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

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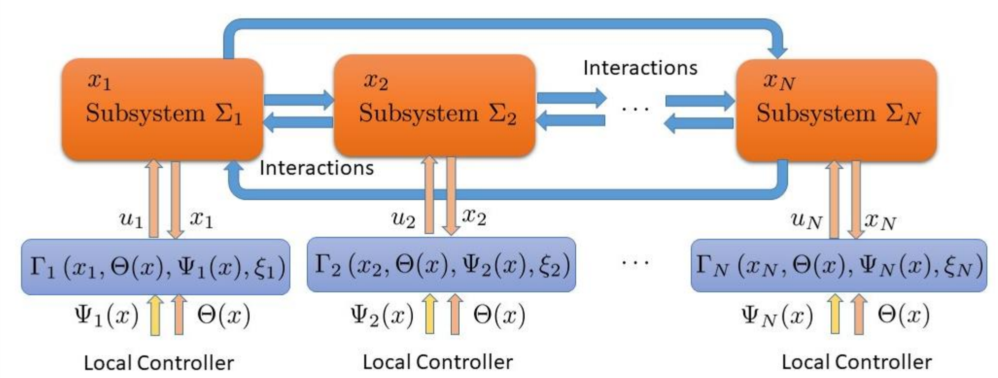
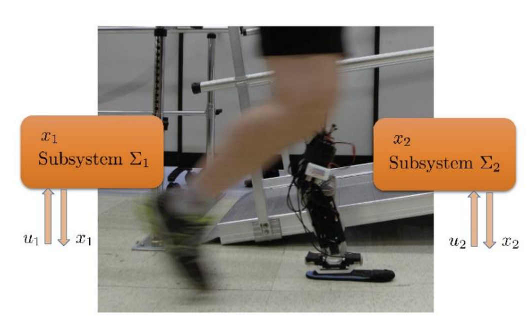
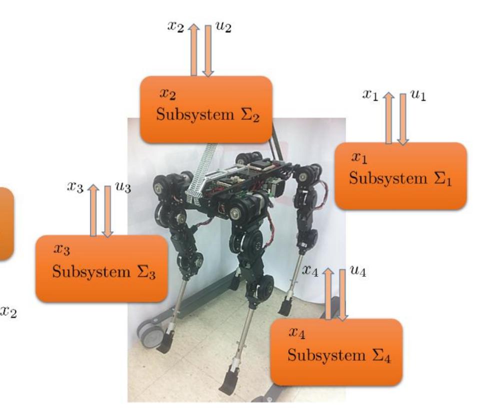
Significance and Challenges

- The centralized nature of nonlinear control methods required to achieve stable locomotion *cannot* scale with the dimensionality of the increasingly sophisticated legged robots.
- This *curse of dimensionality* presents a key roadblock to the application of traditional centralized nonlinear controllers to legged robots, which can be addressed by systematically decentralizing these control methods.
- Although powered prosthetic legs already use decentralized feedback controllers related to joint impedance, this linear control method requires different control parameters at different time periods to handle the nonlinear dynamics of the gait cycle.
- This necessitates the application of decentralized nonlinear feedback controllers and thereby underlines the need for algorithms to systematically design these controllers.

