Constraint Aware Planning and Control for Cyber-Physical Systems

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Overview

Challenge:

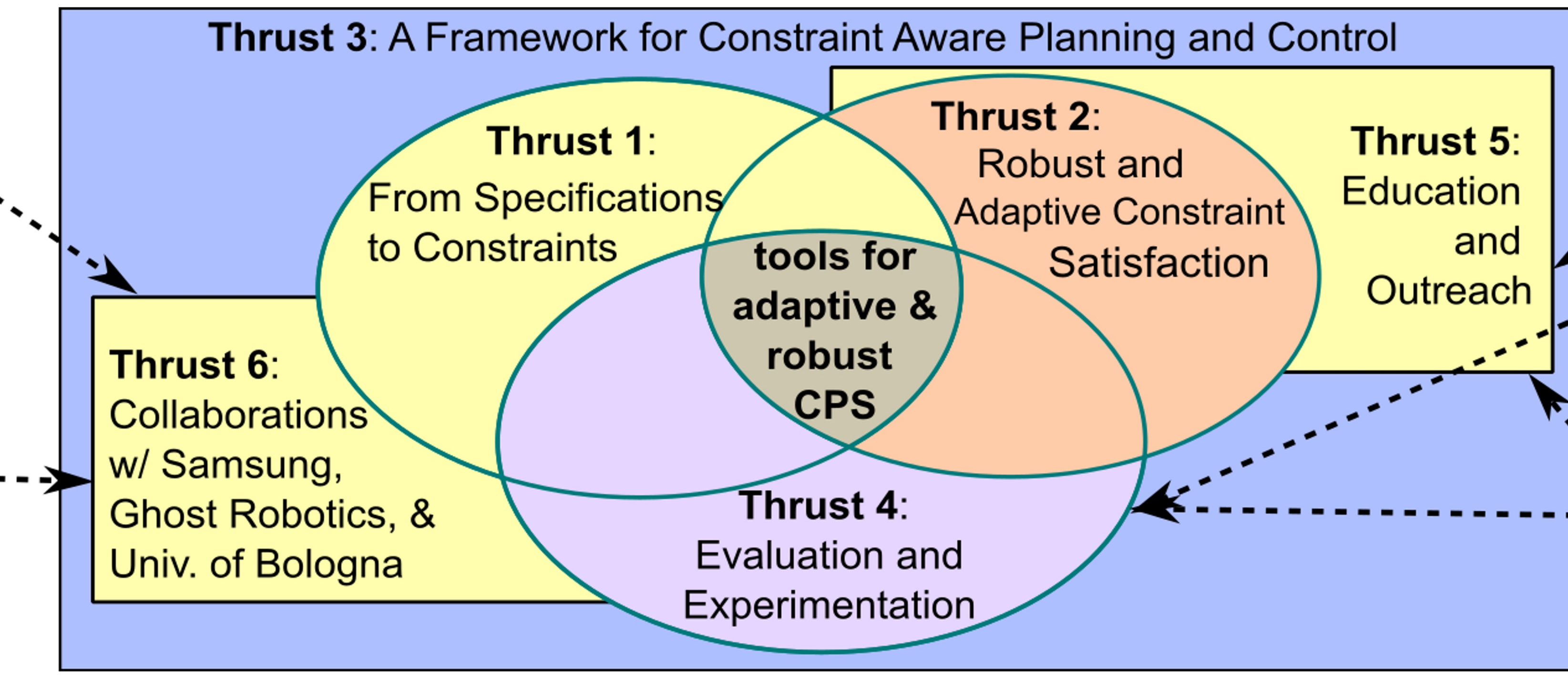
Enable robust, adaptive planning & control for nonlinear, nonsmooth, & constrained systems, while respecting their physical constraints and meeting specifications.

Significance:

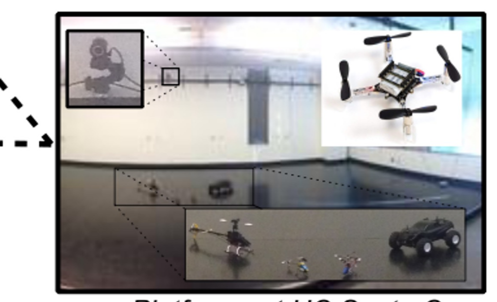
The need for this project arises from the difficulty of combining planning, safety, and robustness in the control of physical systems in general and hybrid cyber-physical systems in particular.

