Collaborative Research: CPS: Frontier:
Computation-Aware Algorithmic Design for Cyber-Physical Systems

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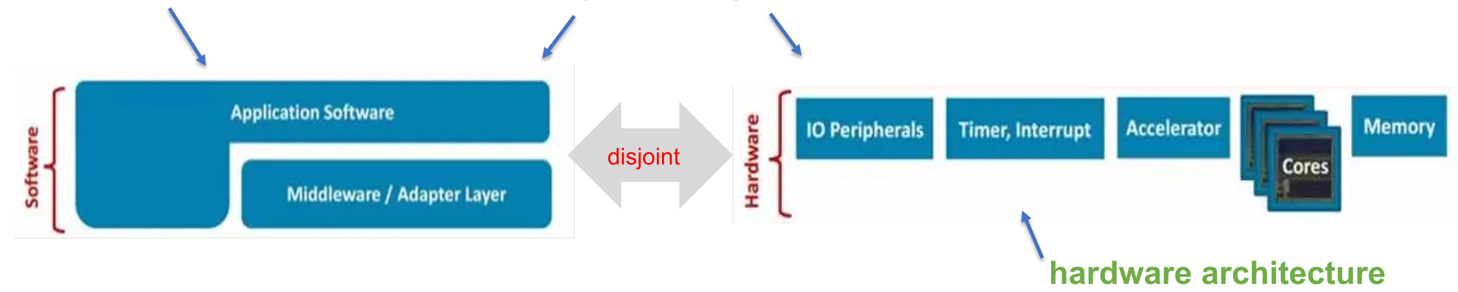
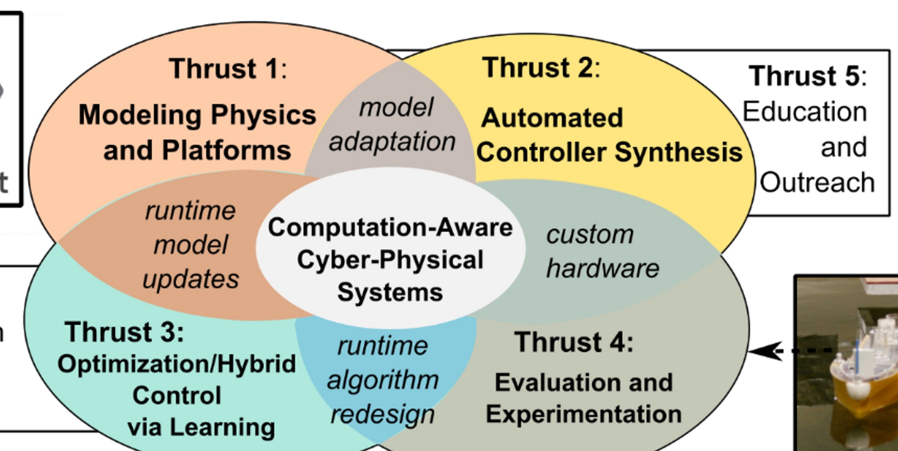
Overview

Project Goal
Generate tools for high-performance joint design of hardware, software, and control algorithms for cyber-physical systems in which control algorithms and computing platforms adapt to each other.

