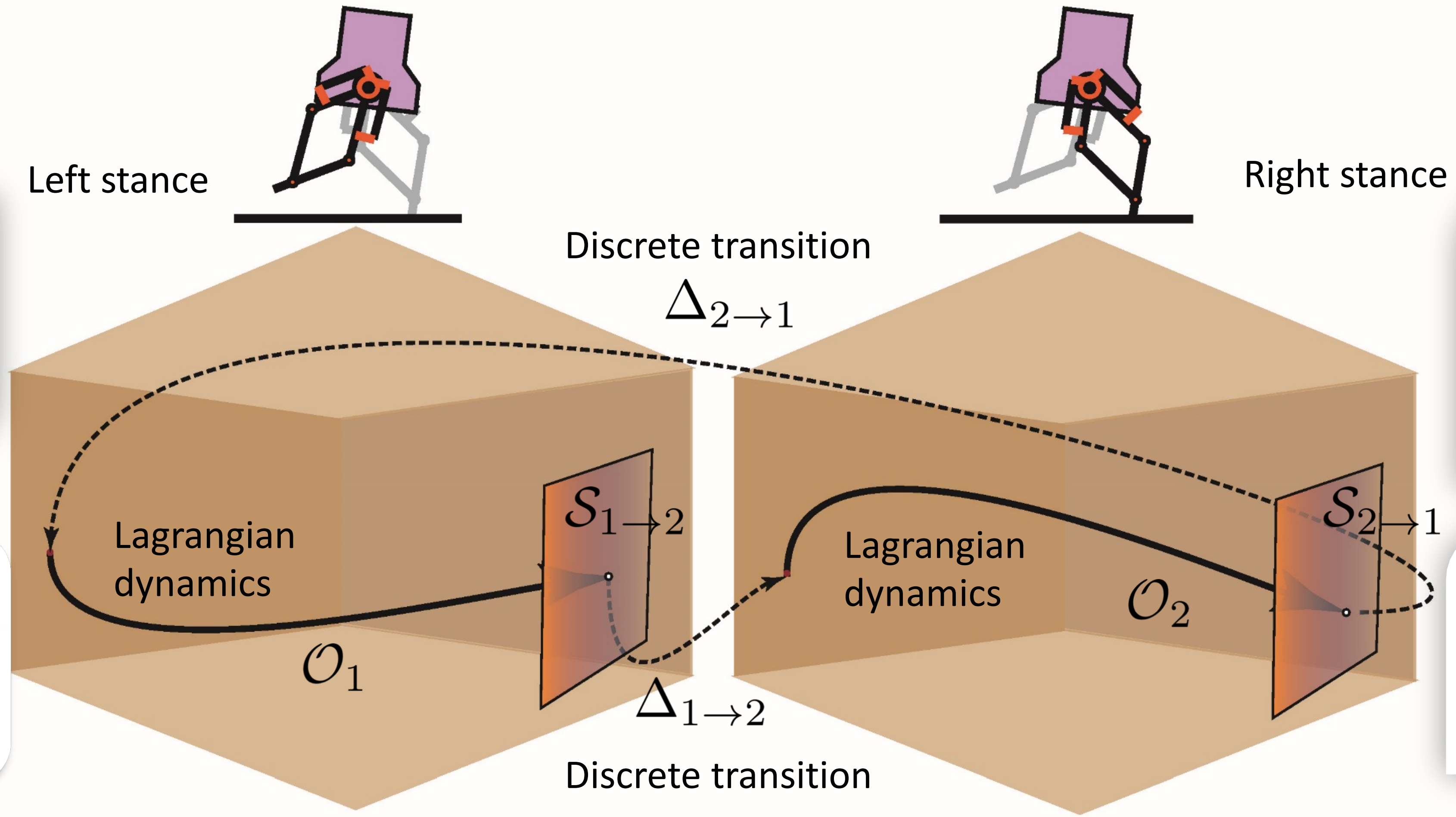


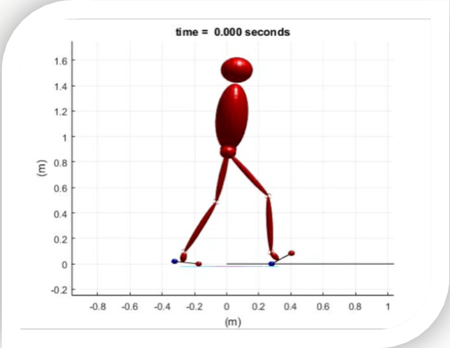
Hybrid Models and Periodic Orbits

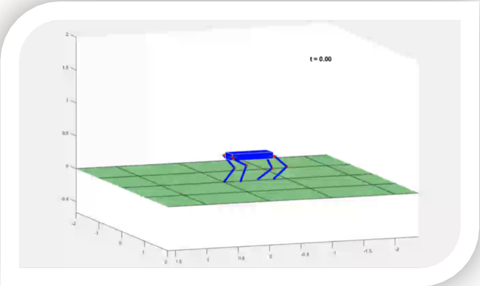
Walking locomotion can be modeled as ***periodic solutions*** *of the hybrid model.*











