Carnegie Mellon University
Electrical & Computer Engineering

Adaptive Safe Control for Driving in Uncertain Environments

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Motivation

Source: Google Image

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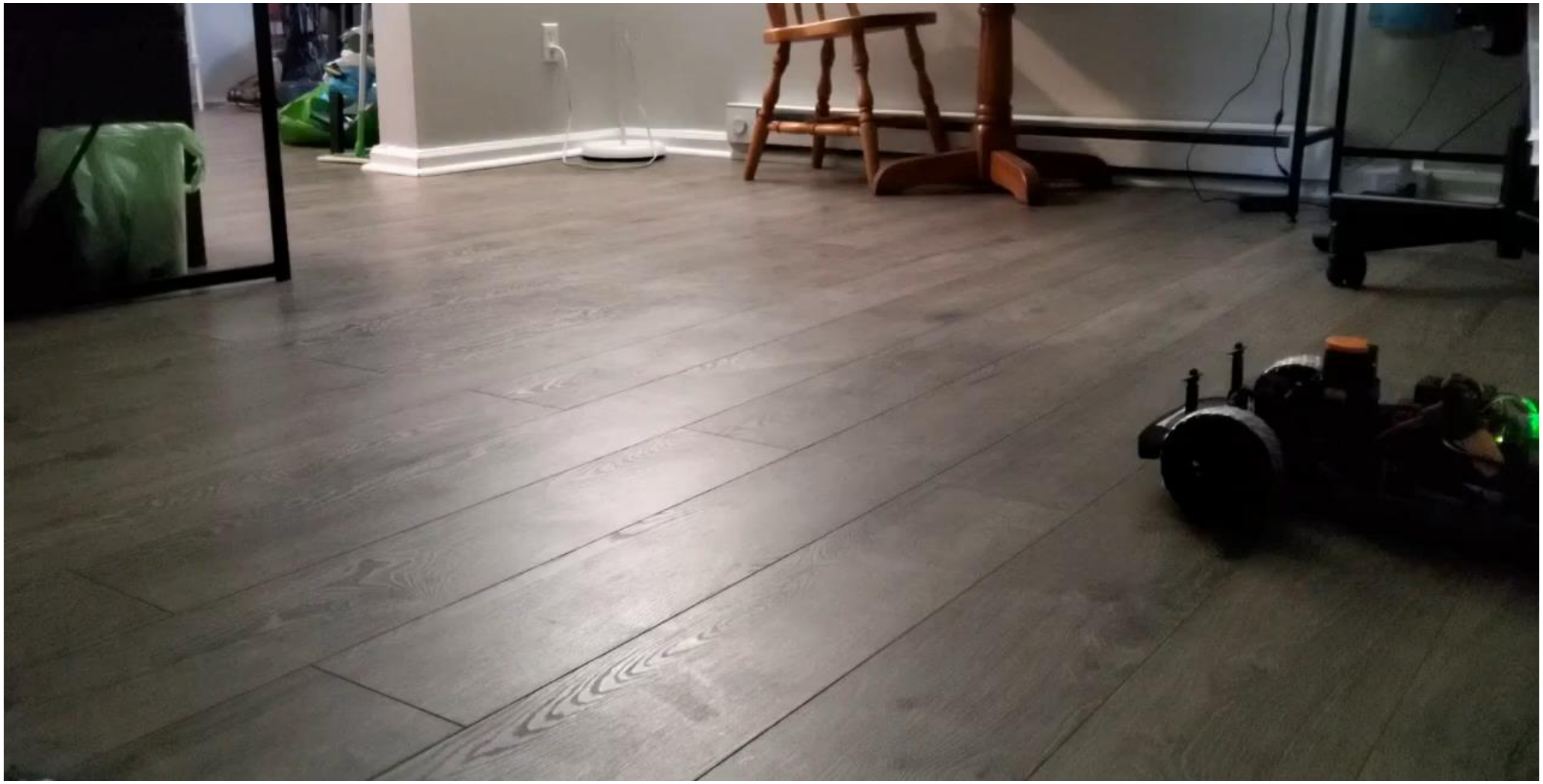
Motivation