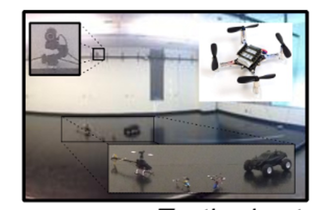


Industry Collaborators: Toyota, Joby, Summer Robotics, woven planet

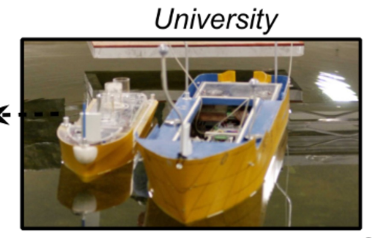
Collaboration with NTNU and IMT Lucca



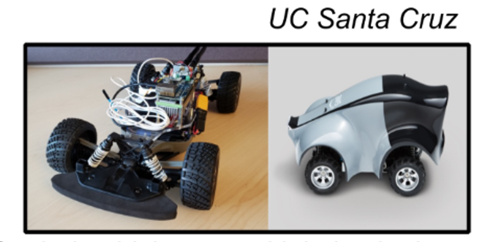
Testbed at Vanderbilt University



Testbeds at UC Santa Cruz



Testbeds at NTNU



Scaled vehicles at multiple institutions

Challenges

Broad Challenges to Modeling Hardware and Software

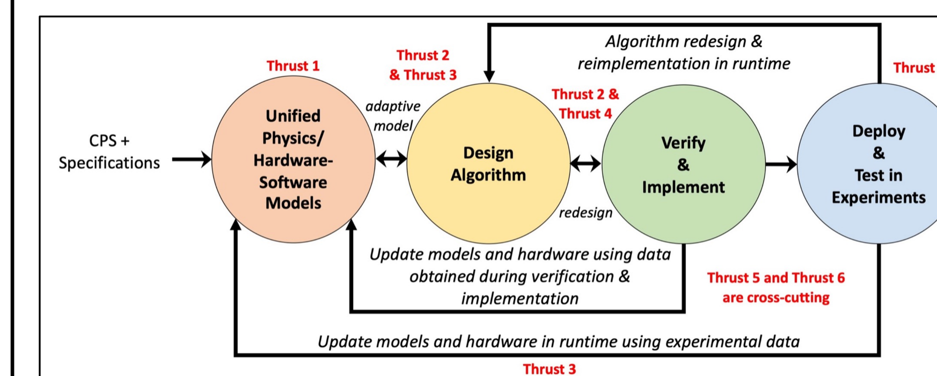
- Building models that integrate hardware and software features is challenging.
- Enabling computation-aware control algorithms requires a detailed understanding of the underlying hardware, performance monitoring capabilities, and means to modify and optimize the hardware.

Challenges to Feedback Control Design for Standard Platforms

- The implementation of the controllers resulting from symbolic approaches on a digital device requires a considerable amount of memory while those resulting from optimization approaches demand high computation power.
- The control algorithms required for intelligent transportation exceed the computational capabilities of single-core processors.
- Porting existing control algorithms to multi-core processors introduces significant software development overheads while the performance benefits are often limited because some algorithms exhibit only narrow scalability.

Integrative Thrusts & Focus

The effort pertains to CPS with attributes including, but not limited to, hardware architecture, physical platforms, hardware-software models, as well as control, safety, optimization, and learning.



Driving Application Domain

Intelligent Transportation Systems

Technical Approach

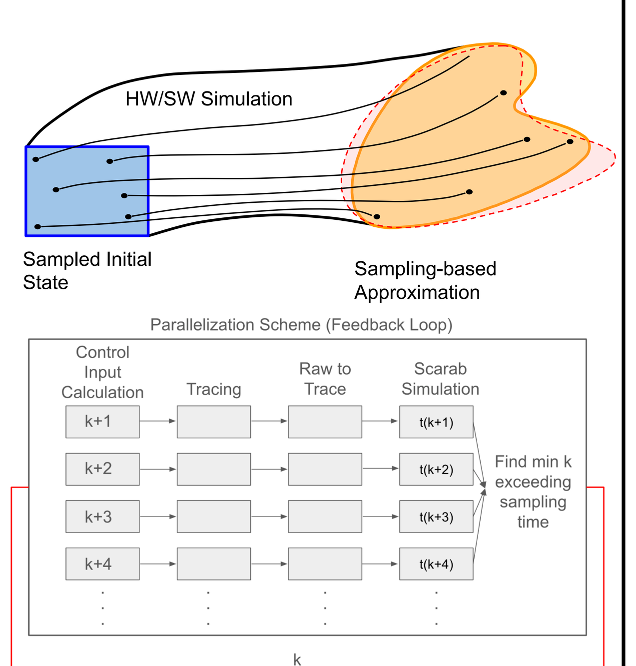
Thrust 1: Iterative Modeling of Physics and Platform

Scarab Simulator-based methodology:

