Frontier: Correct-by-Design Control Software Synthesis for Highly Dynamic Systems

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Objectives

- Develop a formal framework for correct-by-construction software synthesis for highly dynamic CPSs.
- Realize this framework experimentally for bipedal robots.

Highly dynamic CPS: Cyber-physical systems where the difference between stable (safe) behavior and catastrophic (unsafe) behavior occurs in milliseconds

Correct by construction: "Specify and compile" instead of "design and verify".

State of the art:

- Control software development for highly dynamic CPSs relies on trial and error;
- small changes in hardware often require extensive labor-intensive retesting and redesign of software;
- no guarantees on closed-loop behavior.

Key Challenges

Curse of dimensionality (e.g., nonlinear models greater than dimension 2) → Hybrid models comprised of motion primitives and low-level control software.

Environmental uncertainty (e.g. terrain variation) → adding adversarial non-determinism to the discrete abstractions; 2-player game for robust synthesis.

Team

- Advisors from Ford and Toyota.
- Prof. Necmiye Ozay, Postdoc Xiangru Xu (UMich),, Postdoc Christian Hubicki (GaTech), Postdoc Austin Jones (GaTech)
- Students: Yuxiao Chen and Petter Nilsson (UMich), Omar Hussien (UCLA), Forrest Berg (TAMU) and Albert Wu (CMU).

Bipedal Robots

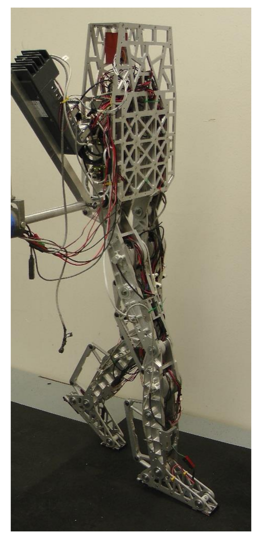
Robot model

$$\left\{\frac{d}{dt}\begin{bmatrix}\theta\\ \dot{\theta}\end{bmatrix} = \begin{bmatrix}\dot{\theta}\\ -D^{-1}(\theta)C(\theta,\dot{\theta})\end{bmatrix} + \begin{bmatrix}0\\ D^{-1}(\theta)B\end{bmatrix}\right.$$

AMBER 3 is described by a 12 dimensional model where θ is the joint angle [rad], $\dot{\theta}$ is the joint velocity [rad/s].

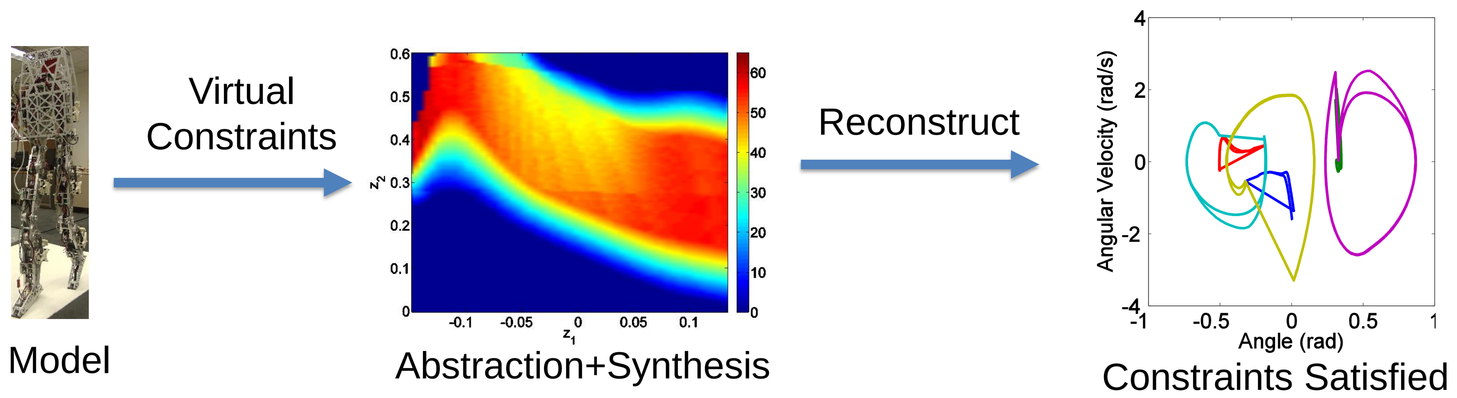
Specifications

- Joint torques required to meet desired bounds.
- Swing foot shouldn't scuff before the end of a step.
- The feet are required to remain flat during a walking gait.