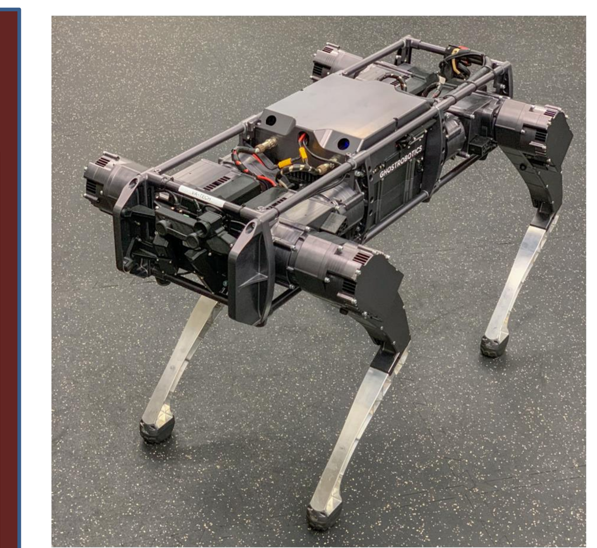


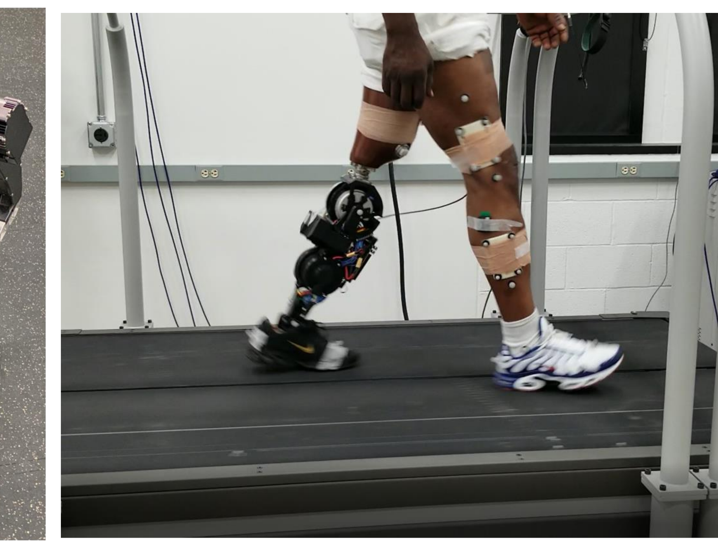


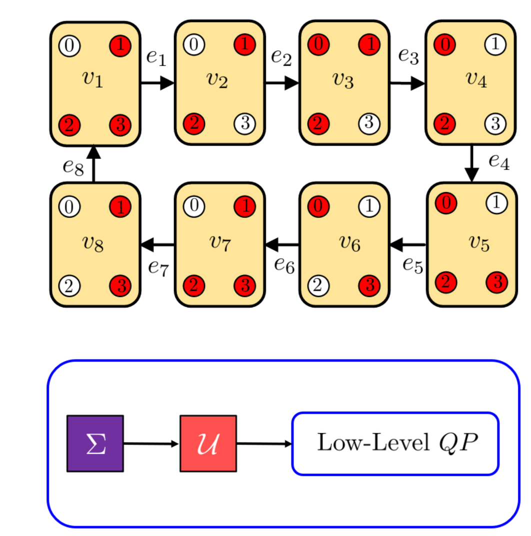


Goals and Scientific Impact

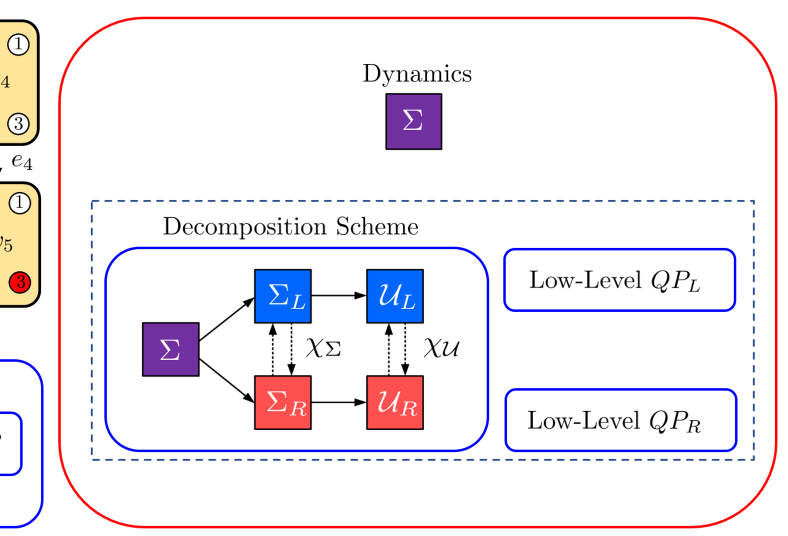
- The **overarching goal** of this project is to investigate a **potentially transformative** decentralized feedback control framework for robustly stabilizing the walking trajectories of legged robots through cooperative subsystems.
- We aim to derive *rigorous optimization algorithms* that provably generate robust decentralized controllers for hybrid systems.
- We aim to investigate decentralized feedback control architectures for robotic quadruped locomotion.
- We aim to investigate decentralized feedback control architectures for robotic prosthetic legs by human amputees subjects.