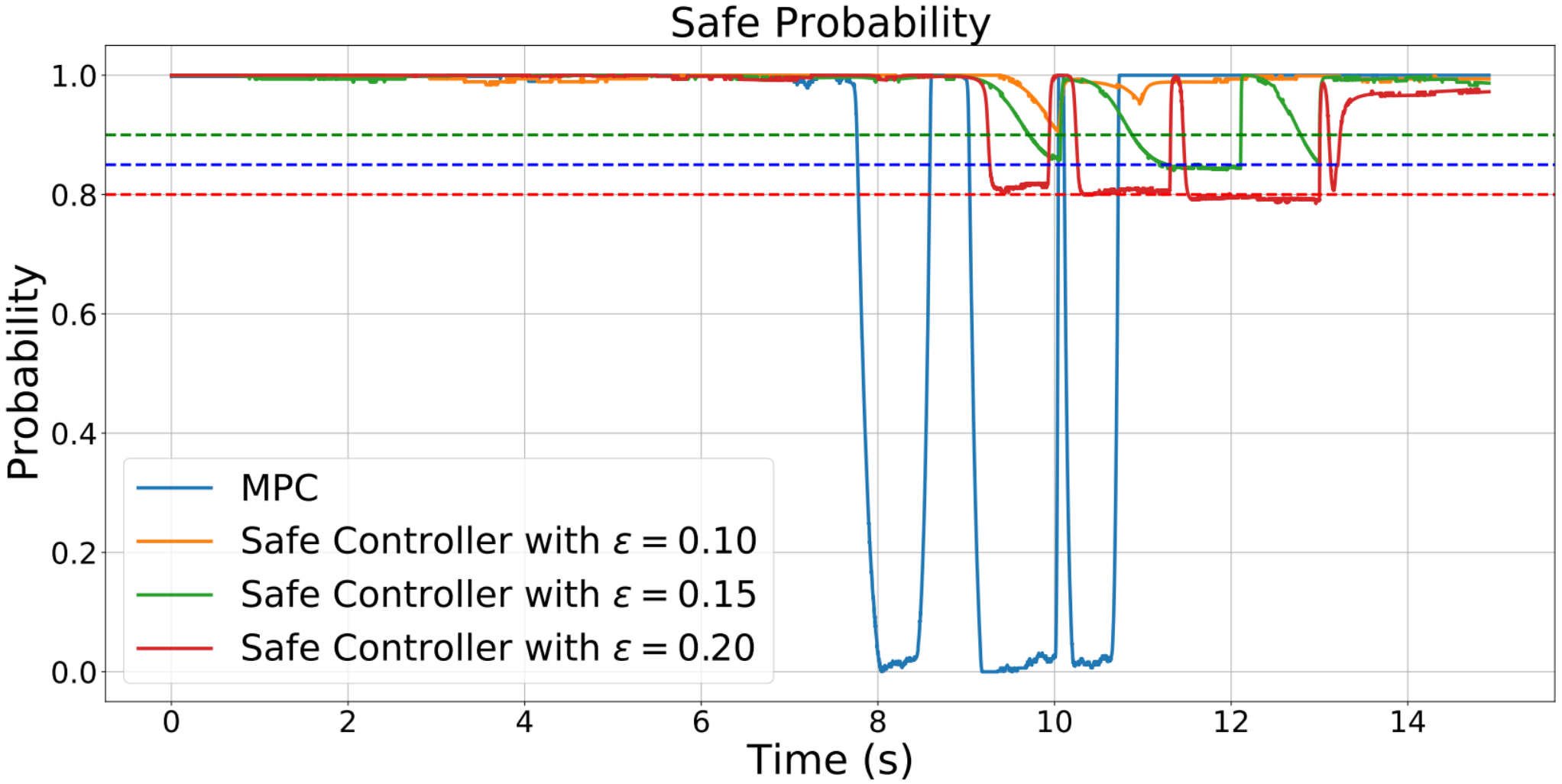
Research Goal

- Control algorithm design for autonomous vehicles
- **Robust**, **adaptive**, and **computationally efficient**
- Guarantee **long-term safety**
- Work under **large uncertainties** and **changing environments**.

Related works

- **Probabilistic safe controls:** over conservatism from attempting robust behaviors to worst-case errors [1-3].
- **Control Barrier/Lyapunov Functions:** difficulty in integrating competing safety v.s. performance objectives [4,5].
- **Reachability based safety:** stringent time-horizon vs computation/reaction-time tradeoffs [6,7].

Advantage 1: Long-term Safety Guarantee



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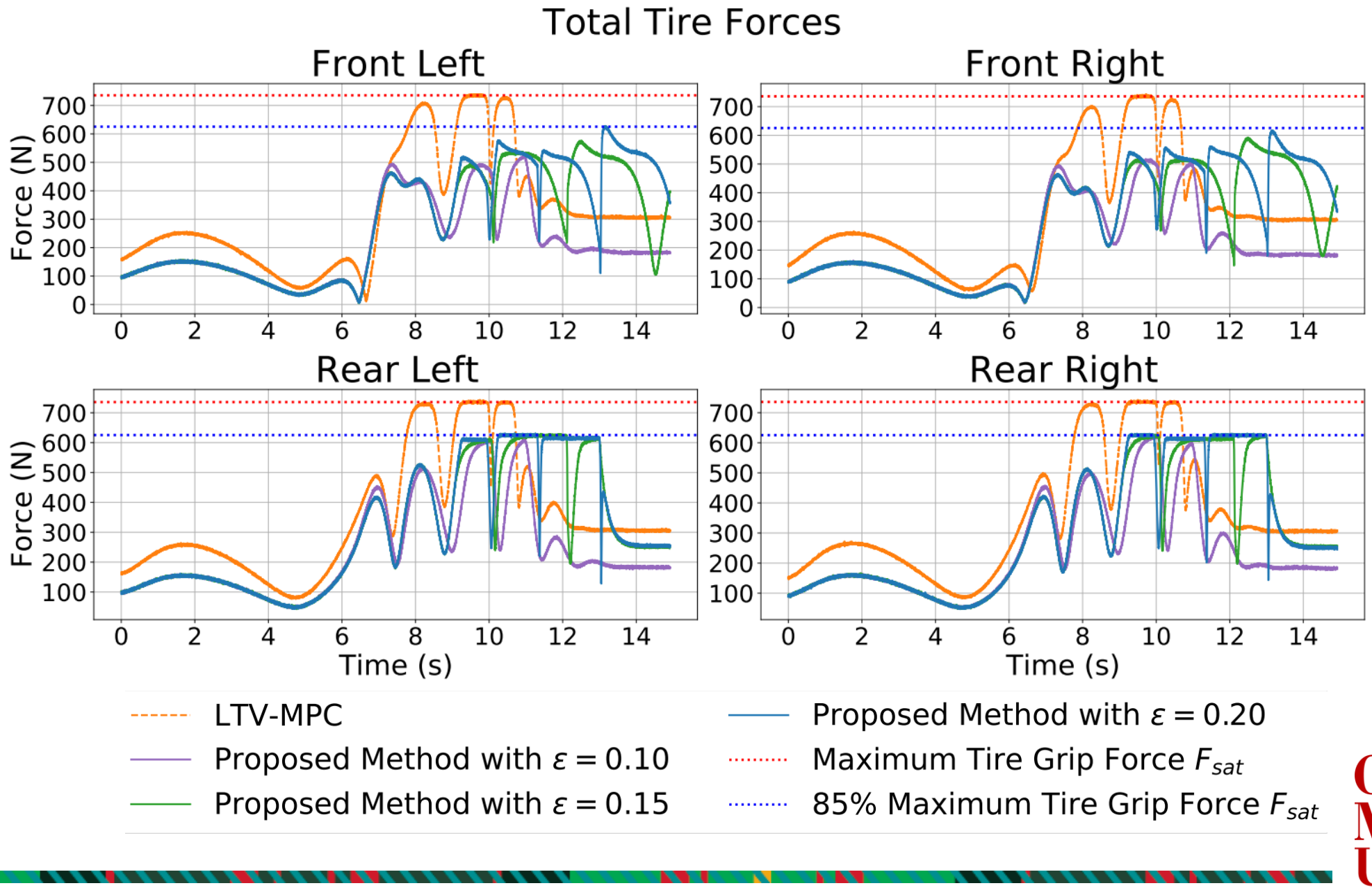
Advantage 1: Long-term Safety Guarantee (Cont'd)



