CPS: Medium: Collaborative Research: Data-Driven Modeling and Preview-Based Control for Cyber-Physical System Safety

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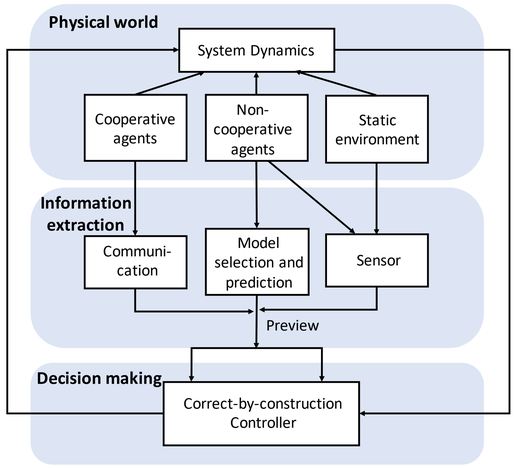
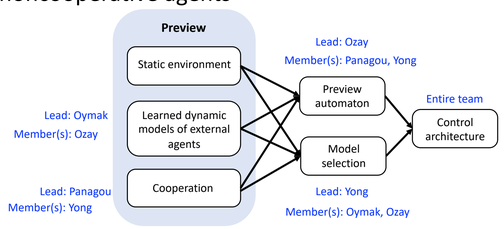
Motivation



The primary objective is to develop the theory and algorithms for the design of provably-safe controllers that can leverage preview information from different sources, such as sensors, maps, forecast information.

- Safety vs conservativeness trade-offs
- How to leverage new sensors, existing data sets, and learning algorithms?
- Multi-agent interactions with cooperative and noncooperative agents



Scientific Impacts

- Understand the role of multi-agent cooperation in providing preview information via data-driven models and communication
- Enable the incorporation of preview information using preview automata
- Develop theory and algorithms for guaranteeing safety with preview information with model selection and state estimation

Broader Impacts

Impact to Society

Application focus: Driver assist systems

- Improving driving safety can save lives

Broadly applicable methodology

- Can generalize to a wide class of CPS, e.g., UAVs, robots, medical devices

Education and Outreach

- Graduate student researchers: Mitchell Black, Mohammad Khajenejad, Zexiang Liu, Yahya Sattar
- Broadening participation in computing and engineering plan targets female undergrads at UM (and Midwest) and minority undergrads at UCR and ASU to prepare and encourage them to pursue graduate studies in STEM.

Selected Publications

[1] Z. Du et al. "Can Transformers Learn Optimal Filtering for Unknown Systems?", IEEE LCSS '23.

[2] Y. Li et al. "Transformers as algorithms: generalization and stability in in-context learning", ICML '23.

[3] M. Black et al. "Future-Focused Control Barrier Functions for Autonomous Vehicle Control", ACC '23.

[4] Z. Liu et al. "Opportunistic Safety Outside the Maximal Controlled Invariant Set." IEEE LCSS'23.

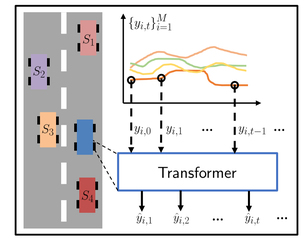
[5] T. Pati et al., "Interval Observers for Hybrid Dynamical Systems with Known Jump Times", IEEE CDC'23.

[6] T. Pati et al. "Preview Control Barrier Functions for Linear Continuous-Time Systems with Previewable Disturbances", ECC'23.

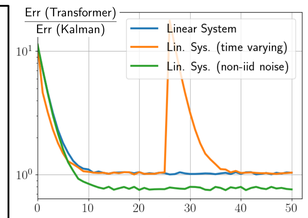
Methods and Results

Unknown System Optimal Filtering via Transformers [1,2]

- Transformer: a neural sequence model in natural language processing. (Foundation of GPTs)
- Imbuing Adaptivity: Train a *single* transformer using data collected from M *various* systems.
- Optimal Prediction: Trained transformer achieves *optimal* prediction for unknown and unseen systems.
- Guarantees: $Excess\ Risk\ \leq \mathcal{O}(1/\sqrt{MT})$



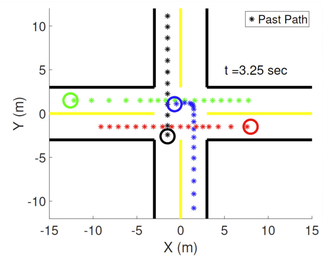
The trained transformer can adapt to and predict for different unseen unknown systems



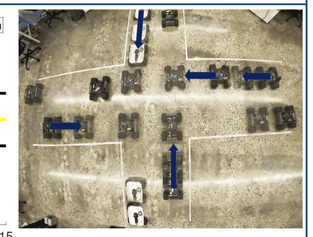
The trained transformer can achieve the optimal performance given by the Kalman filter and even works for time-varying and non-iid noise cases.

Future-Focused Control Barrier Functions (CBFs) [3]:

- ff-CBF: Virtual barrier dictating control actions that avoid collisions predicted under a zero-acceleration policy over an arbitrarily long future time interval.
- relaxed future-focused CBF (rff-CBF) relaxes the virtual ff-CBF barrier far from the physical barrier
- Empirical study on system safety and performance



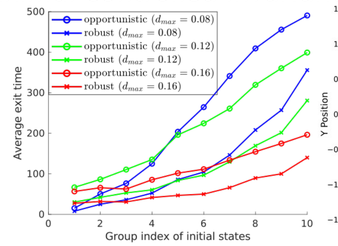
XY trajectories for Trial 650 of the rff-CBF simulation set



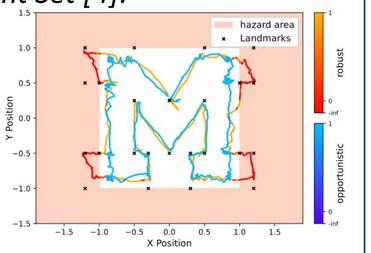
Five rovers safely traverse a four-way intersection in the PI Panagou's lab, using a decentralized rff-CBF-QP control law. The rovers at their initial positions are marked with arrows pointing in the direction of motion.

Opportunistic Safety Beyond the Maximal Controlled Invariant Set [4]:

- A novel safety control framework is proposed to enable safe operation beyond the domain of traditional safety barriers.
- The proposed controller can be efficiently synthesized by existing toolboxes.
- Case studies demonstrate exceptional resilience to unforeseen disturbances and modeling errors.



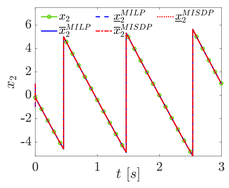
Average safe time in lane keeping control under unexpected disturbances.



A drone avoids reaching the hazard area while tracking a user-defined reference path under unexpected disturbances.

Run-Time Set-Valued Estimation [5]:

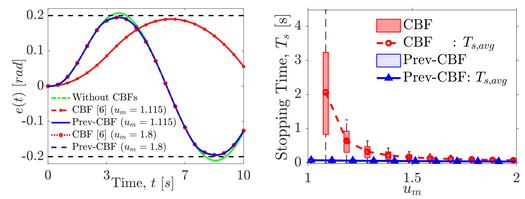
- Design interval observer for hybrid systems via mixed-monotone decompositions.
- Leverage positivity of error system dynamics for less conservative quadratic and linear common Lyapunov functions



Nonlinear bouncing ball example with non-zero dwell time.

Preview Control Barrier Functions [6]:

- Prev-CBF: A closed-form input-constrained CBF that uses preview information to reduce stopping time.



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