Recent Advances in Estimation, Safety, and Control

Ricardo Sanfelice
Department Electrical and Computer Engineering
University of California

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Outline of Recent Results

1. **Estimation**
   - Parameter Estimation via Hybrid Methods
     ACC 21a, ACC 21b, ACC 21c, CDC 22a (submitted)
   - Observers for Hybrid Systems
     CDC 21a, CDC 21b, Automatica 22 (to appear)
2. **Safety**
   - Safety Certificates
     ACC 22a, TAC 22, ESAIM 22 + CoE collab
   - Applications of Safety
     ACC 22b, CCTA 22a and CCTA 22b (submitted) + CoE collab
3. **Feedback Control and Optimization**
   - Hybrid Control and Learning
     ACC 22c, ACC 22d, CCTA 22a (submitted), CDC 22b (submitted)
   - Optimization with Computational Constraints
     CPSWeek-IoT 22 Workshop + AFRL/RV collab + CoE collab.

Questions Driving Research Agenda

These observations motivate the following questions:

- How to guarantee the monotonicity condition

$$t \mapsto B(\phi(t; x_o)) \text{ is nonincreasing}$$

  and

$$\text{the set } K_e \text{ is "forward invariant" for } \dot{x} = f(x)$$

  without checking/computing every solution?
  - How to deal with nonuniqueness, finite escape time, and solutions ending prematurely?
- What are necessary conditions for safety (and invariance)?

... for dynamical systems given by

$$\mathcal{H} \begin{cases} \dot{x} \in F(x) & x \in C \\ x^+ \in G(x) & x \in D \end{cases}$$

- When B is continuously differentiable, our sufficient conditions take the form

$$\langle \nabla B(x), F(x) \rangle \leq \; 0$$

Note that since invariance should just guarantee trajectories do not leave a set, we should only be asking that this condition holds on the boundary or a neighborhood of the set.

Hence, we require

$$\langle \nabla B(x), f(x) \rangle \leq \; 0 \qquad \forall x \in (U(\partial K_e) \backslash K_e)$$

where $U(\partial K_e)$ is a neighborhood of K_e, so $(U(\partial K_e) \backslash K_e)$ are points outside right outside K_e!

Sampling-based safety of constrained control system

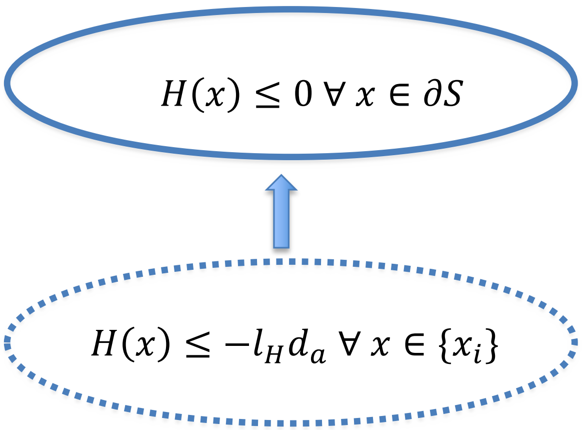
Joint work with Kunal Garg and Alvaro Cardenas

Consider the dynamical control system:

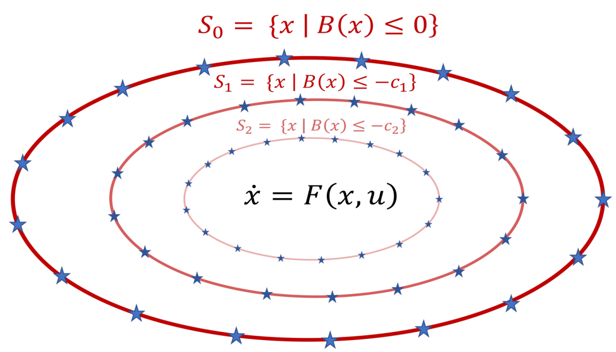
$$\dot{x} = F(x,u), \qquad x(0) \in S = \{\, x \mid B(x) \leq 0\}, u \in \mathcal{U}$$