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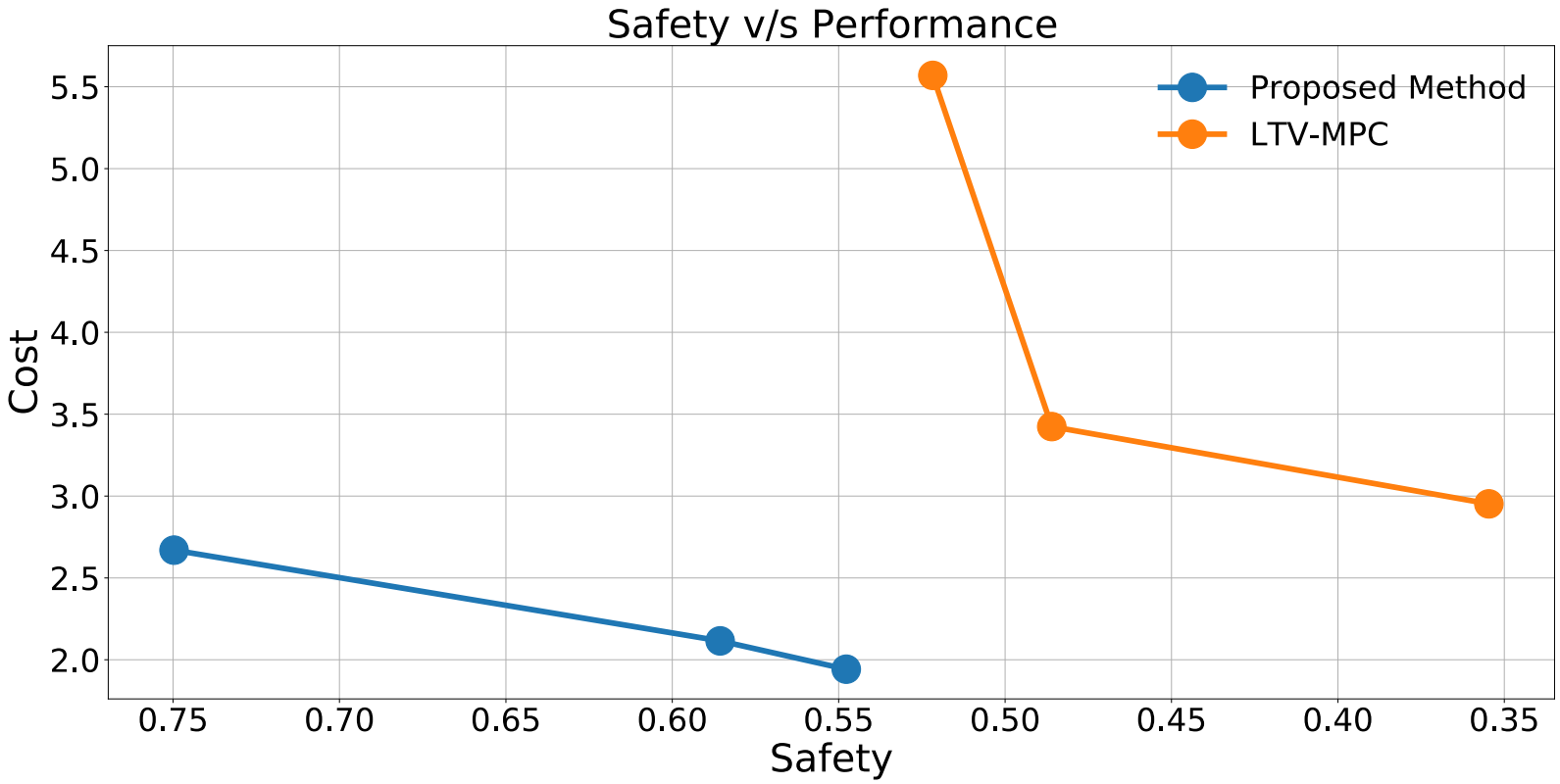
Advantage 2: Better Performance Tradeoffs