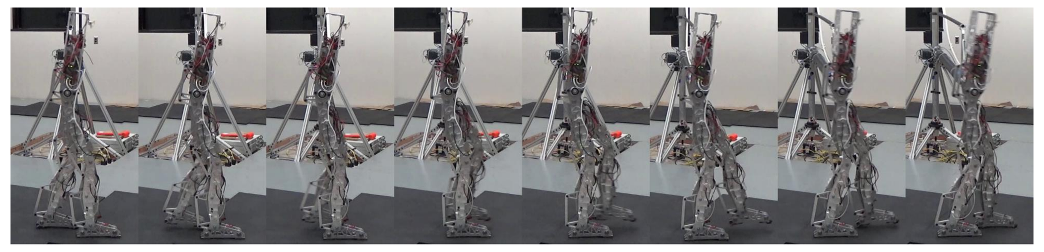
Correct-by-design controller

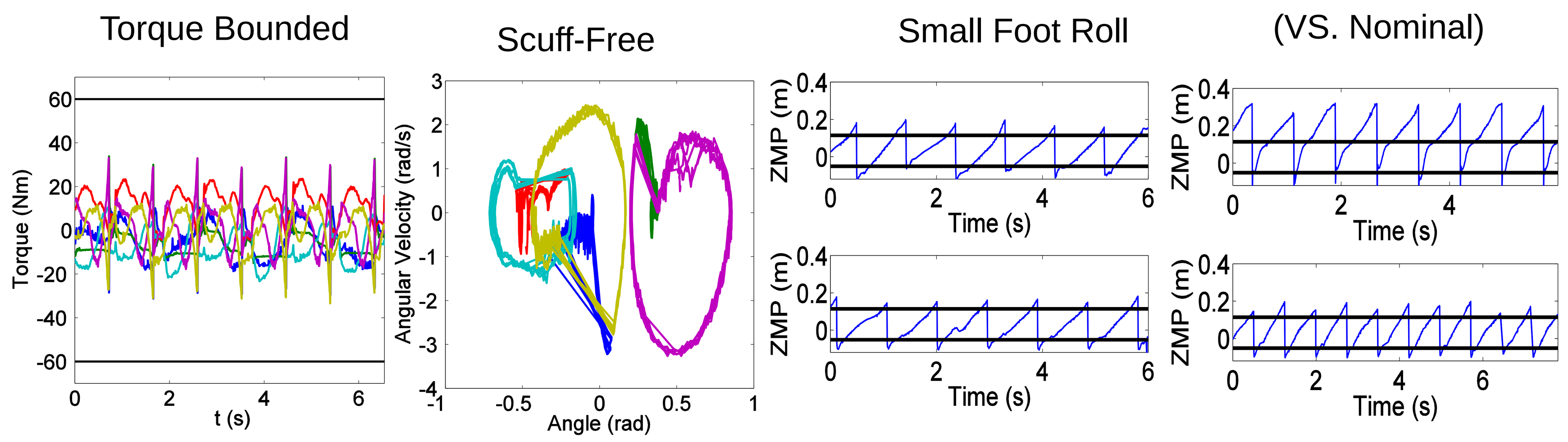
- Specifications enforced by non-linear control methods + provably correct abstraction-based planning



Experimental Results

- Walking achieved on AMBER3





3D Humanoid Implementation

DURUS Humanoid

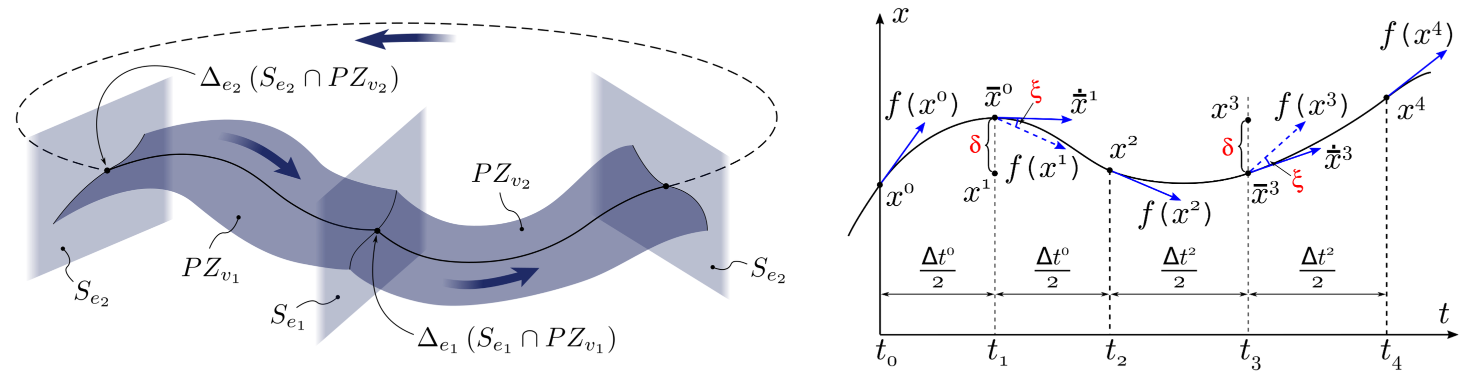
DURUS is a spring-legged humanoid robot with 15 actuators and 23 DOF.