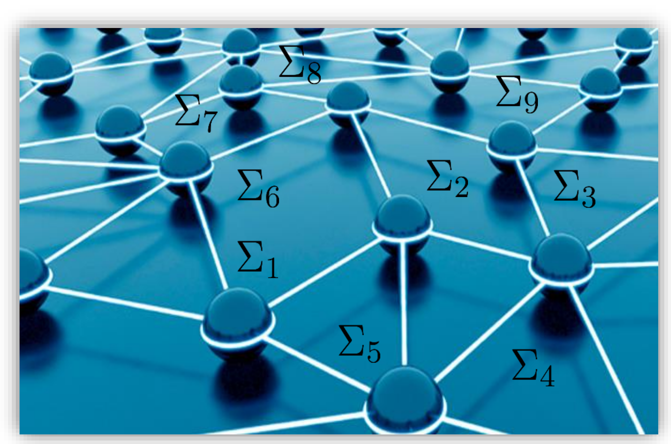
Centralized Controller Synthesis

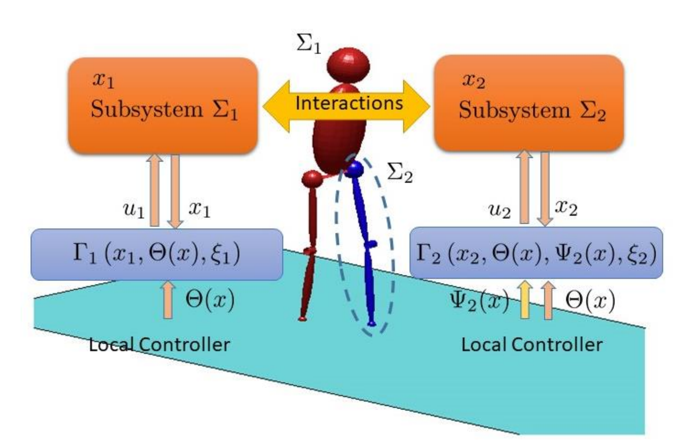


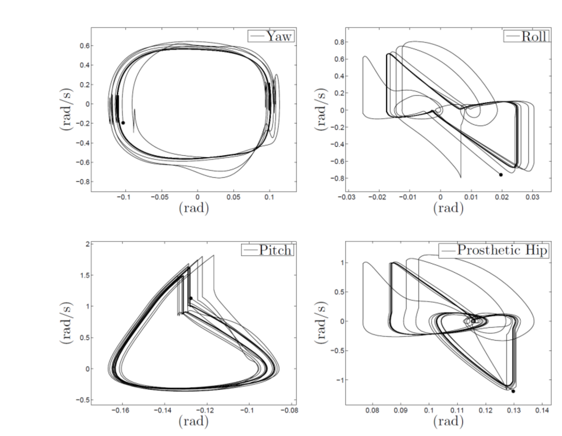
Decentralized Controller Synthesis

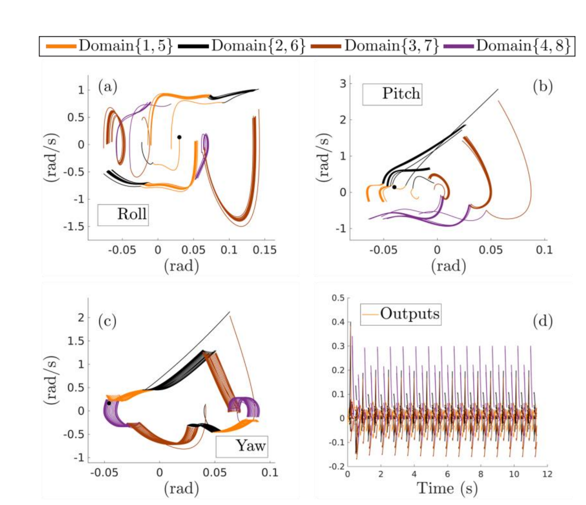
Technical Approach and Key Innovations

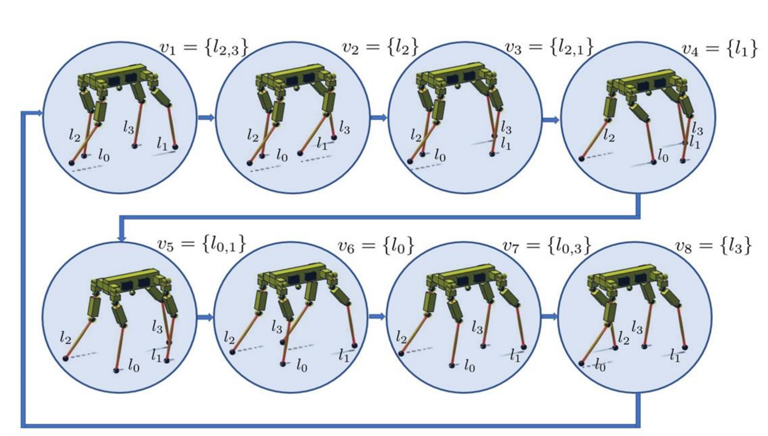
- We propose rigorous algorithms to design a class of decentralized nonlinear feedback controllers that robustly stabilize periodic orbits for the hybrid models of cooperative walking.
- The proposed algorithms assume a finite set of parameterized local controllers which are coordinated based on a common *phasing variable*.
- We investigate nonlinear stability tools for hybrid systems to formulate the problem of designing robust decentralized nonlinear controllers as an iterative optimization problem involving BMIs and LMIs.
- By design these optimization problems can be solved easily with available software packages.

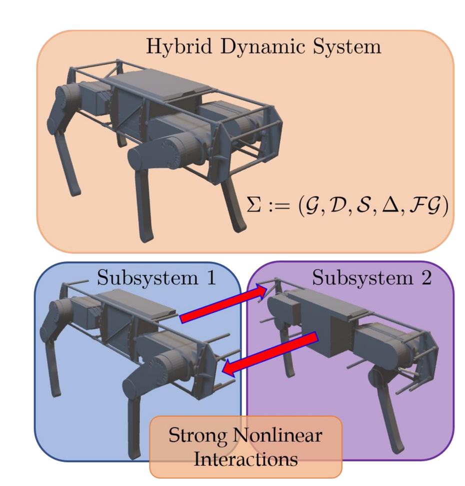












Publications

- K. Akbari Hamed and R. D. Gregg, "Decentralized event-based controllers for robust stabilization of hybrid periodic orbits," *IEEE Transactions on Automatic Control*, 2019
- K. Akbari Hamed, B. Safaee, and R. D. Gregg, "Dynamic output controllers for exponential stabilization of periodic orbits for multi-domain hybrid models of robotic locomotion," *ASME Journal of Dynamic Systems, Measurement, and Control*, 2019
- J. C. Horn, A. Mohammadi, K. Akbari Hamed, R. D. Gregg, "Nonholonomic virtual constraint design for variable-incline bipedal robotic walking," *IEEE Robotics and Automation Letters*, 2020
- J. C. Horn, A. Mohammadi, K. Akbari Hamed, and R. D. Gregg, "Hybrid zero dynamics of bipedal robots under nonholonomic virtual constraints," *IEEE Control Systems Letters*, 2019
- K. Akbari Hamed and R. D. Gregg, "Decentralized feedback controllers for robust stabilization of periodic orbits of hybrid systems: Application to bipedal waking," *IEEE Transactions on Control Systems Technology*, 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*, 2018