cost:
deviation from the reference trajectory



safety: satisfaction of the tire force limits

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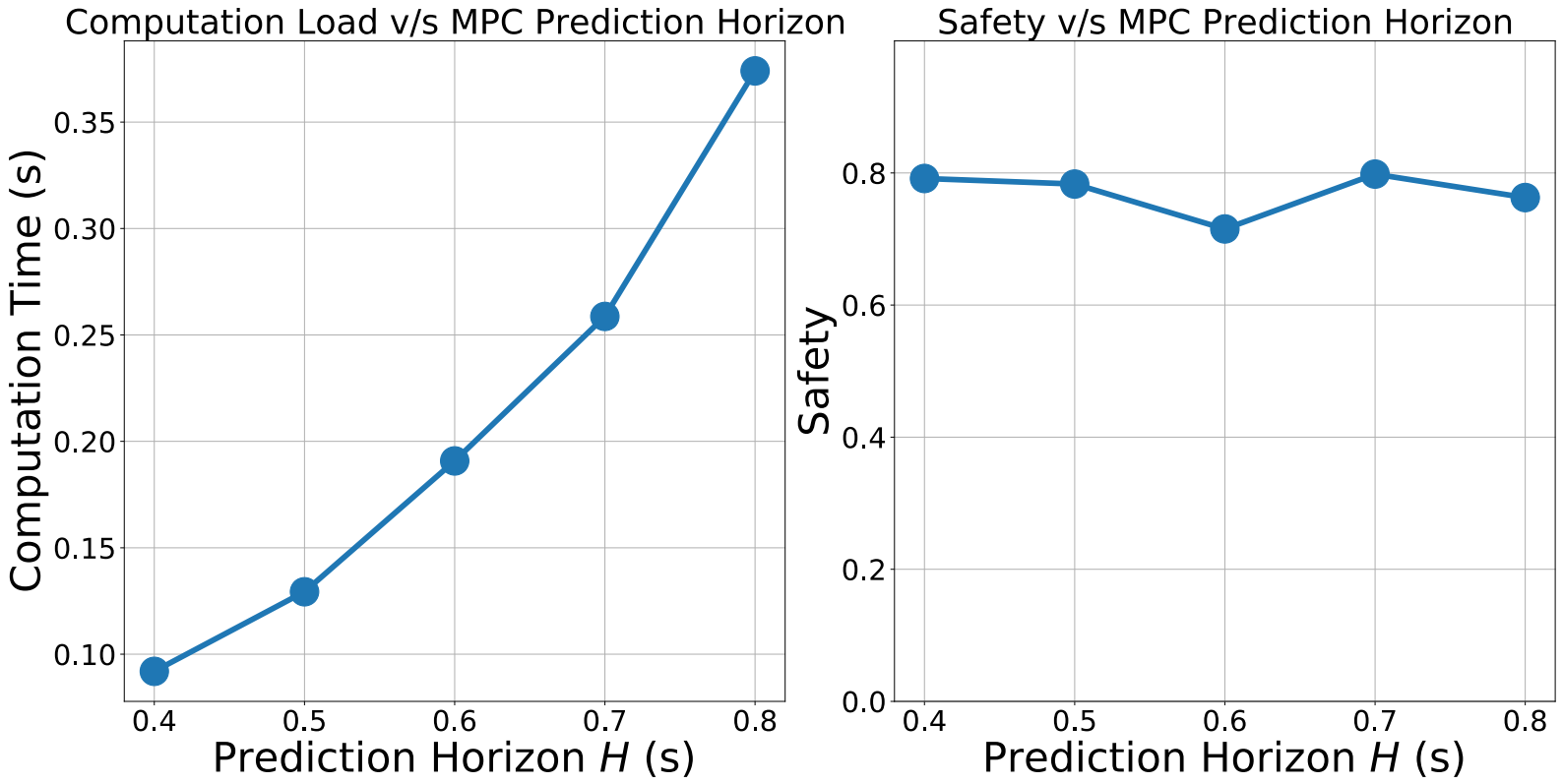
Advantage 3: Less Computation Costs

- Computation of MPC grows in $O(H^3)$
- Safety will not be compromised even with short outlook horizons



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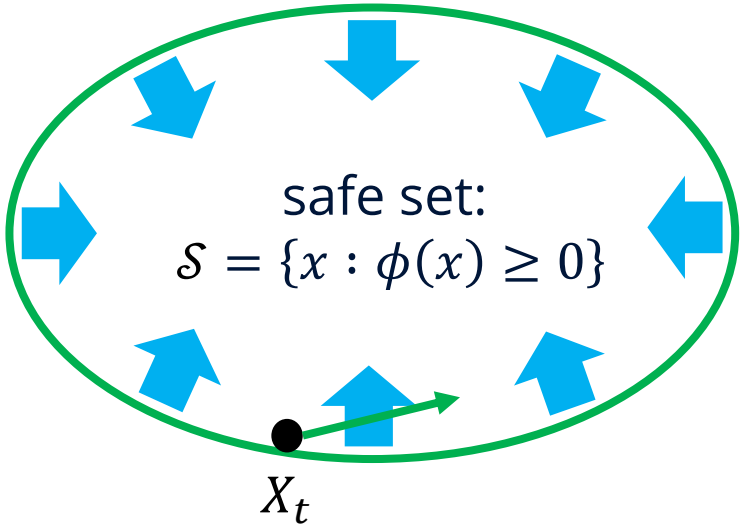
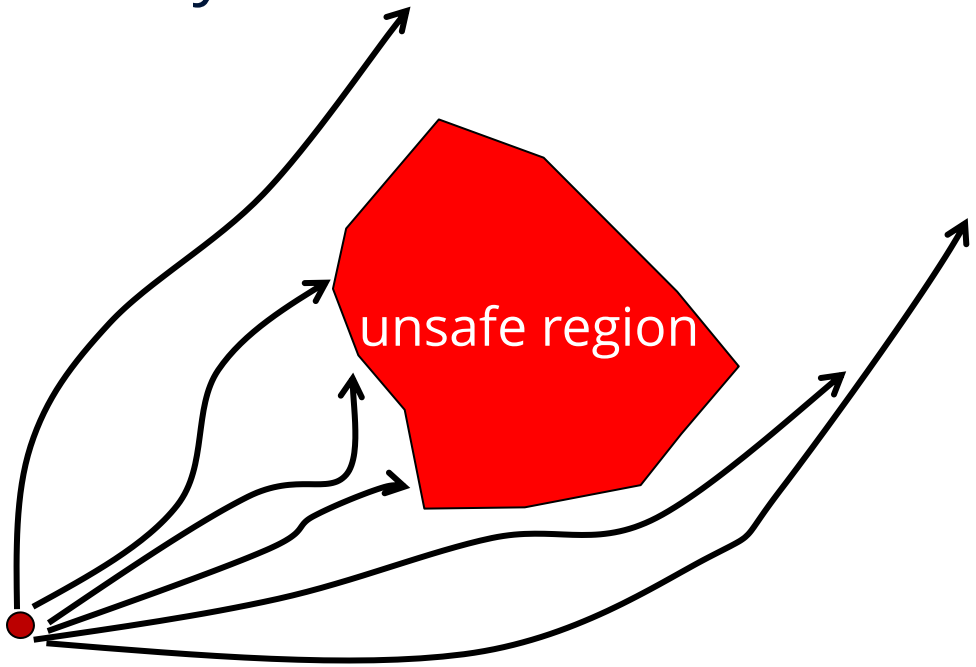
Proposed Method: Intuition