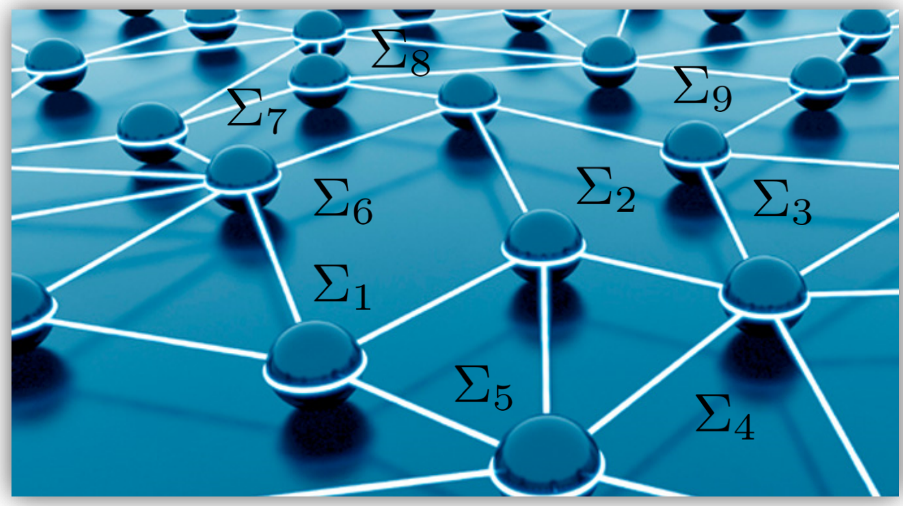
Cooperative Hybrid Subsystems

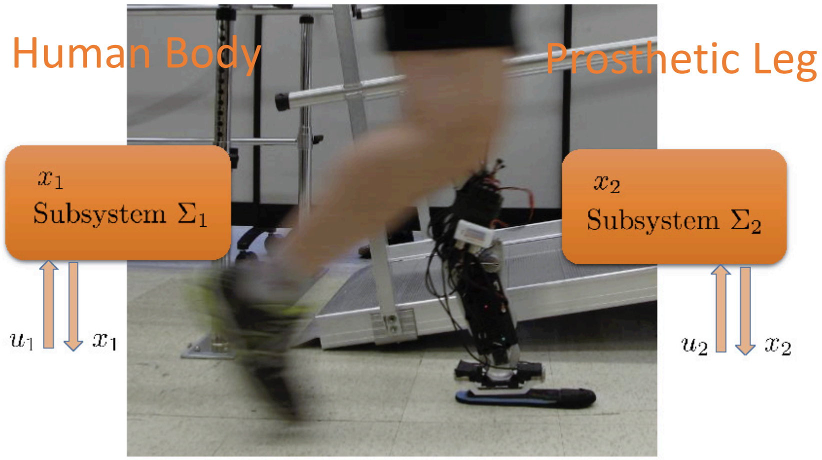
Subsystem i
$1 \le i \le N$

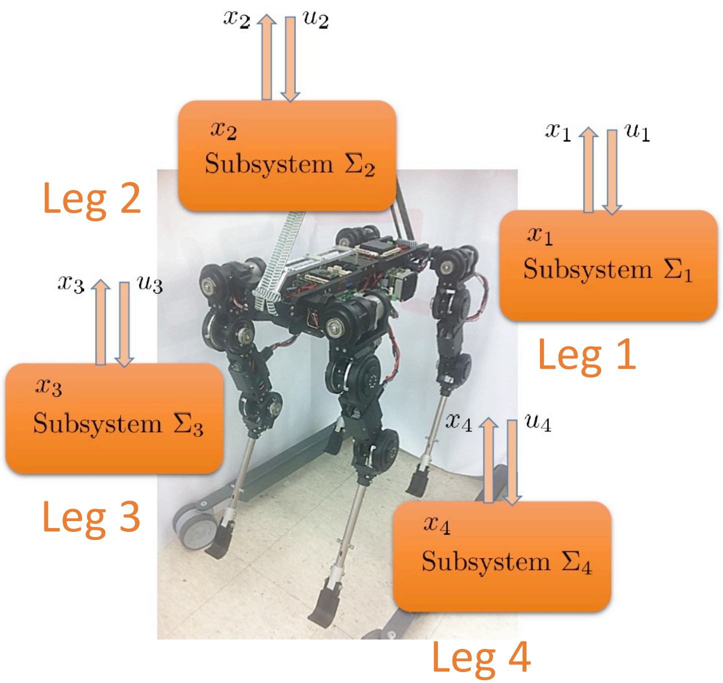
$$\Sigma_i : \begin{cases} \dot{x}_i = f_i(x_1, x_2, \cdots, x_N) + \sum_{j=1}^{N} g_{ij}(x_1, x_2, \cdots, x_N)\, u_j, & x^- \notin \mathcal{S} \\ x_i^+ = \Delta_i(x_1^-, x_2^-, \cdots, x_N^-) + d_i, & x^- \in \mathcal{S} \end{cases}$$

$x_i \in \mathcal{X}_i \subset R^{n_i}$: Local State Variables
$u_i \in \mathcal{U}_i \subset R^{m_i}$: Local Control Inputs
$d_i \in \mathcal{D}_i \subset R^{n_i}$: Local Uncertainty

$$x = (x_1^\top, x_2^\top, \cdots, x_N^\top)^\top$$
$$u = (u_1^\top, u_2^\top, \cdots, u_N^\top)^\top$$



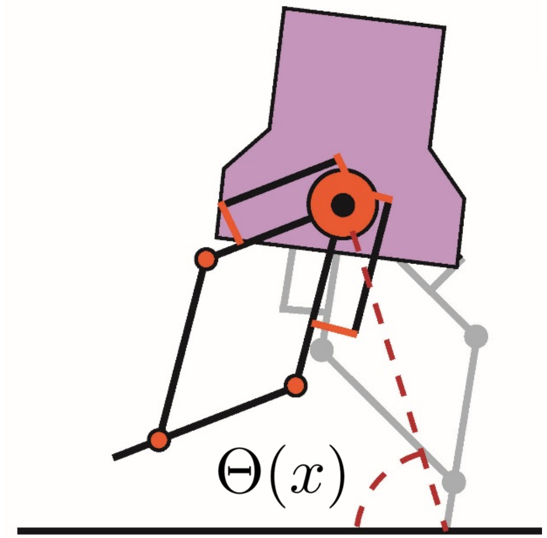


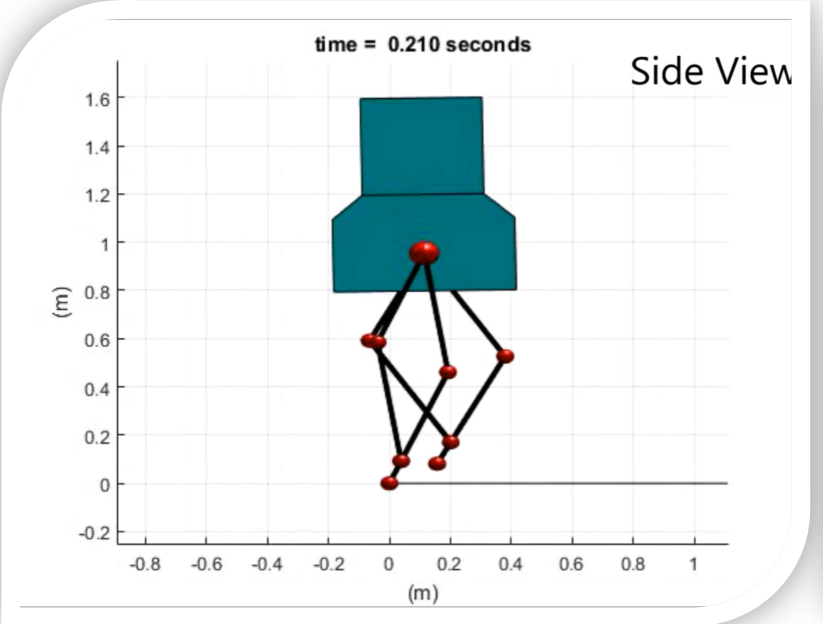


Coordination of Subsystems

Phasing Variable: *A strictly increasing scalar variable that represents the progress of the robot on the periodic orbit*

Example: The links are synchronized by the crank angle (**phasing variable**).





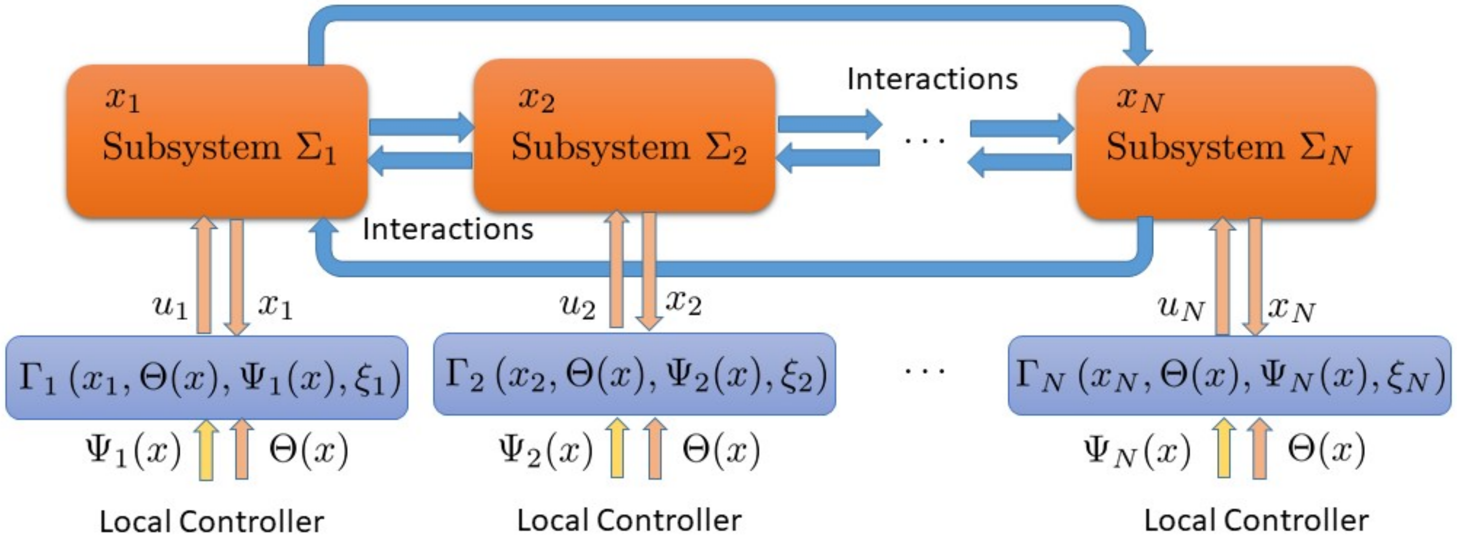
Example: Typical phasing variable for bipedal walking

