UNIVERSITY OF TRENTO

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IDRA
INTERDEPARTMENTAL ROBOTICS LABS

Beyond Terminal Constraints: Safe Robot Control

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[1] Receding-Constraint MPC using a Learned Approximate Control-Invariant Set. IEEE ICRA 2024
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[3] Beyond Terminal Constraints: Reliable Robot Control with Learned Safe Sets. IJRR 2026 (under review)

Safety Definition

What is safety?

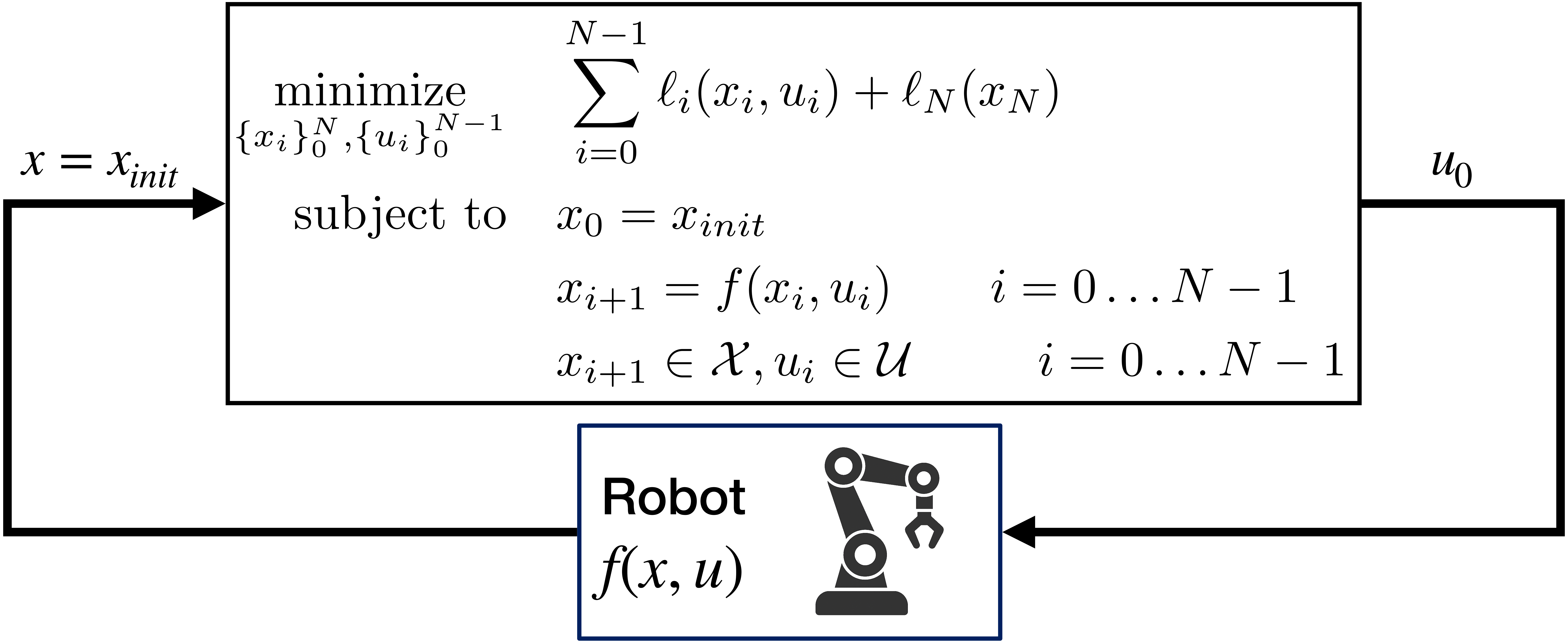
- Joint angle, velocity, torque limits
- Collision avoidance
  - Self-collision
  - Static obstacles (e.g., table, wall)

$$x \in \mathscr{X}, u \in \mathscr{U}$$

  - Dynamic obstacles (e.g., humans, other robots)
- Collision management:
  - Contact shall not result in pain or injury