Control barrier functions:



Reachability:



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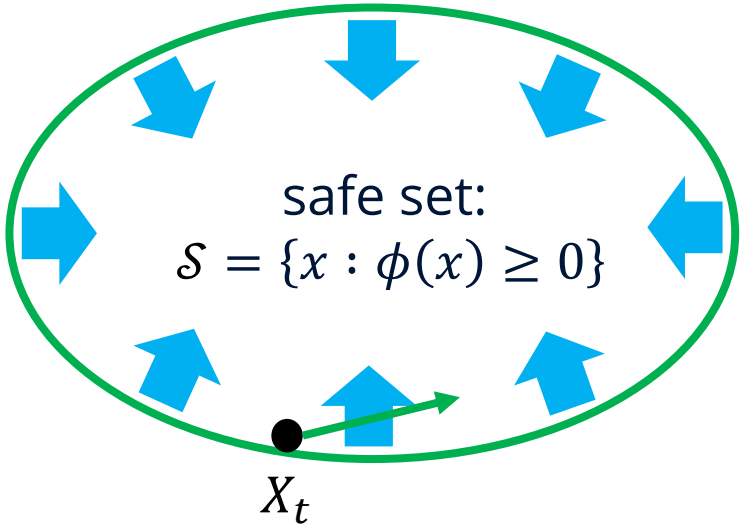
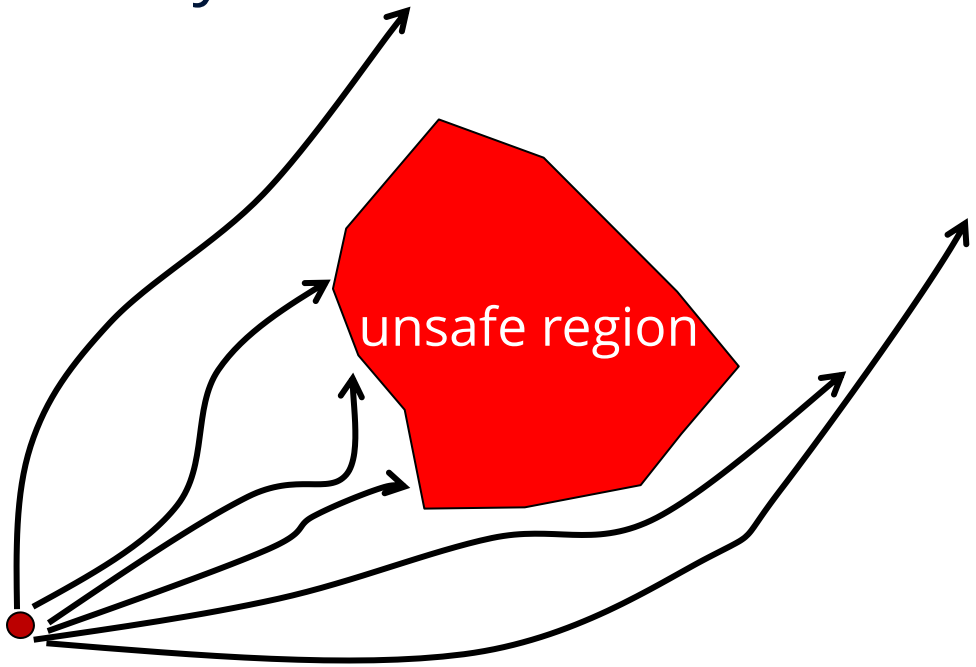


Reachability:



Forward rollout trajectories

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Proposed Method: Intuition

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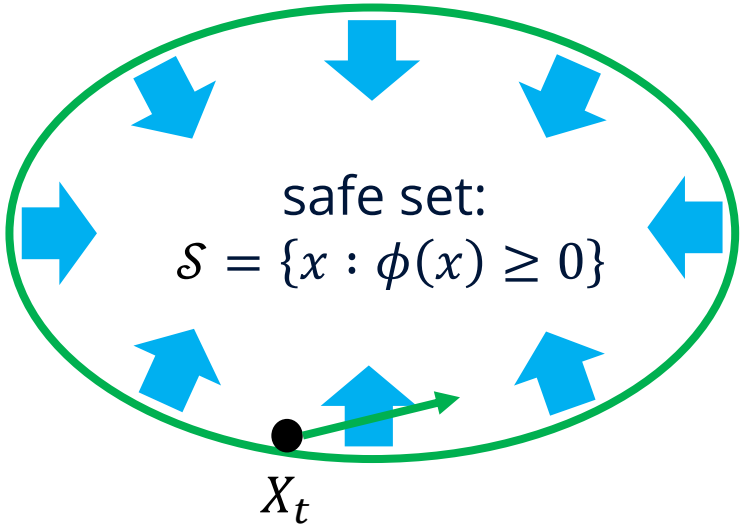