- K. Akbari Hamed, W. Ma, A. D. Ames, "Dynamically stable 3D quadruped walking with multi-domain hybrid system models and virtual constraint controllers," *American Control Conference*, 2019
- K. Akbari Hamed, R. D. Gregg, A. D. Ames, "Exponentially stabilizing controllers for multi-contact 3D bipedal locomotion," *American Control Conference*, 2018
- K. Akbari Hamed, A. D. Ames, and R. D. Gregg, "Observer-based feedback controllers for exponential stabilization of hybrid periodic orbits: Application to underactuated bipedal walking," *American Control Conference*, 2018

Broader Impacts on Society

- The project has *broad societal impacts*. Estimates indicate that by 2050 the U.S. will incur a two-fold increase in the incidence of amputation and stroke, due largely to the prevalence of vascular disease. This underlines the importance of our proposed decentralized control algorithms to guarantee the stability of hybrid local-central controllers during cooperative human-machine walking.
- This control technology will overcome a key roadblock to deploying agile and/or human-like co-robots to assist, or stand in for, humans in dangerous situations such as industrial accidents, homeland security events, or natural disasters.

Broader Impacts on Education and Outreach

- The integrated educational plan will have a *broad impact* on advancing robotics and control education by 1) designing a new course on legged locomotion, 2) partnership with VT and UT Dallas diversity programs, and 3) engagement of undergraduate students in research.
- Frequent lab tours to K-12 students and teachers to inspire students to pursue an education in STEM subjects.
- Legged robots appeal to "kids" of all ages and our multi-disciplinary research in controls, optimization algorithms, and robotics together with outreach activities will promote STEM subjects.

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