Proposed Decentralized Controllers

Class of parameterized and general nonlinear feedback laws

$$u_i = \Gamma_i\left(x_i, \Theta(x), \Psi_i(x), \xi_i\right), \quad i \in \{1, 2, \cdots, N\}$$

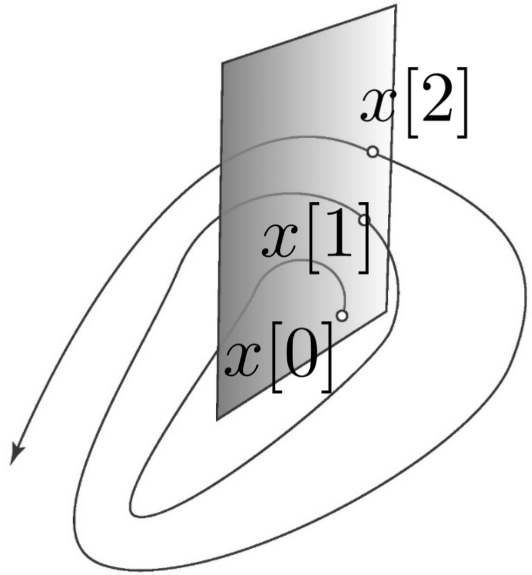
- Feedback laws have access to their own **local measurements** (local state variables) as well as a **subset of measurable global variables**.



Robust Stabilization Problem

Parameterized Poincaré Map with controlled outputs and exogenous inputs

$$\mathcal{P} : \begin{cases} x[k+1] = P\left(x[k], \xi, d[k]\right) \\ c[k] = c\left(x[k]\right) \end{cases}$$



$d[k] \in \mathcal{D}$: discrete-time uncertainty (exogenous inputs)
$c[k] \in \mathcal{C}$: discrete-time outputs to be controlled

Linearization around $(x, d) = (x^\star, 0)$

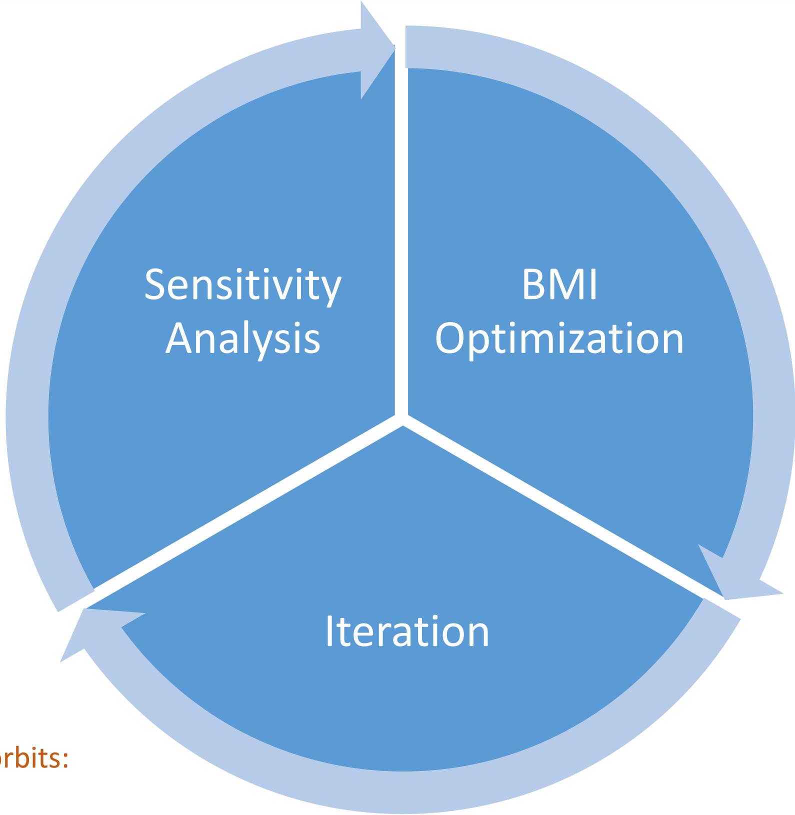
$$\partial\mathcal{P} : \begin{cases} \delta x[k+1] = \dfrac{\partial P}{\partial x}\left(x^\star, \xi, 0\right)\, \delta x[k] + \dfrac{\partial P}{\partial d}\left(x^\star, \xi, 0\right)\, d[k] \\ \delta c[k] = \dfrac{\partial c}{\partial x}\left(x^\star\right)\, \delta x[k] \end{cases}$$

Iterative Semidefinite Programs

We develop an effective numerical algorithm based on a sequence of iterative and offline optimization problems involving Bilinear and Linear Matrix Inequalities (BMIs and LMIs) to overcome specific difficulties arising from the lack of closed-form expression for the Poincaré map, high dimensionality, and underactuation in tuning the parameters of decentralized feedback controllers.

$$\|T_{dc}\|^2_{\mathcal{H}_2} := \frac{1}{2\pi}\int_{-\pi}^{\pi} \mathrm{trace}\left(T^{\mathsf{H}}_{dc}\left(e^{j\omega}\right)T_{dc}\left(e^{j\omega}\right)\right)\mathrm{d}\omega < \mu$$

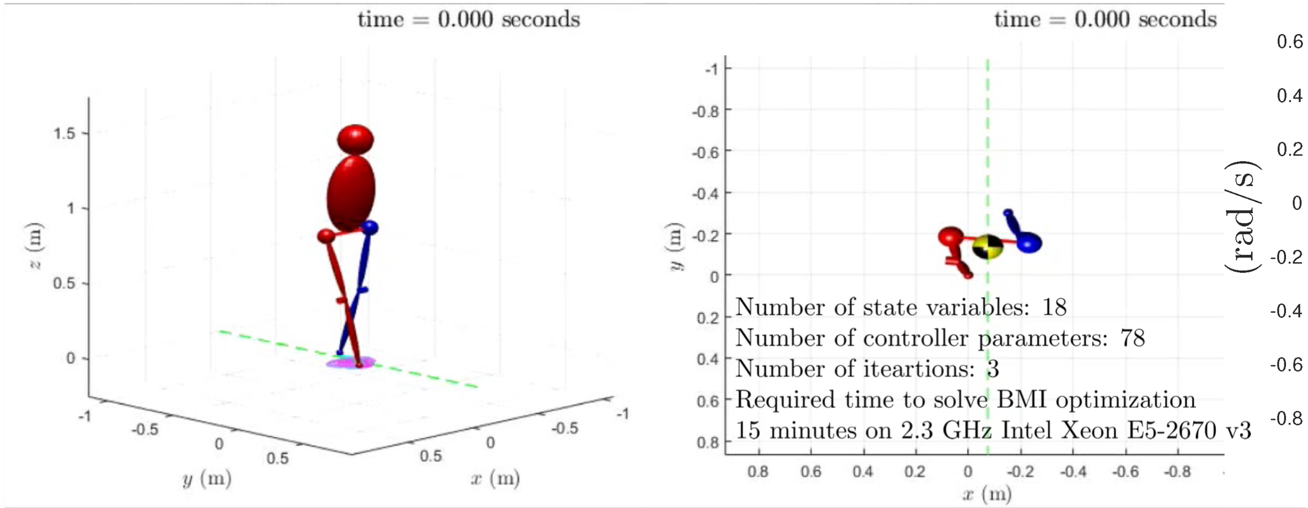
$$\|T_{dc}\|^2_{\mathcal{H}_\infty} := \sup_{\|d\|_{\mathcal{L}_2}} \frac{\|\delta c\|_{\mathcal{L}_2}}{\|d\|_{\mathcal{L}_2}} < \mu$$