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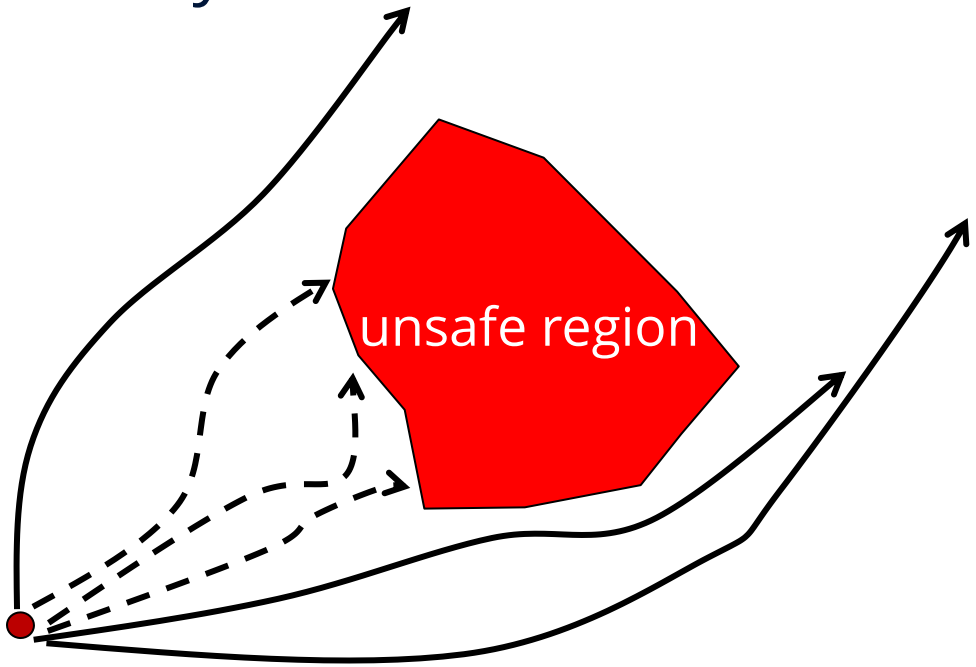

Forward rollout trajectories

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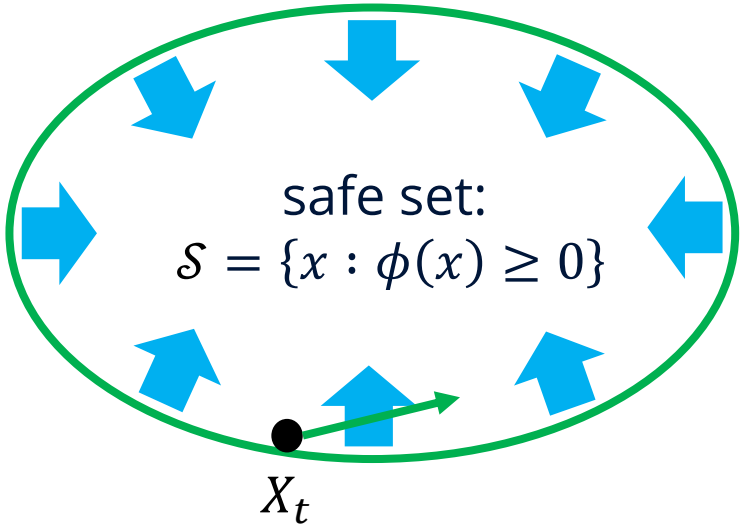

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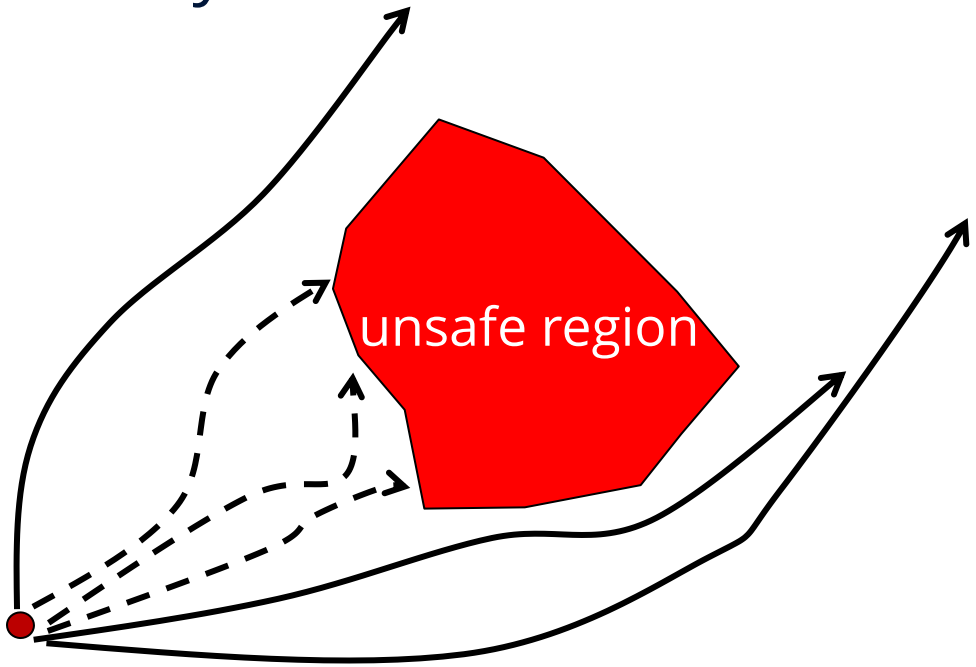