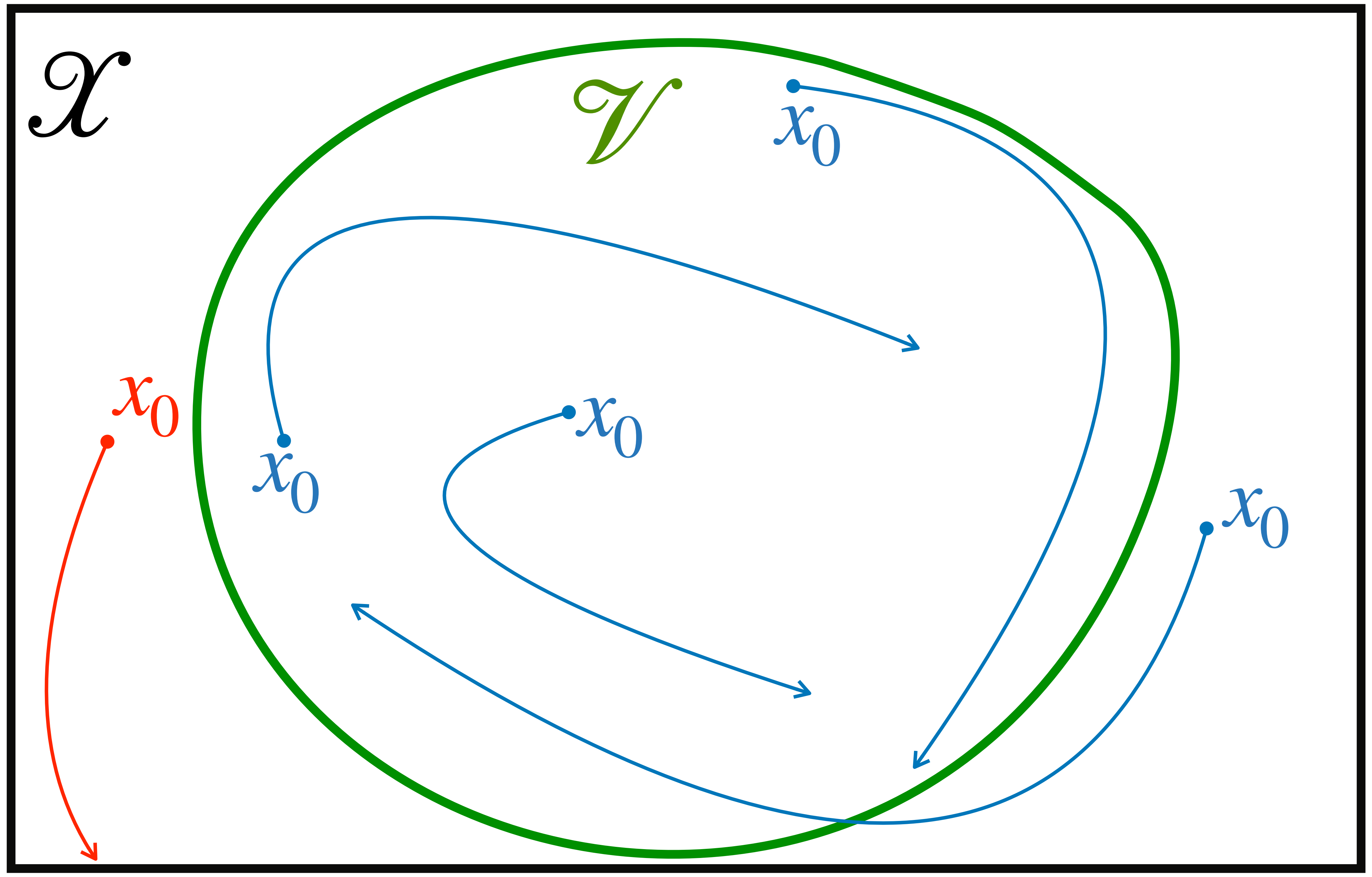
Model Predictive Control

Trajectory Optimization inside the control loop



Safety via Control Invariant Sets

$\mathscr{V} \subseteq \mathscr{X}$ is a control invariant set ⟷ Once x is in $\mathscr{V}$, it can remain in $\mathscr{V}$



Recursive Feasibility

Model Predictive Control (MPC)

Using a CIS $\mathscr{V}$ as terminal set ensures recursive feasibility in MPC

$$
\begin{aligned}
\underset{\{x_i\}_0^N, \{u_i\}_0^{N-1}}{\text{minimize}} \quad & \sum_{i=0}^{N-1} \ell_i(x_i, u_i) + \ell_N(x_N) \\
\text{subject to} \quad & x_0 = x_{init} \\
& x_{i+1} = f(x_i, u_i) && i = 0 \dots N-1 \\
& x_i \in \mathcal{X}, u_i \in \mathcal{U} && i = 0 \dots N-1 \\
& \boxed{x_N \in \hat{\mathcal{V}}}
\end{aligned}
$$

Beyond Control Invariant Sets (CIS)

- CIS are unknown for nonlinear systems
- Numerical approximation techniques exist, however:
  - computationally demanding (curse of dimensionality)
  - compute approximate CIS → safety guarantees are lost!