Specifications

- Minimize cost of transport (CoT)
- Enforce Hybrid Zero Dynamics (HZD) constraints for periodic walking.

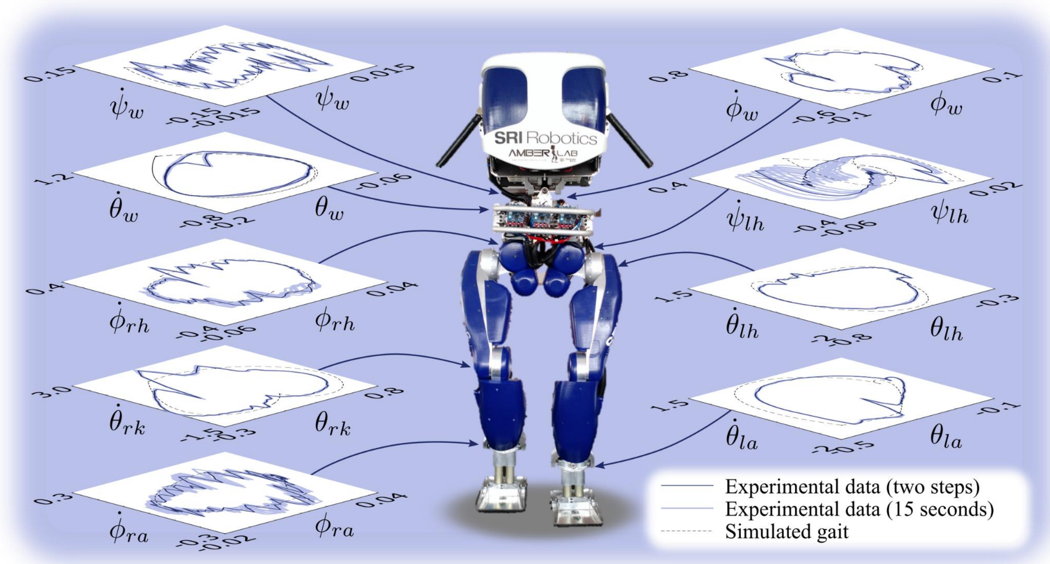
Large-scale HZD Optimization

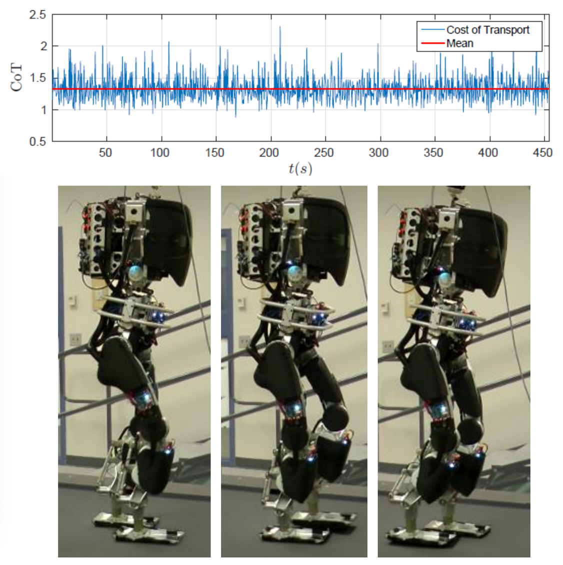
- Direct-collocation-based optimization of virtual constraints scales to dimensionality of humanoids



Experimental Results

- 3D dynamic walking achieved on DURUS (CoT: 1.3).





Future Work

- Extend formal methods to underactuated robots.
- Mitigate curse of dimensionality for 3D walking by composing sub-system abstractions.

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