Encoded safety probability $\Psi(X_t)$ ⟵ Forward rollout trajectories

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Proposed Method: Intuition

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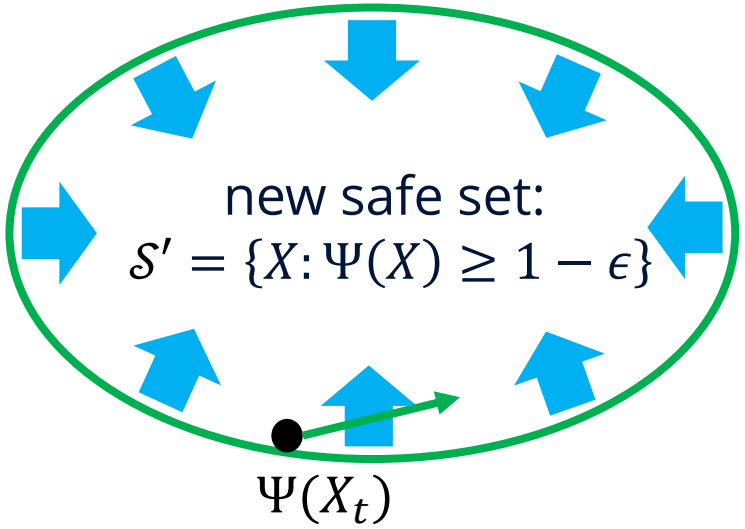
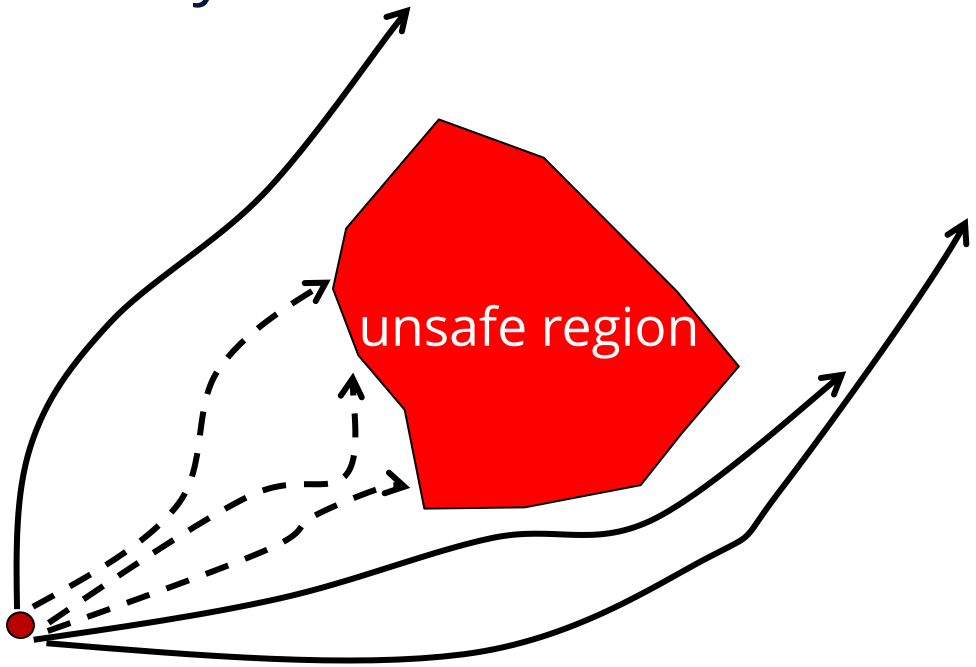


Reachability:



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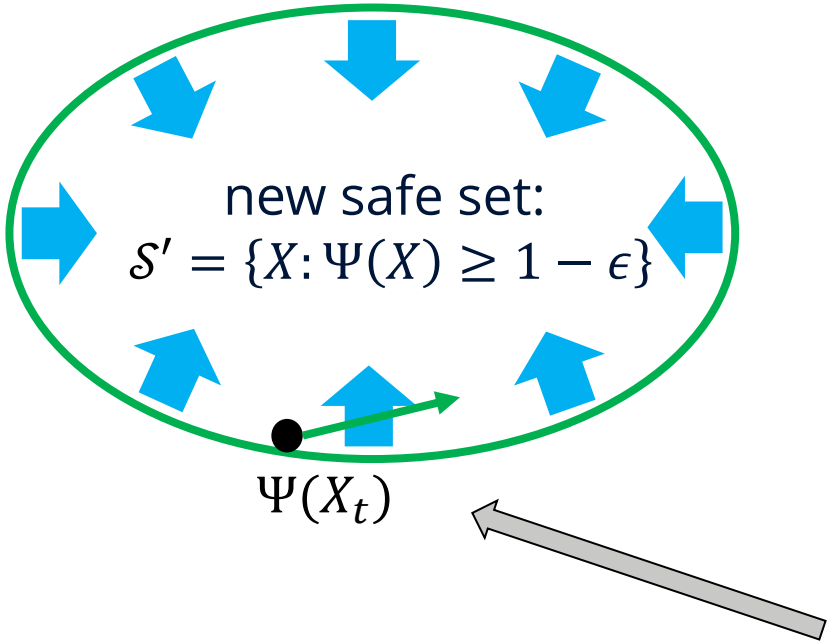
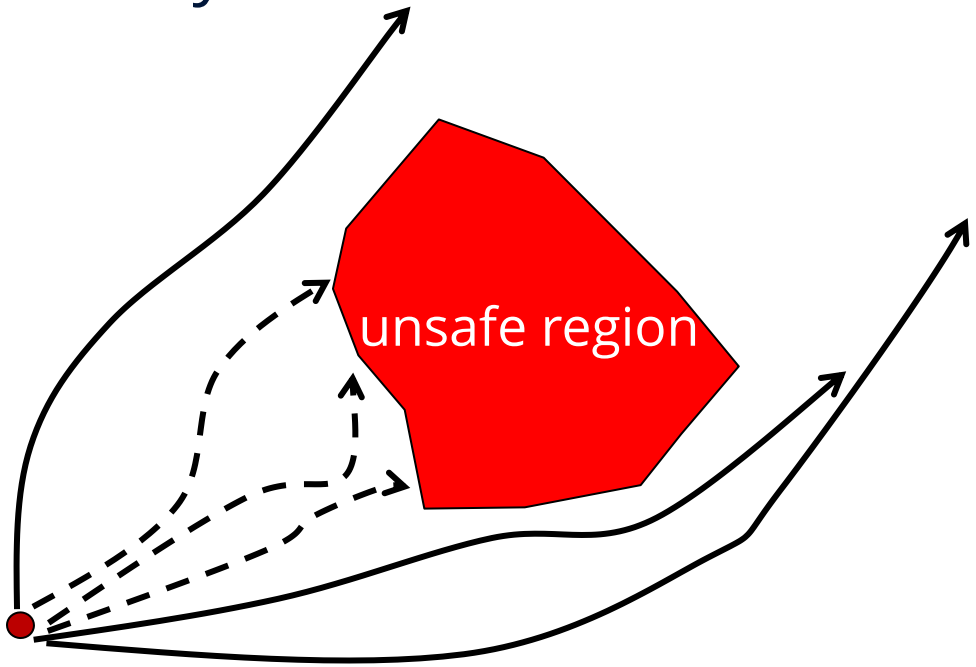