Industry Collaborators

Collaboration with U Bologna on regulation for aerial vehicles



Platforms at University of Michigan



Platforms at UC Santa Cruz

Solutions:

- **Generate a framework for the design of algorithms that self-adapt to jointly plan the motion and control the CPS, with robustness.**
- **Design algorithms that self-learn and self-adapt in real time to cope with unexpected changes in the physics and in the specification to enable autonomous systems to perform tasks robustly and safely.**
- **Formulate tools that reason about specifications and physics as vertically-integrated modular and reconfigurable constraints.**

Technical Approach

Thrust 1: From Specifications and Physics to Geometric Planning Informed by Constraints

Approach: Classical control focuses on physics based models, robustified against noise and modeling error using feedback. We enrich the tools available with: 1) hard constraints defined via a pullback from relevant output spaces; 2) soft constraints defined through the manipulation of the Riemannian pseudometric of the state-space; 3) learned constraints, defined in data-driven from using examples of desirable behaviors.
The hard and soft constraints together can be used to solve for an actuation policy at high speeds, while still maintaining the semantic origins of each constraint, and informing the response to its violation

Thrust 2: Robust and Adaptive Constraint Satisfaction

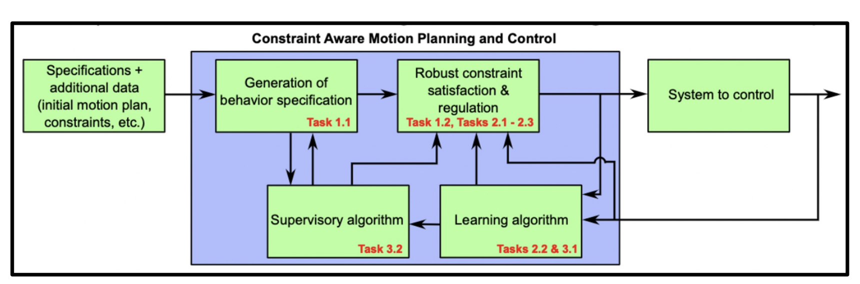
Approach: Using the constraints determined from physics and specifications in Thrust 1, we will develop notions and tools to assure robust and adaptive satisfaction of those constraints.

We will investigate the following notions of robust safety:

- An "always robust" constraint satisfaction notion that preserves the satisfaction of the constraints in the presence of sufficiently small disturbances.
- An "approximate robust" notion guaranteeing that constraint satisfaction degrades gracefully.
- A "selective robust" notion.

Thrust 3: A Framework for Dynamic Constraint Aware Planning and Control

Approach: We bring together the results from Thrust 1 and Thrust 2 to build a framework for robust and adaptive planning and control with awareness of the physical and specification constraints.



This framework implements algorithms that make the decision of which constraints to use at each time while guaranteeing their robust satisfactionwith adaptation to disturbances. These algorithms will be essentially ready-made for constrained motion planning.