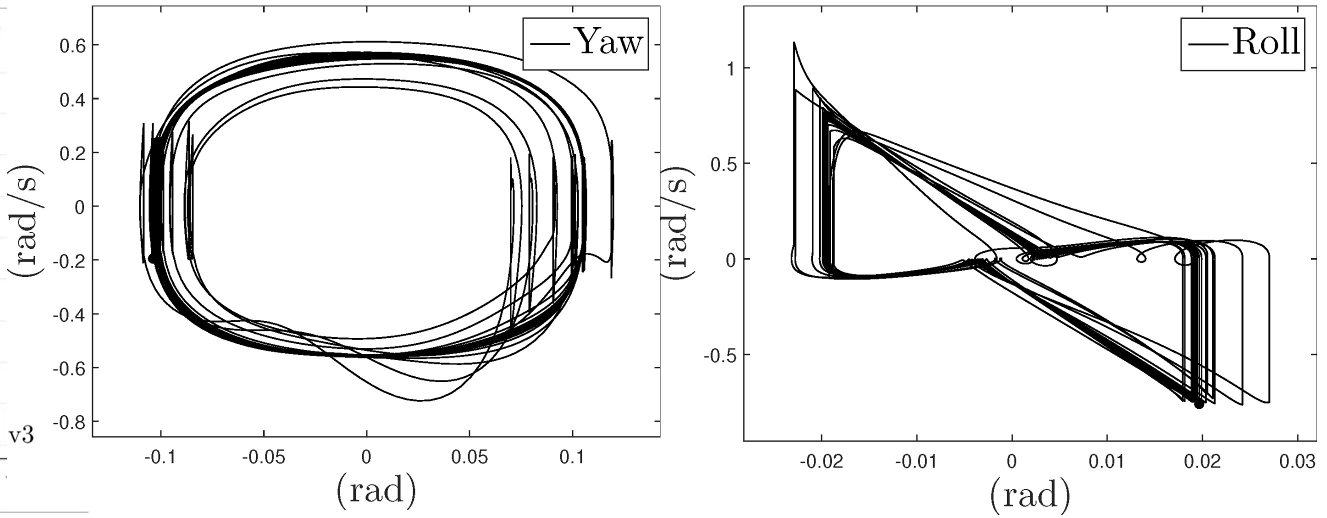
- K. Akbari Hamed and R. D. Gregg, "Decentralized event-based controllers for robust stabilization of hybrid periodic orbits: Application to underactuated 3D bipedal walking," *IEEE Transactions on Automatic Control*, In Press, August 2018
- K. Akbari Hamed and R. D. Gregg, "Decentralized feedback controllers for robust stabilization of periodic orbits of hybrid systems: Application to bipedal walking," *IEEE Transactions on Control Systems Technology*, vol. 25, issue 4, pp. 1153-1167, July 2017

Application to Prosthetic Legs

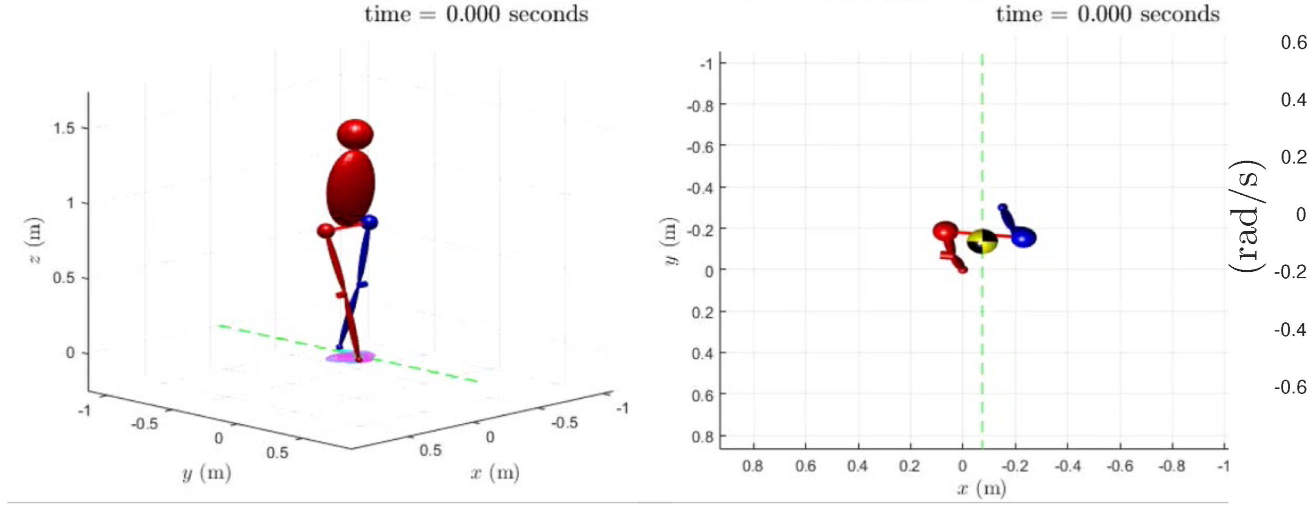
$\mathcal{H}_2$-Optimal Decentralized Control



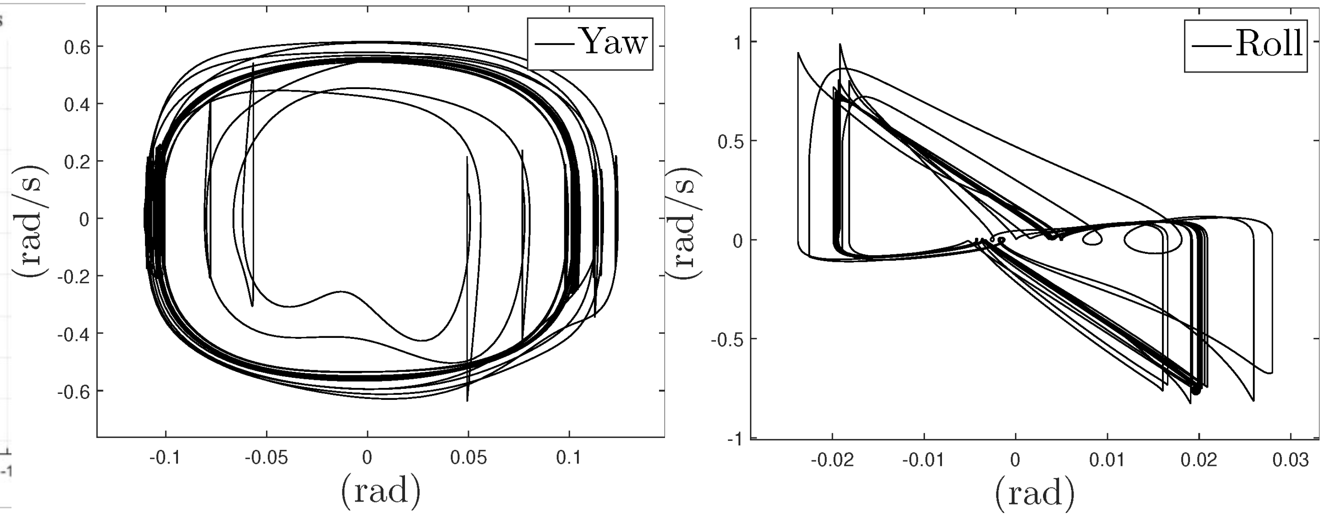
$\mathcal{H}_2$-Optimal Decentralized Control