Reachability:



Encoded safety probability $\Psi(X_t)$ ⟵ Forward rollout trajectories

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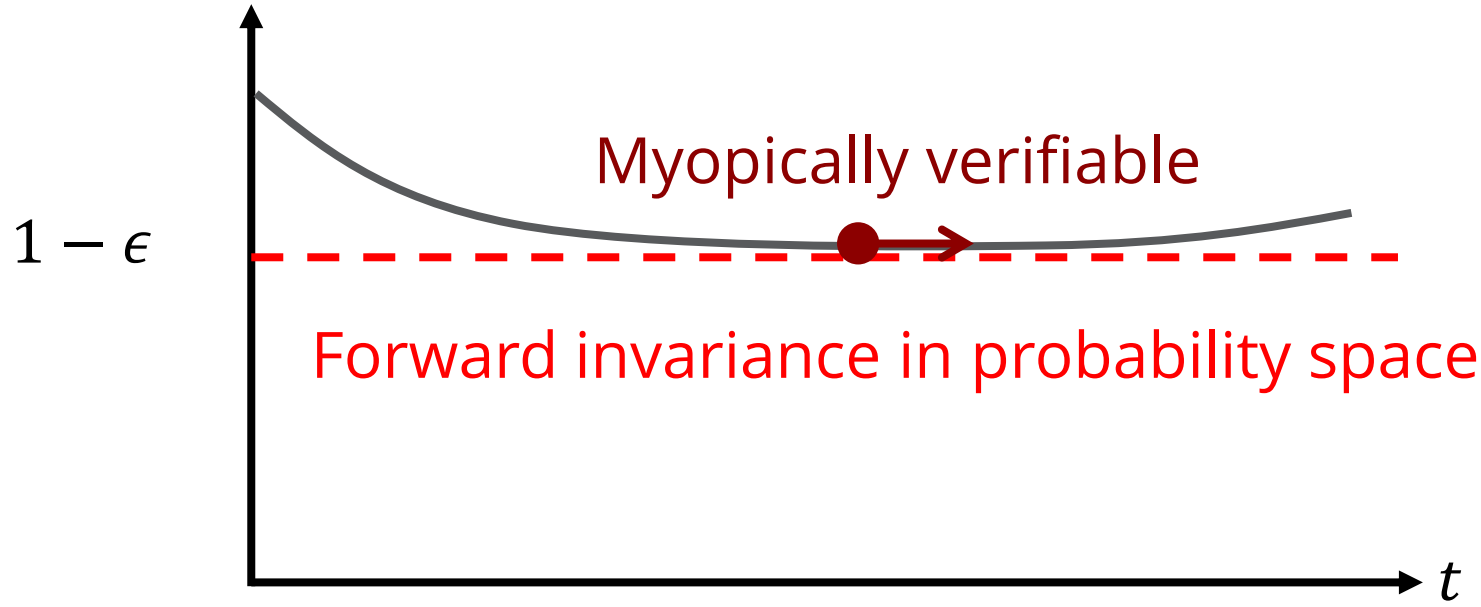
Safe Control Method

Long-term safe probability

$$\Psi(X_t) = \Pr(X_\tau \in \mathcal{C}, \tau \in [t, t+T] | X_t, \xi_t)$$



Reliability

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Safe Control Method

$$\Psi(X_t) = \Pr(X_\tau \in \mathcal{S}, \tau \in [t, t+T] | X_t, \xi_t)$$

$$A\Psi(X_t) \geq -\gamma(\Psi(X_t) - (1-\epsilon))$$

time derivative of safe probability

desired safe probability

$\gamma: \mathbb{R} \to \mathbb{R}$ is a concave function, with $\gamma(q) \leq q, \forall q \in \mathbb{R}$.

Safe Control Method

$$A\Psi(X_t) \geq -\gamma(\Psi(X_t) - (1-\epsilon))$$

linear with respect to u

$$A\Psi(X_t) = \mathcal{L}_f\Psi(X_t) + \big(\mathcal{L}_g\Psi(X_t)\big)u + \frac{1}{2}\mathrm{tr}([\sigma(X_t)]^\intercal \mathrm{Hess}\Psi(X_t)[\sigma(X_t)])$$

constant given system dynamics

$$dX_t = (f(X_t) + g(X_t)U_t)dt + \sigma(X_t)dW$$

Efficiency

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Safe Control Method

nominal controller $U_t = N(X_t)$ ensures desired performance without considering safety

The proposed safe controller:

$$U_t = \arg\min_u J(N(X_t), u)$$

$$\text{s.t. } A\Psi(X_t) \geq -\gamma(\Psi(X_t) - (1-\epsilon))$$

Objective function that penalizes derivation from desired performance, constrained by safety condition.

Modularity

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Conclusion

Theme: Safe control strategy for vehicle lateral force control

Features:

- **Provable long-term safety guarantee**
- **Can deal with uncertainties and adapt to changes**
- **Better trade-off between performance, safety, and computation**

Thanks for listening!

Reference

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