- Modeling and simulation infrastructure for analysis of computational performance and utilization
- Enables estimation of computation times of controllers on various computing platforms
- Scarab-in-the-loop simulation allows simulation of control system performance that incorporates accurate computational delays
- Parallelization accelerates simulator performance
- Error correction feedback loop restarts the simulation from the initial error timestep when computation time exceeds sampling time

Reachability results:

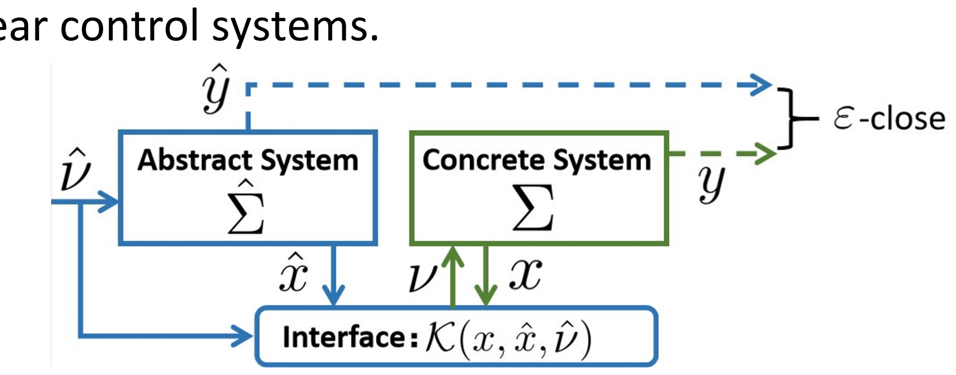
- Data-driven, statistical learning reachable set estimation methods
- Scarab's data-driven approach ensures applicability to complex simulation models



Thrust 2: Automated Synthesis of Controllers

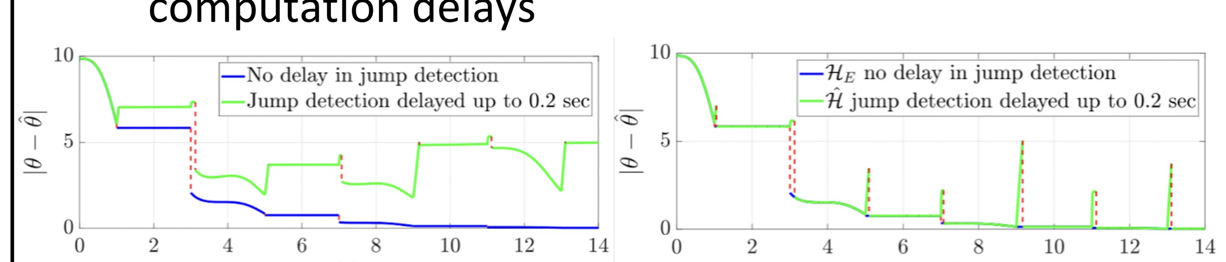
Simulation Relation for Hierarchical Control

- General approximate alternative simulation (gAAS) relation to characterize the similarity between two systems while allowing their output error to be smaller compared with traditional results.
- Systematic approaches to compute the maximal gAAS relation and refine controllers for discrete systems
- Methodologies for computing gAAS relations for linear control systems.



Parameter Estimation under Computation Delays

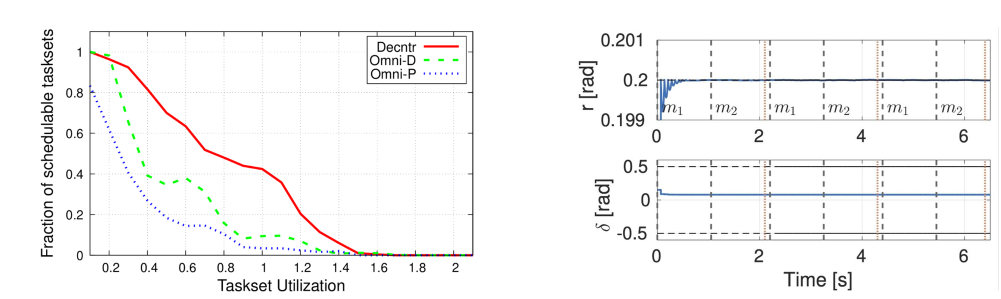
- Estimation of parameters without exact knowledge of the mode transition times
- A new algorithm for parameter estimation with computation delays