$\mathcal{H}_\infty$-Optimal Decentralized Control

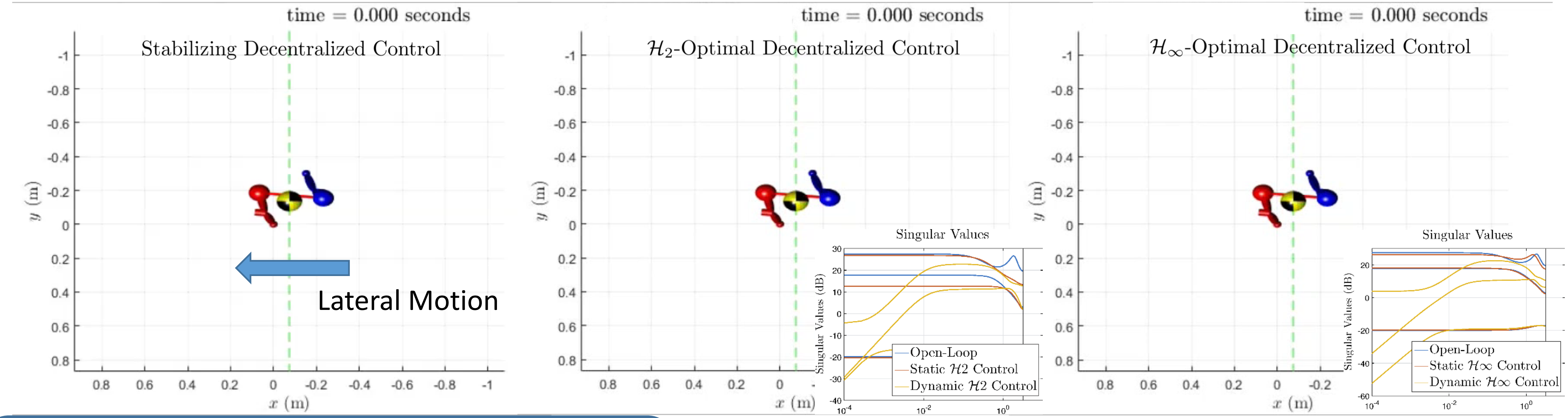


$\mathcal{H}_\infty$-Optimal Decentralized Control



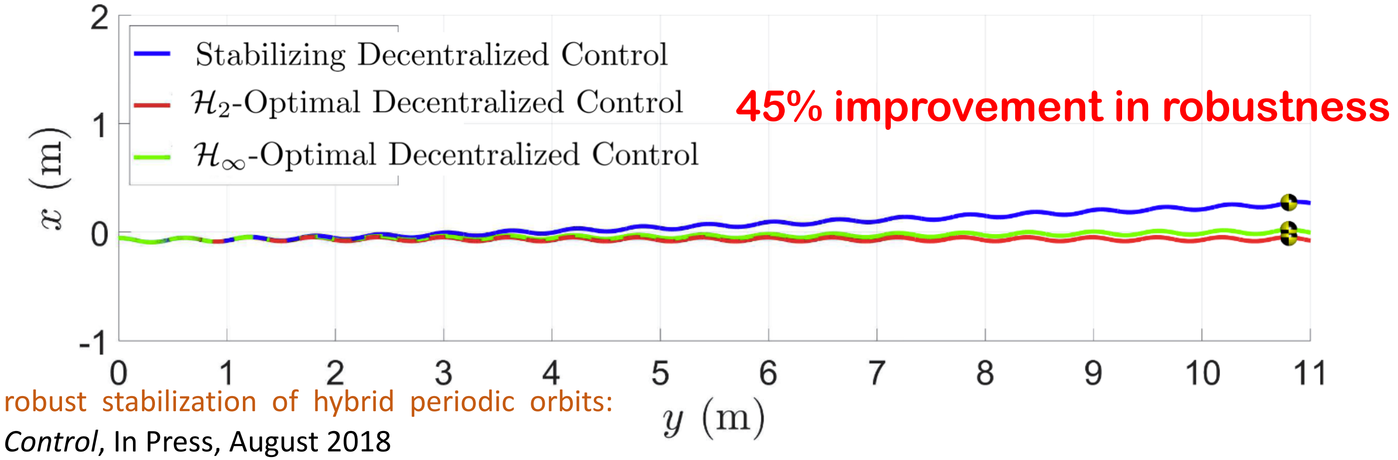
- K. Akbari Hamed and R. D. Gregg, “Decentralized event-based controllers for robust stabilization of hybrid periodic orbits: Application to underactuated 3D bipedal walking,” *IEEE Transactions on Automatic Control*, In Press, August 2018

Application to Prosthetic Legs



$$\Sigma : \begin{cases} \dot{x} = f(x) + g(x)\,u, & x^- \notin \mathcal{S} \\ x^+ = \Delta(x^-) + d, & x^- \in \mathcal{S} \end{cases}$$

Step Disturbance Input in the Velocity Components of the Impact Map



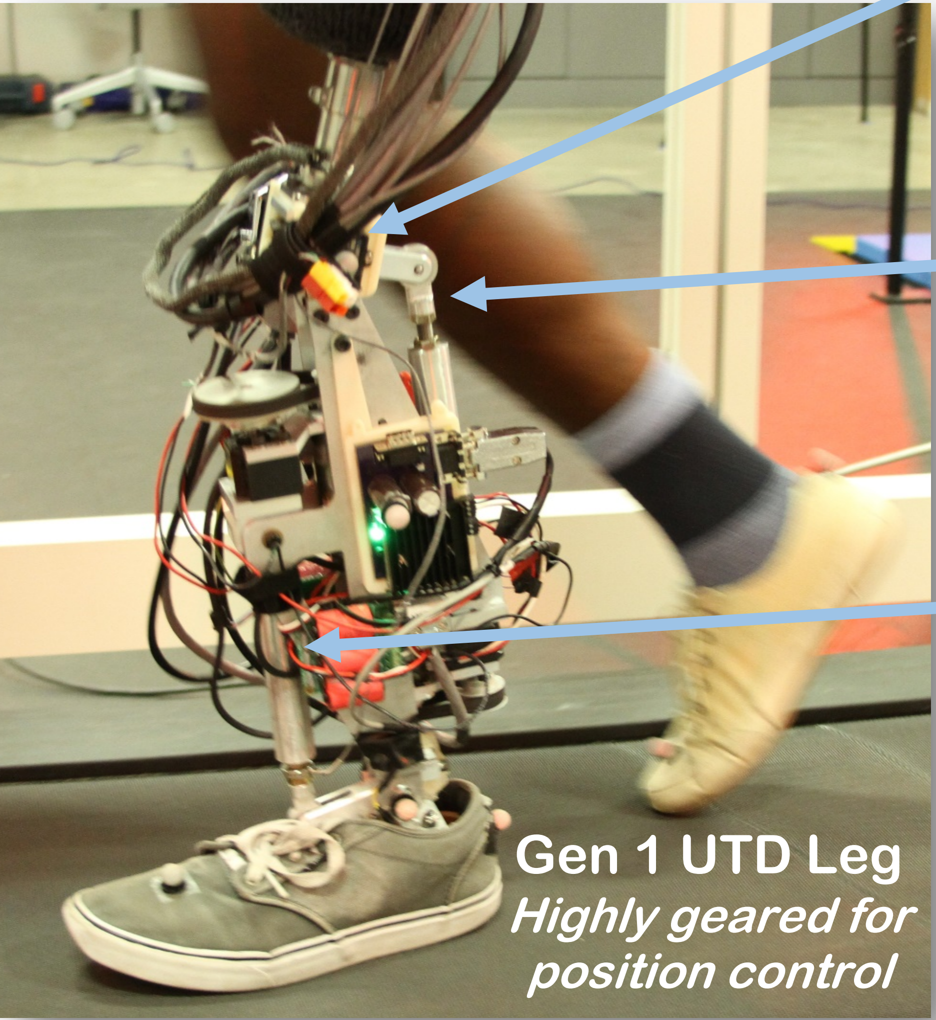
- K. Akbari Hamed and R. D. Gregg, "Decentralized event-based controllers for robust stabilization of hybrid periodic orbits: Application to underactuated 3D bipedal walking," *IEEE Transactions on Automatic Control*, In Press, August 2018
- K. Akbari Hamed and R. D. Gregg, "Decentralized feedback controllers for robust stabilization of periodic orbits of hybrid systems: Application to bipedal walking," *IEEE Transactions on Control Systems Technology*, vol. 25, issue 4, pp. 1153-1167, July 2017