Thrust 4: Evaluation/Experimentation Plan

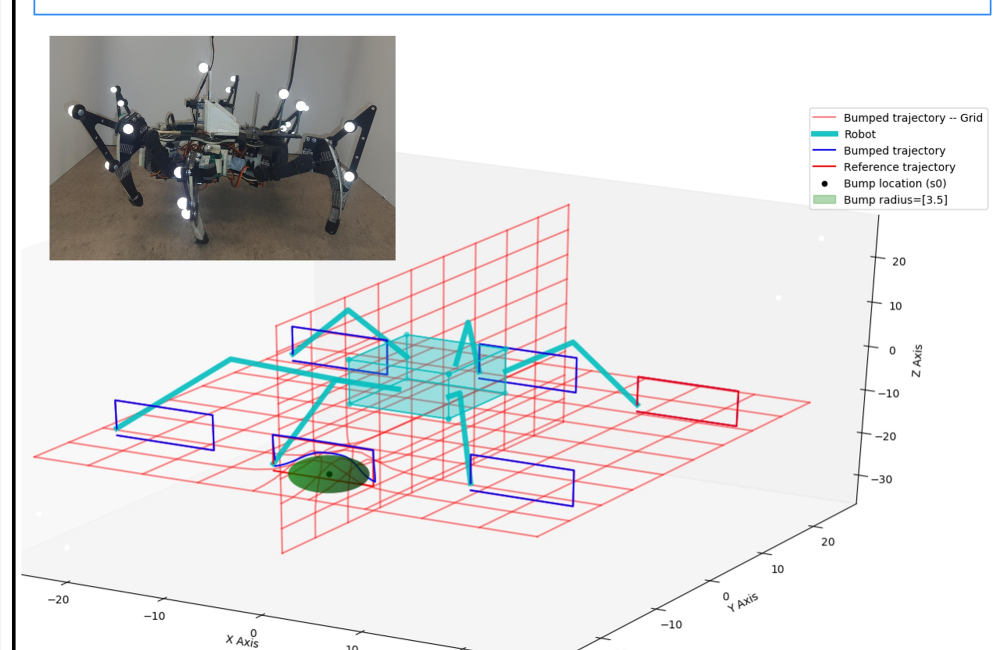
Approach: We will test the effectiveness of our control methods with several legged robotic platforms: an 18-DOF kinematic hexapod robot (SpiderBot, see right), a 10-DOF dynamically running hexapod robot with ground contact detection, and a commercial ``dog-like" dynamic quadruped with 12-DOF actuation.

Initially, we will test our ideas regarding rapid recovery from damage using the slowly moving SpiderBot. We will test the feasibility of quickly updating constraint lists using the ground-contact detecting hexapod, and apply the principles we learnt to larger Ghost Robotics Spirit robot.

Results

Data Driven Constraints For Recovery From Damage [1]

Goal: Demonstrate the utility of learning implicit constraints from an example behavior, and using those constraints to recover the behavior quickly once the robot suffers damage.



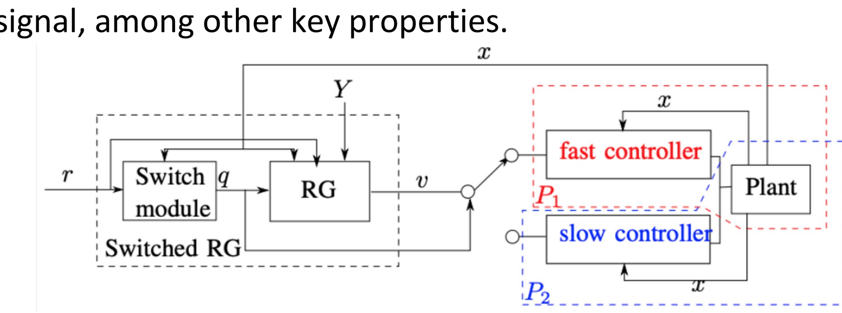
The "SpiderBot" platform is an 18 DOF hexapod with an on-board PixyCam for tracking colored beacons. The robot is also equipped with motion tracking markers allowing its true world-frame configuration to be recorded in real-time.

We are currently exploring a biologically inspired method to search the space of trajectories when recovering from damage using the approach explored in previous reporting periods. This method diffeomorphically deforms the space around the robot while leaving the robot kinematic model intact. Because the deformation is not related to robot's complexity, it can easily scale to 18 DOF or even much higher dimensions.

Safety with Multiple Constraints [3]

Goal: Design a switched reference governor framework to achieve high performance tracking under constraints.

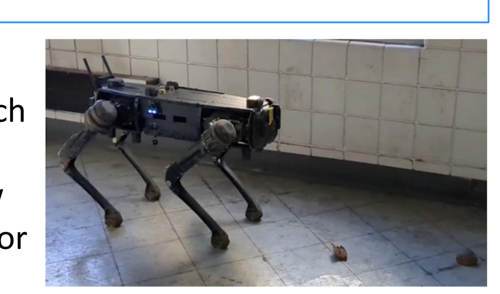
We designed a switched reference governor (RG) algorithm to achieve rapid and non-oscillatory convergence to a given reference signal while satisfying the imposed constraints by switching between a fast controller and a non-oscillatory controller. We showed robust switching, recursive feasibility and convergence of the virtual reference to the reference signal, among other key properties.



Control of multi-contact slipping [2]

Goal: Collaborate with industry to extend multi-legged robot control and safety into domains where multiple legs slip on the ground.

We built a robot with 6DoF force-torque sensors on each leg and developed a novel calibration method to allow us to validate our method for modeling multi-legged slip.