$H(x) \coloneqq \inf_{u \in \mathcal{U}} \{L_F B(x,u)\} \leq 0 \;\; \forall x \in \partial S \Rightarrow$ Forward invariance of S

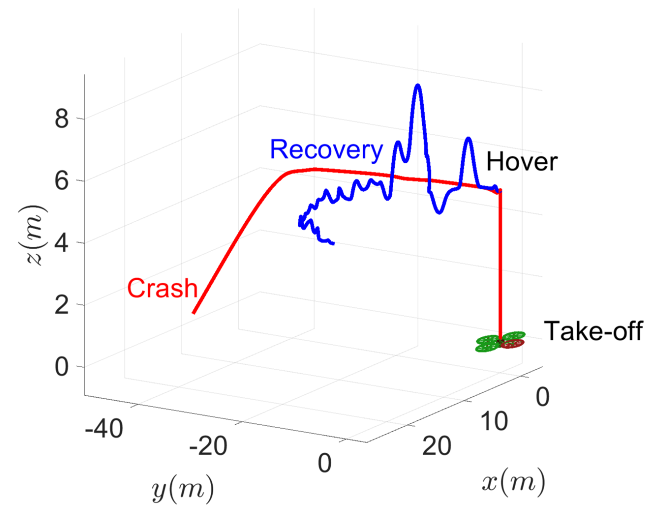
Infeasible to verify: ∂S contains infinite points



Computationally efficient and scalable to higher dimensions



Iterative method to compute viability domain



CBF-based attack detection and recovery with provable safety

Garg, K., Cardenas, A.A., Sanfelice, R.G., "Sampling-based Computation of Viability Domain to Prevent Safety Violations by Attackers", under review.
Garg, K., Sanfelice, R.G., Cardenas, A.A., " Control barrier function based attack-recovery with provable guarantees", under review.

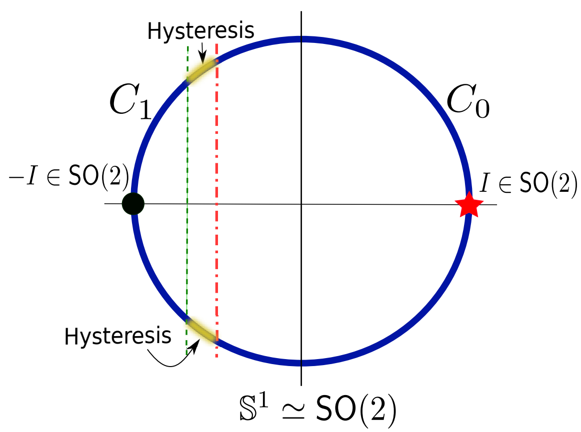
Hybrid Geometric Controls

- System on Lie groups

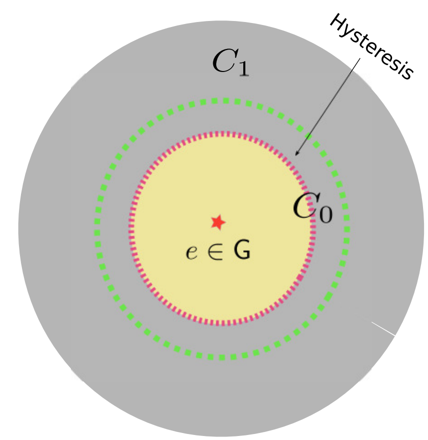
joint work with Adeel Akhtar

$$\dot{g} = X(g,u) = g\left(A + \sum_{i=1}^{m} B_i u_i\right) = g\xi,$$

  - Region C_0 containing the identity.
  - Region C_1 containing all other critical points.
- Hybrid Controls
  - Design an asymptotically stable geometric controller κ_0 and an open loop geometric controller κ_1 and combine them using hybrid framework.
  - Hysteresis region leads to robustness.
  - The resulting hybrid controller is robust.