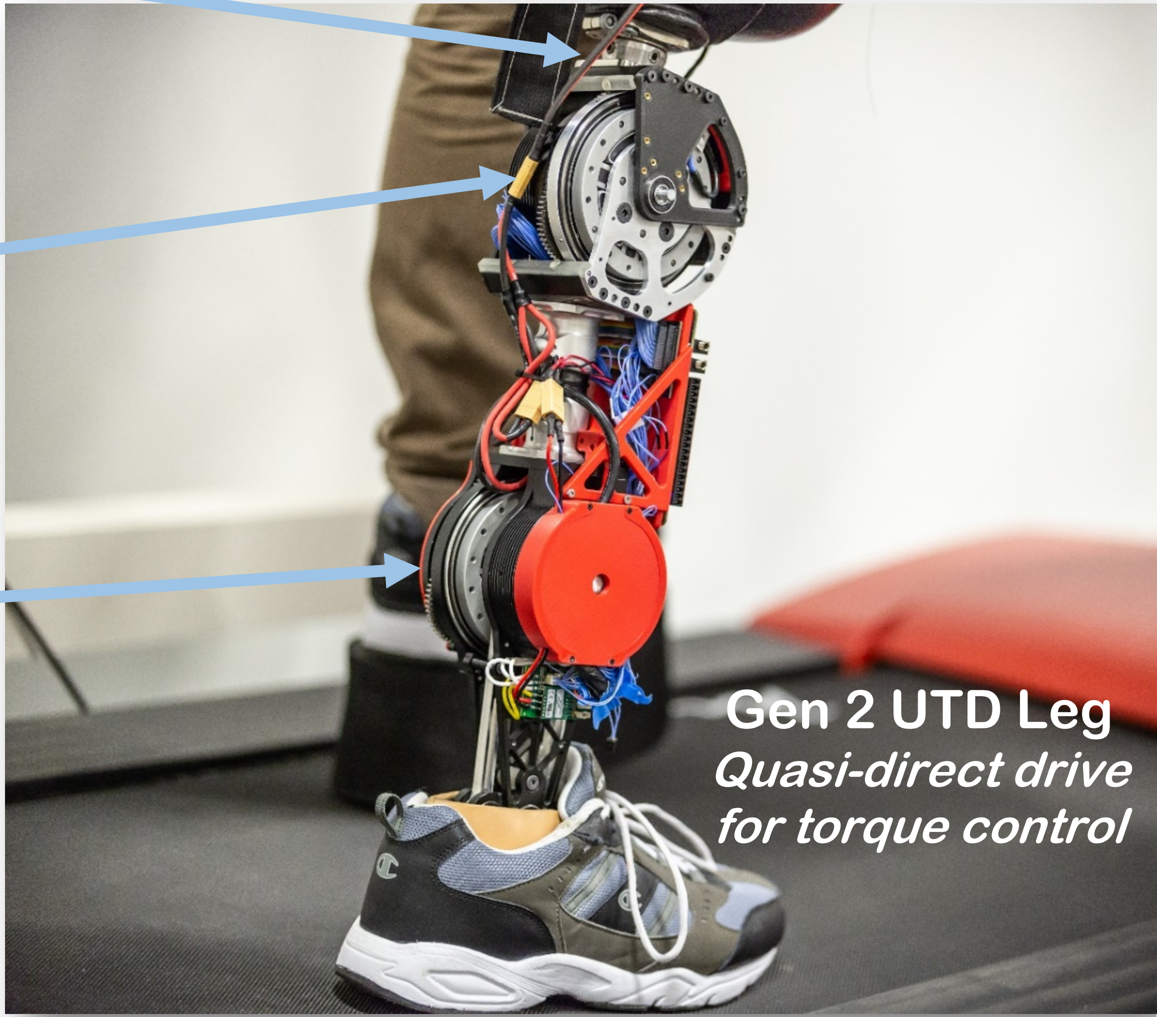
Two Prosthesis Testbeds for Decentralized Control

inertial measurement unit
for phase variable

knee actuator

ankle actuator

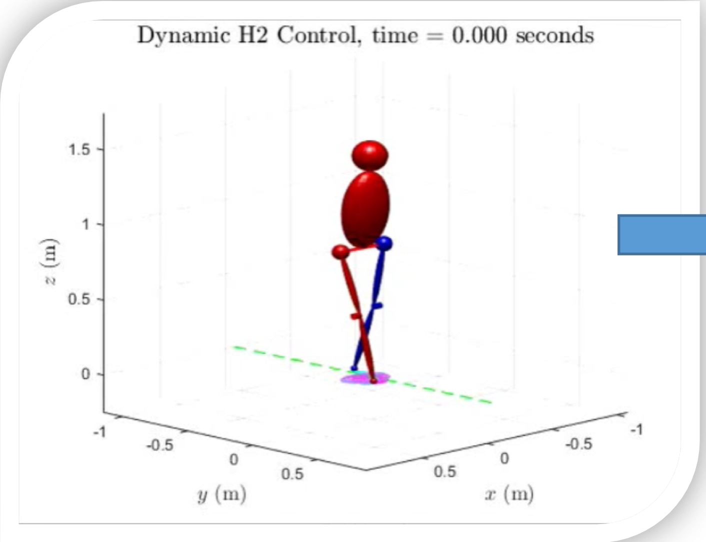


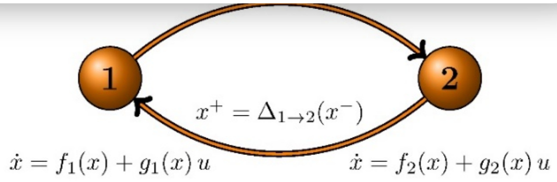


- D. Quintero, D. J. Villarreal, D. J. Lambert, S. Kapp and R. D. Gregg, "Continuous-phase control of a powered knee-ankle prosthesis: Amputee experiments across speeds and inclines," *IEEE Transactions on Robotics*, vol. 34, no. 3, pp. 686-701, June 2018