We also applied this method to data obtain under this grant from Ghost Robotics, consisting of robot slipping data and point cloud information.

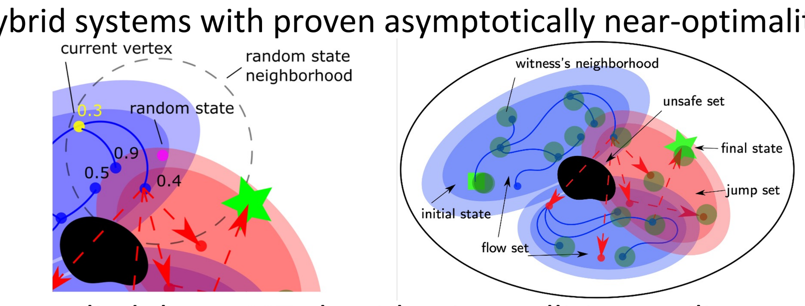
Motion Planning for Hybrid Dynamical Systems [4]

Goal: Design a sampling-based motion planning algorithm for hybrid systems with optimality guarantee.

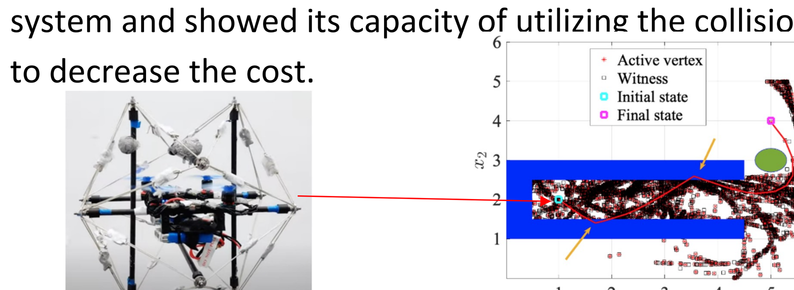
1. We formulated the optimal motion planning problems for hybrid systems where the hybrid systems and the cost function can be formulated as follows:

$$\mathcal{H} : \begin{cases} \dot{x} = f(x,u) & (x,u) \in C \\ x^+ = g(x,u) & (x,u) \in D \end{cases} \quad c(\phi) := \left(\sum_{j=0}^{J} \int_{t_j}^{t_{j+1}} L_C(\phi(t,j))dt \right) + \left(\sum_{j=0}^{J-1} L_D(\phi(t_{j+1},j)) \right)$$

1. We proposed a stable sparse rapidly-exploring random trees (SST) algorithm, called HySST, to solve optimal motion planning problem for hybrid systems with proven asymptotically near-optimality.



1. We applied the HySST algorithm in a collision-resilient aerial vehicle system and showed its capacity of utilizing the collision with the walls to decrease the cost.



Educational and Outreach Impacts:

- Collaboration with colleagues at the University of Bologna.
- Outreach to high school students through Summer outreach and STEM mentoring.
- Publishing of teacher resources online and offering of teacher training

Selected Products

[1] G. Council, S. Revzen "Recovery of Behaviors Encoded via Bilateral Constraints", arXiv:2005.00506, September 2022.
[2] Z. Wu, D. Zhao, and S. Revzen "Modeling multi-legged robot locomotion with slipping and its experimental validation" (in review IJRR; arXiv:2310.20669 (2023))
[3] N. Wang, S. D. Cairano and R. G. Sanfelice "A Switched Reference Governor for High Performance Trajectory Tracking", to appear in American Control Conference, 2024.
[4] N. Wang and R. G. Sanfelice "HySST: An Asymptotically Near-Optimal Motion Planning Algorithm for Hybrid Systems", IEEE Conference on Decision and Control, 2023.

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Intellectual merit

- Mathematical framework to rigorously formulate learning-based planning and control for CPS with awareness of its constraints.
- Novel architectures that lead to robust adaptive constraint satisfaction.
- Deep understanding of roles and priorities of system constraints in CPS.
- Tools and design techniques that permit engineers to deploy constraint aware algorithms.

Broader impacts

- Broad application of the results to CPS that require planning and control, especially autonomous systems in air and ground transportation.
- Benefit to industry developing multi-legged robotic systems and solutions for real-time planning & control under dynamic obstacles.