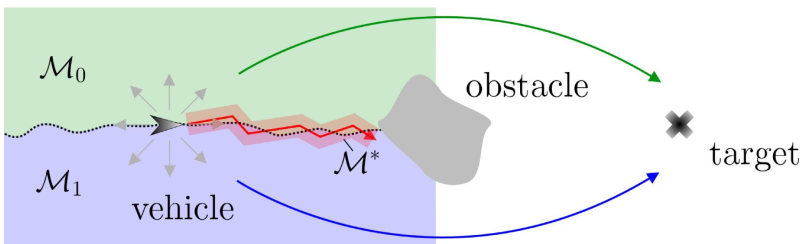
Global Stabilization



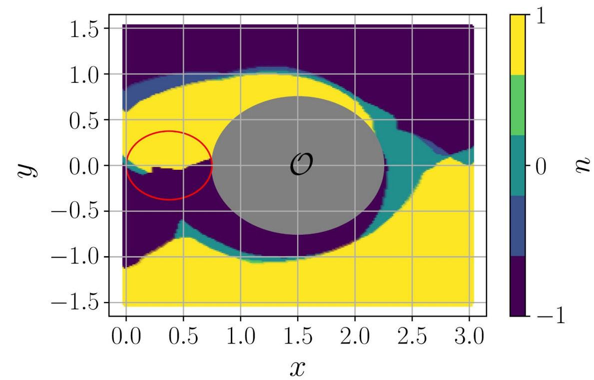
Matrix Lie groups

Hysteresis-based Reinforcement Learning (HyRL):

Robustifying Reinforcement Learning-based Control Policies via Hybrid Control.

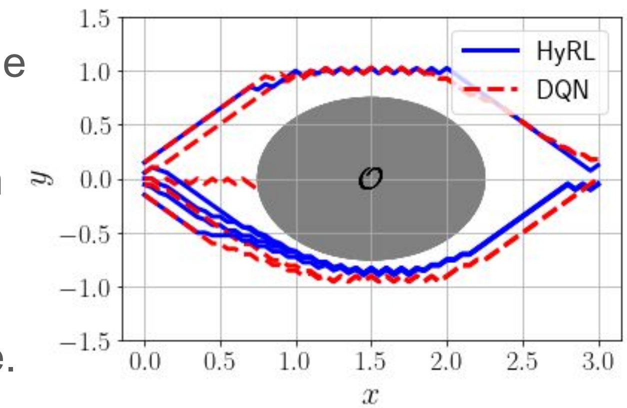


Autonomous vehicle obstacle avoidance. The vehicle has to steer left or right past the obstacle. In red, the area for which, due to measurement nose, the vehicle can crash into the obstacle.



The policy found by DQN: solutions evolve in opposite directions for a small change in y.

- Policies obtained from RL methods may lack robustness guarantees.
  - Solutions evolve in <u>opposite</u> directions for a small change in the state.
- HyRL overcomes this by augmenting an existing RL algorithm with <u>hysteresis switching</u> and two stages of learning.
  - The hybrid closed-loop system obtained by HyRL is robust against measurement noise of a given magnitude.