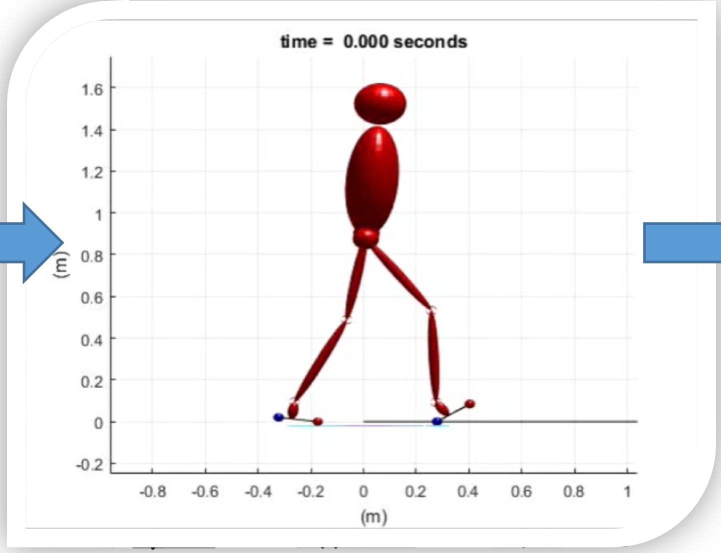
Application to Prosthetic Legs

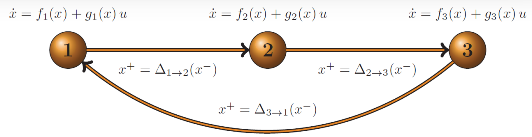
Double-Domain Model



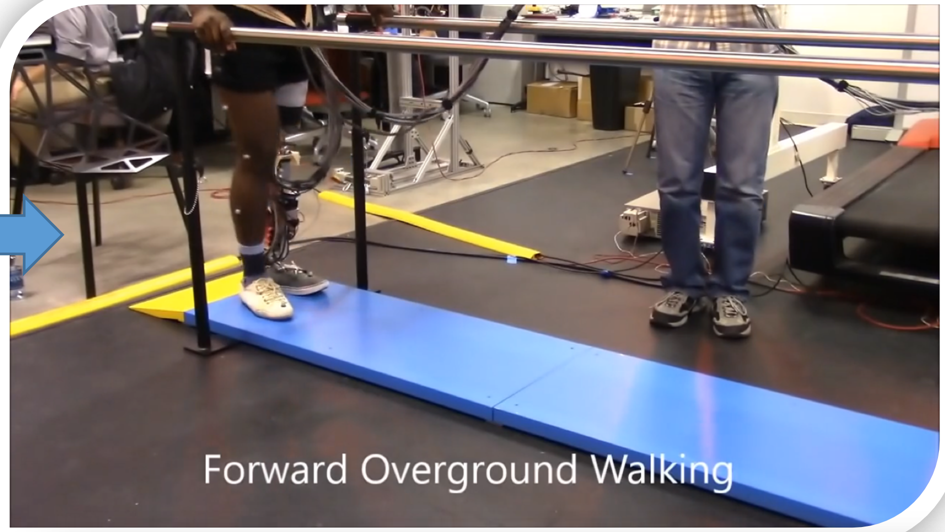


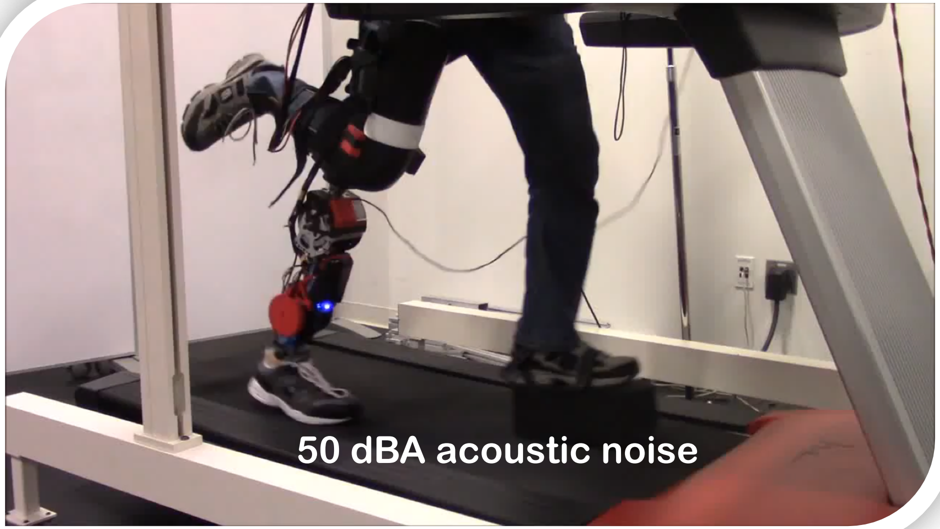
Multi-Domain Model





Next step: To transfer the algorithm to the UT Dallas leg

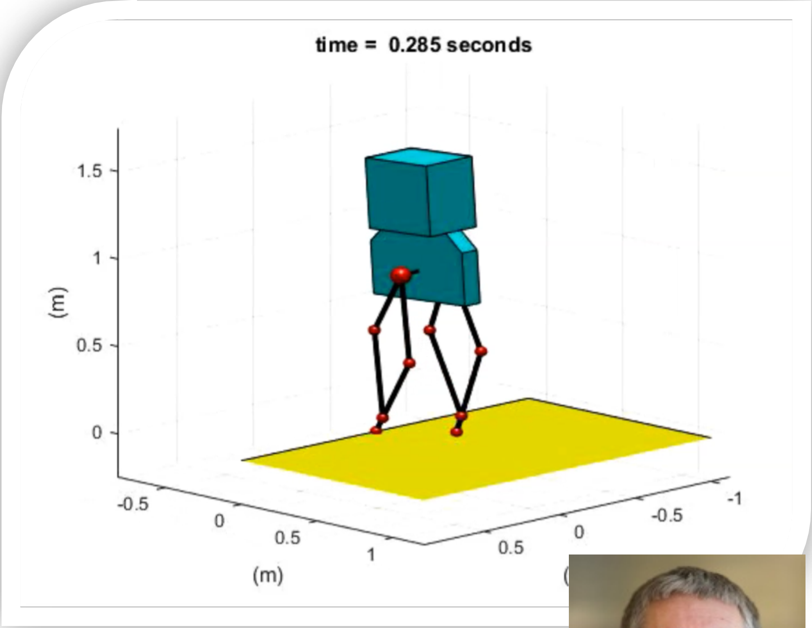




- K. Akbari Hamed and R. D. Gregg, "Decentralized event-based controllers for robust stabilization of hybrid periodic orbits: Application to underactuated 3D bipedal walking," *IEEE Transactions on Automatic Control*, In Press, August 2018
- K. Akbari Hamed and R. D. Gregg, "Decentralized feedback controllers for robust stabilization of periodic orbits of hybrid systems: Application to bipedal walking," *IEEE Transactions on Control Systems Technology*, vol. 25, issue 4, pp. 1153-1167, July 2017
- D. Quintero, D. J. Villarreal, D. J. Lambert, S. Kapp and R. D. Gregg, "Continuous-phase control of a powered knee-ankle prosthesis: Amputee experiments across speeds and inclines," *IEEE Transactions on Robotics*, vol. 34, no. 3, pp. 686-701, June 2018
- K. Akbari Hamed, R. D. Gregg, and A. D. Ames, "Exponentially stabilizing controllers for multi-contact 3D bipedal locomotion," *American Control Conference (ACC)*, pp. 2210-2217, Milwaukee, WI, June 2018