Thrust 3: Real-time Optimization and Adaptive Control through Learning

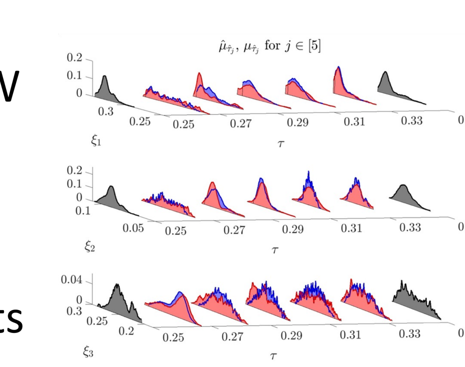
DECNTR: Optimizing Safety and Schedulability with Multi-Mode Control and Resource Allocation Co-Design:

- Design of controllers that can switch between different implementations and different sampling rates.
- DECNTR dynamically adapts resource allocation and sampling rates at mode changes to maximize safety, real-time performance and robustness



Learning Time-varying Stochastic Hardware Resource Usage by Control Software

- HW resource (e.g., memory bandwidth, processor availability) in CPS are time-varying, jointly correlated
- Formulated and solved multimarginal Schrödinger bridge problem for learning most likely joint evolution of HW resource availability from measured profile data
- Computation scales linearly w.r.t. dimension and # snapshots



Thrust 4: Multi-platform Computational and CPS Validation

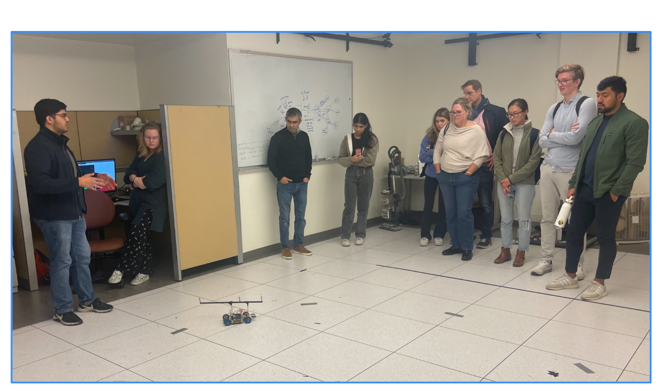
Full-scale Validation:

- Continued to mature validation toolchain
- Safety-based controller enables open-road testing of novel controllers
- Prototyped toolchain in new course with 9 student teams.

CS and CEE Students with the open-road testbed. Demos were done on a 15-week timeline, and all ran on the open road.

Validation in scaled vehicles:

- Implementation of MPC controller in ground vehicles
- Tracking control experiments testing computational limitations of MPC
- Experimental demonstration



Thrust 5: Education and Outreach *(highlights)*

- Expanding underrepresented minorities in CPS across campuses: UCSC, UC Berkeley, U. Penn, Vanderbilt Univ., CU Boulder
- Seminars by Linh Phan at UC Berkeley, Majid Zamani at the Penn State University, and Ricardo Sanfelice at CU Boulder
- Computation-aware Algorithmic Design of CPS (CAADCPS) workshops in CPS-IoT Week 2023
- New course in Autonomy and Traffic by Jonathan Sprinkle at Vanderbilt University
- Coursera course on "Modeling of Autonomous Systems" by Majid Zamani
- New tutorial series "101 Topics in Control, Optimization and ML" by Abhishek Halder at Iowa State University

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Intellectual merit

- New CPSs hardware and control software that adapt to the specifications and the environment they are deployed on.
- New tools to codesign hardware and control software reducing development cost and time.

Broader impacts

- Improving the safety and energy-efficiency of autonomous systems.
- Providing open source models, algorithms, software, and platform designs for deployment in industrial systems.
- Train the workforce of the future in CPS.

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8. C. A. Montenegro G., S. Jimenez, R. G. Sanfelice. A Data-Driven Approach for Certifying Asymptotic Stability and Cost Evaluation for Hybrid Systems. HSCC, 2024.