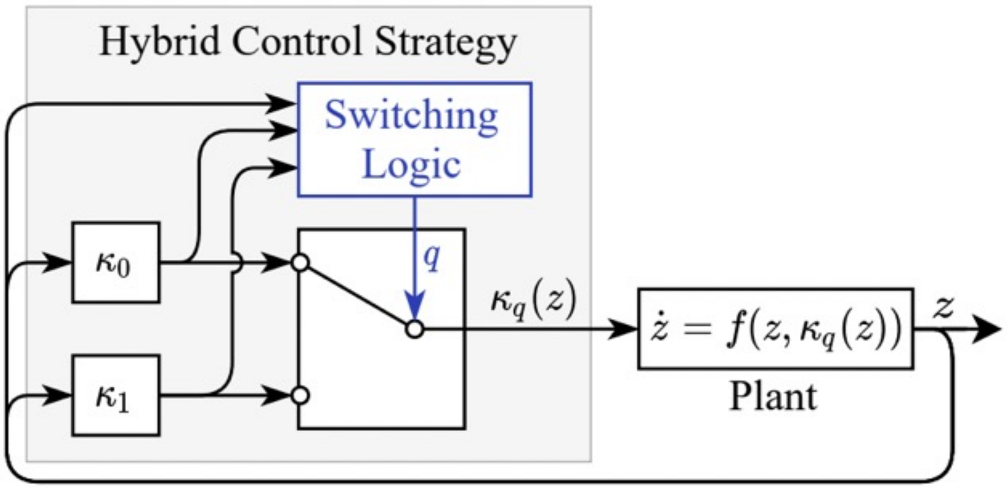


DQN and HyRL solutions in the presence of the same measurement noise signal of magnitude 0.1. The DQN policy is not robust against the measurement noise, unlike HyRL.

joint work with Jan de Priester and Nathan van de Wouw

J. de Priester, R. G. Sanfelice, N. van de Wouw, "Hysteresis-Based RL: Robustifying Reinforcement Learning-base Control Policies via Hybrid Control", To appear in the Proceedings of the American Control Conference, June, 2022. Available at https://arxiv.org/abs/2204.00654.