Application to Autonomous Bipedal Robots

ATRIAS
- **3D bipedal robot with 13 DOFs and 7 DOUs (6 Actuators)**
- **55 Kg**

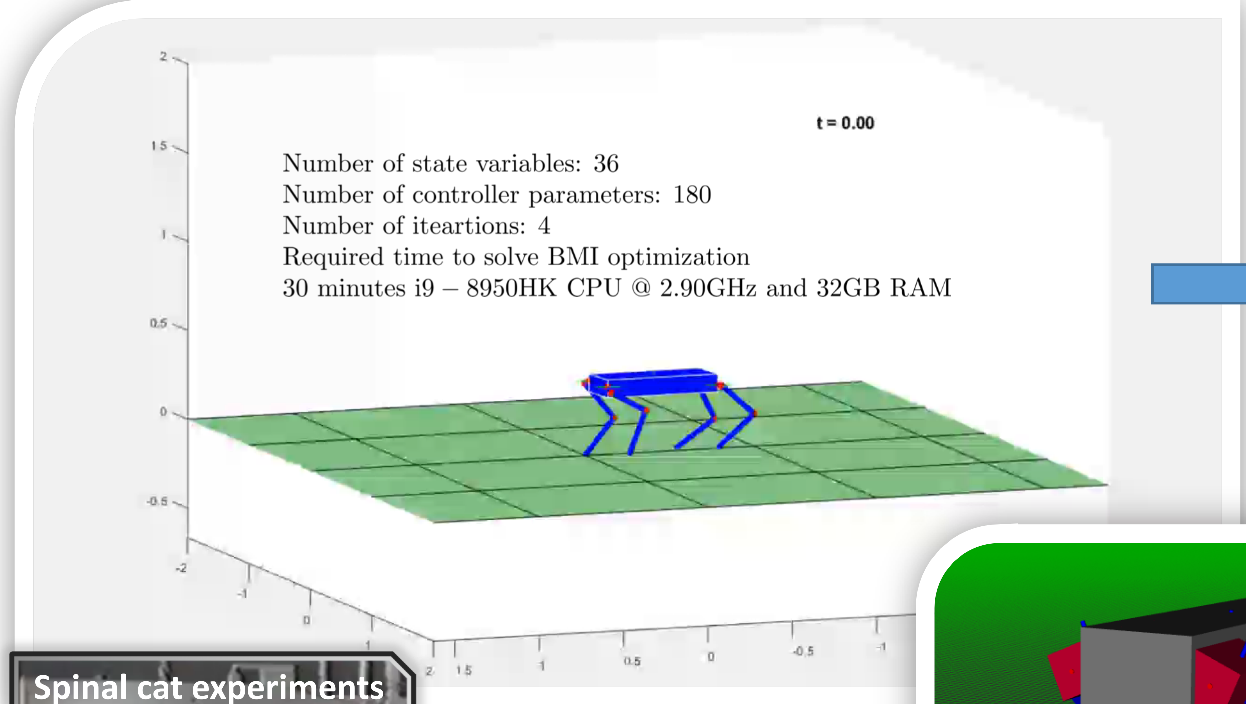


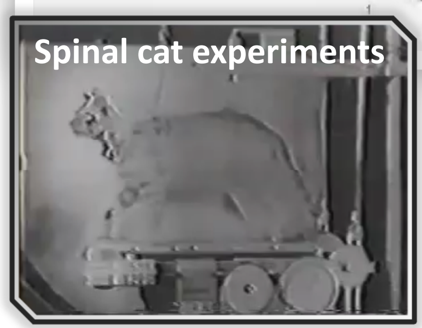
Dr. Jessy Grizzle
UMich

- K. Akbari Hamed, B. G. Buss, and J. W. Grizzle, "Exponentially stabilizing continuous-time controllers for periodic orbits of hybrid systems: Application to bipedal locomotion with ground height variations," *The International Journal of Robotics Research*, vol. 35, issue 8, pp. 977-999, August 2016
- B. G. Buss, K. Akbari Hamed, B. A. Griffin, and J. W. Grizzle, "Experimental results for 3D bipedal robot walking based on systematic optimization of virtual constraints," *The 2016 American Control Conferences (ACC)*, pp. 4785-4792, Boston, MA, July 2016

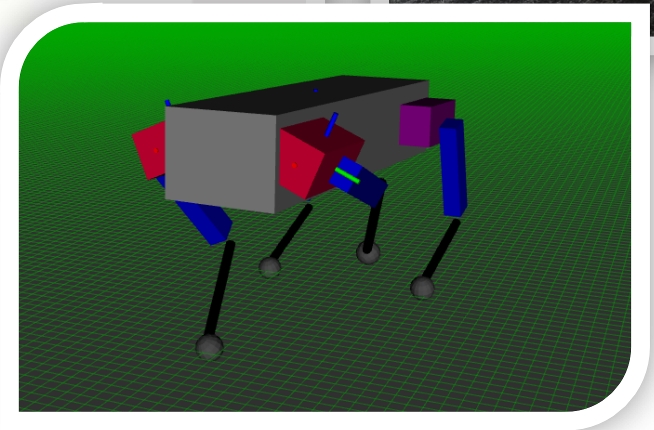
Application to Autonomous Quadruped Robots

Dynamic Stable 3D Quadruped Walking with the BMI Algorithm (Amble Gait)





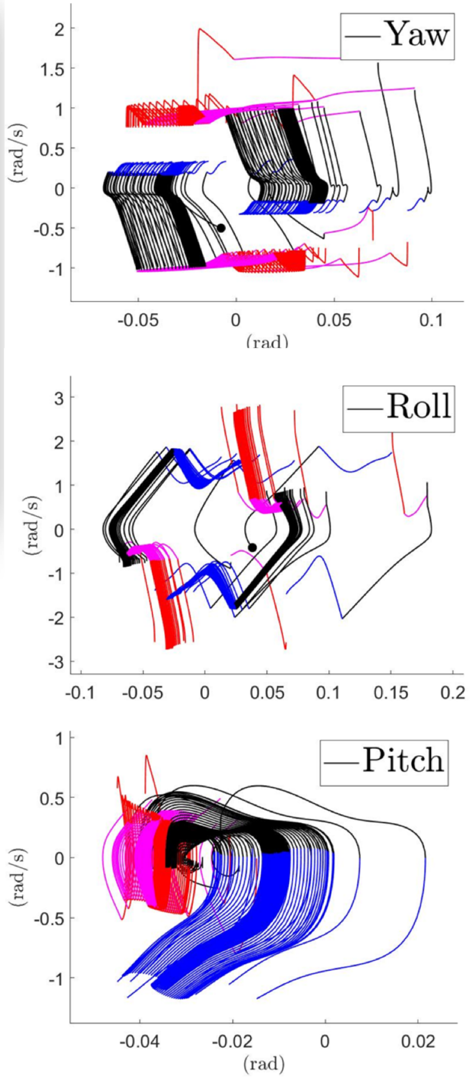
Next step: To transfer the algorithm to Vision 60 at VT



Vision 60

- 3D quadruped robot with 18 DOFs and 6 DOUs (12 Actuators)
- 20 Kg

Dr. Aaron Ames
Caltech



- K. Akbari Hamed, W. Ma, A. D. Ames, "Dynamically stable 3D quadruped walking with multi-domain hybrid system models and virtual constraint controllers," 2019 American Control Conference, Under Review, 2018

Thank you for your attention.