Opportunistic Hybrid Control Exploiting Properties of Uncertified Controller

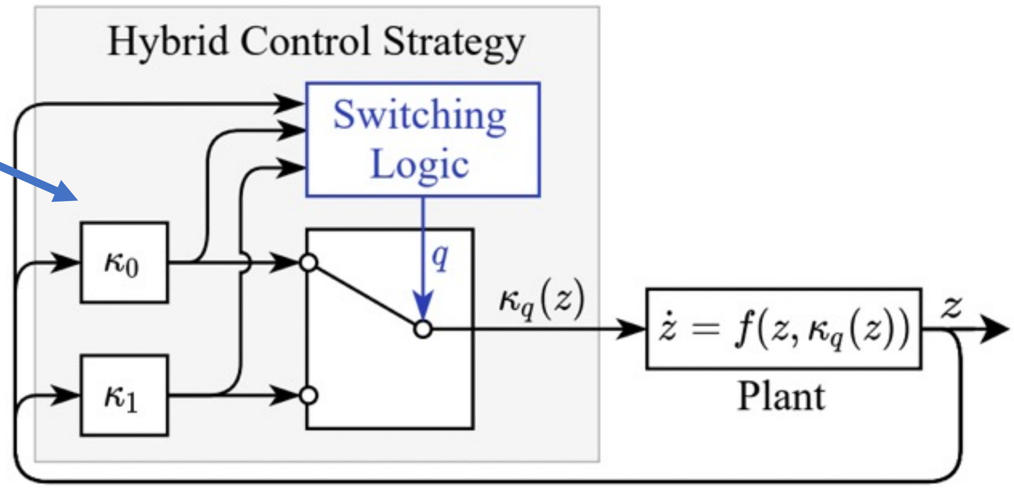


joint work with Paul Wintz and Joao Hespanha

Selected as Best Student Paper finalist for ACC 2022

Opportunistic Hybrid Control Exploiting Properties of Uncertified Controller

Certified via Lyapunov function V



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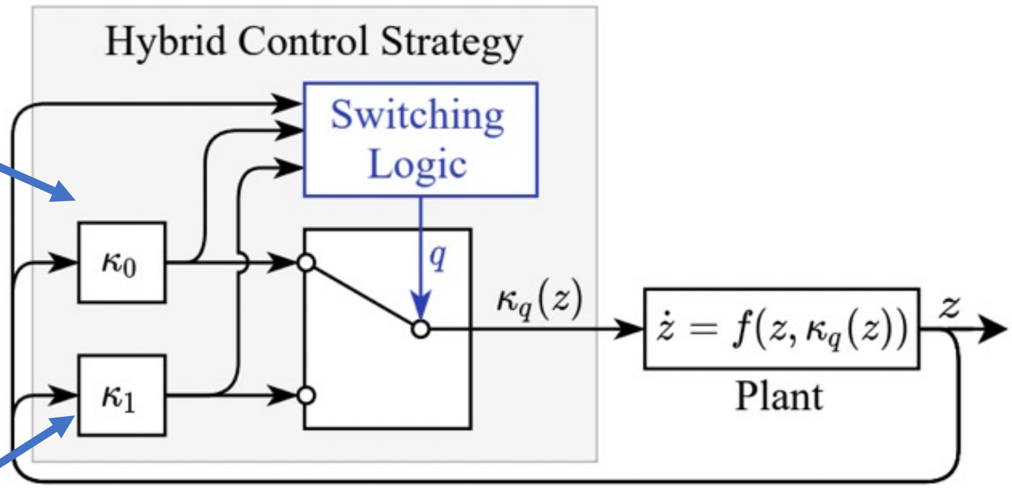

Uncertified controller!

- Heuristics
- Online optimization-based feedback
- NN-based controller
- …

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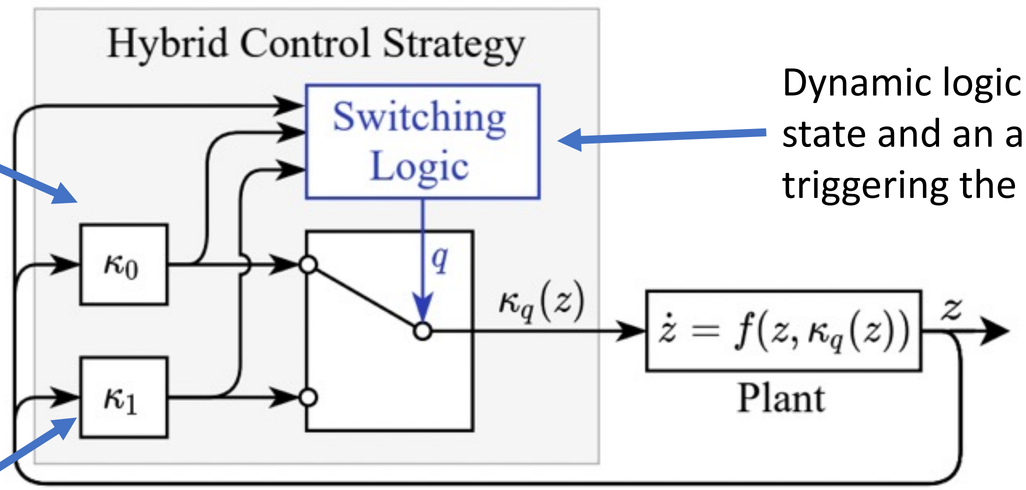

Dynamic logic with a discrete state and an auxiliary state triggering the switches

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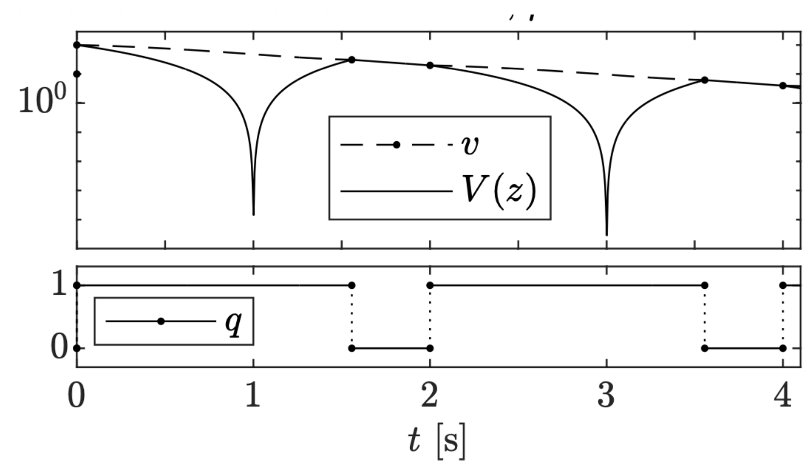

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