Do we really need Control Invariant Sets to ensure safety?

Beyond Control Invariant Sets

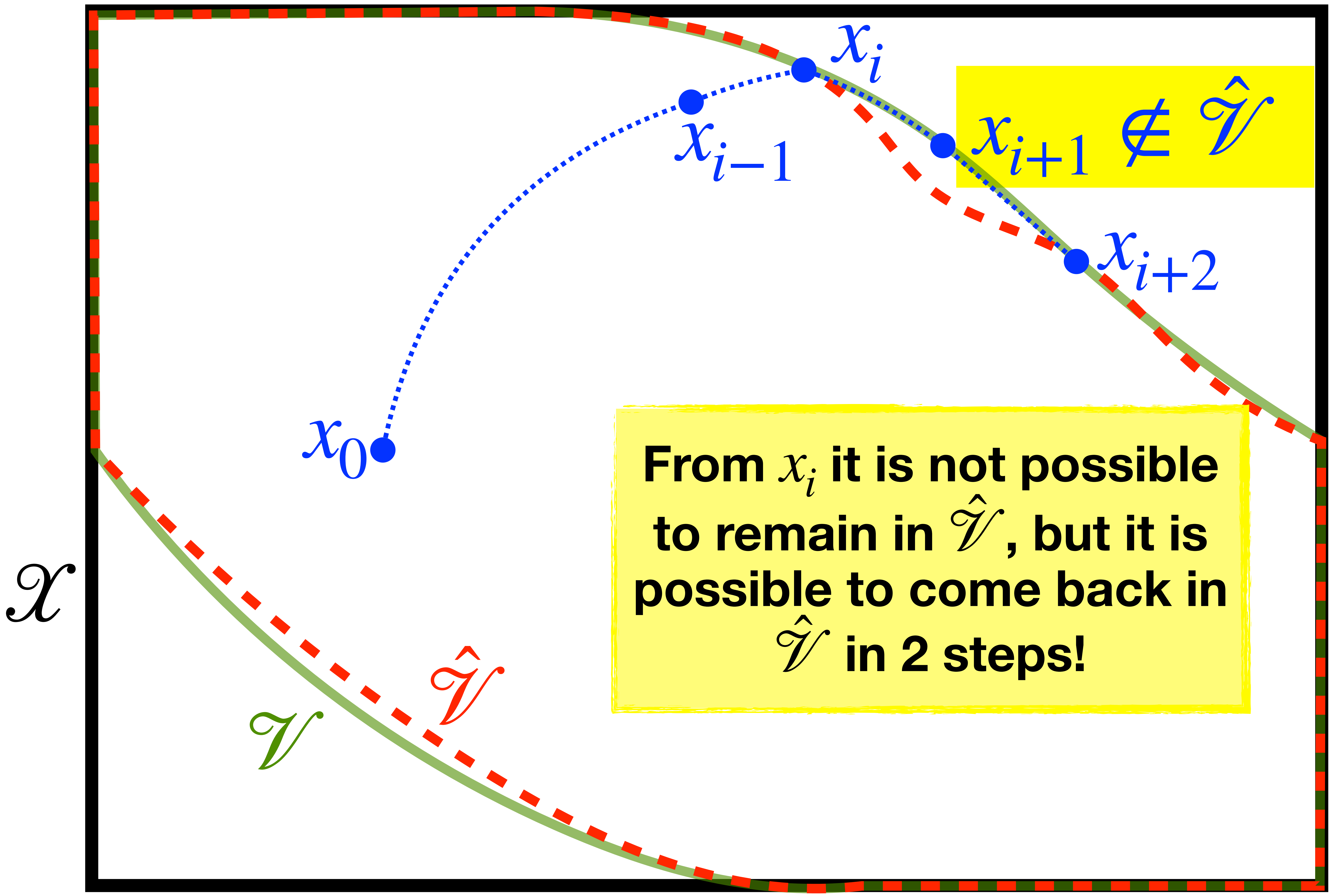
Beyond Control Invariant Sets

Two hypotheses:

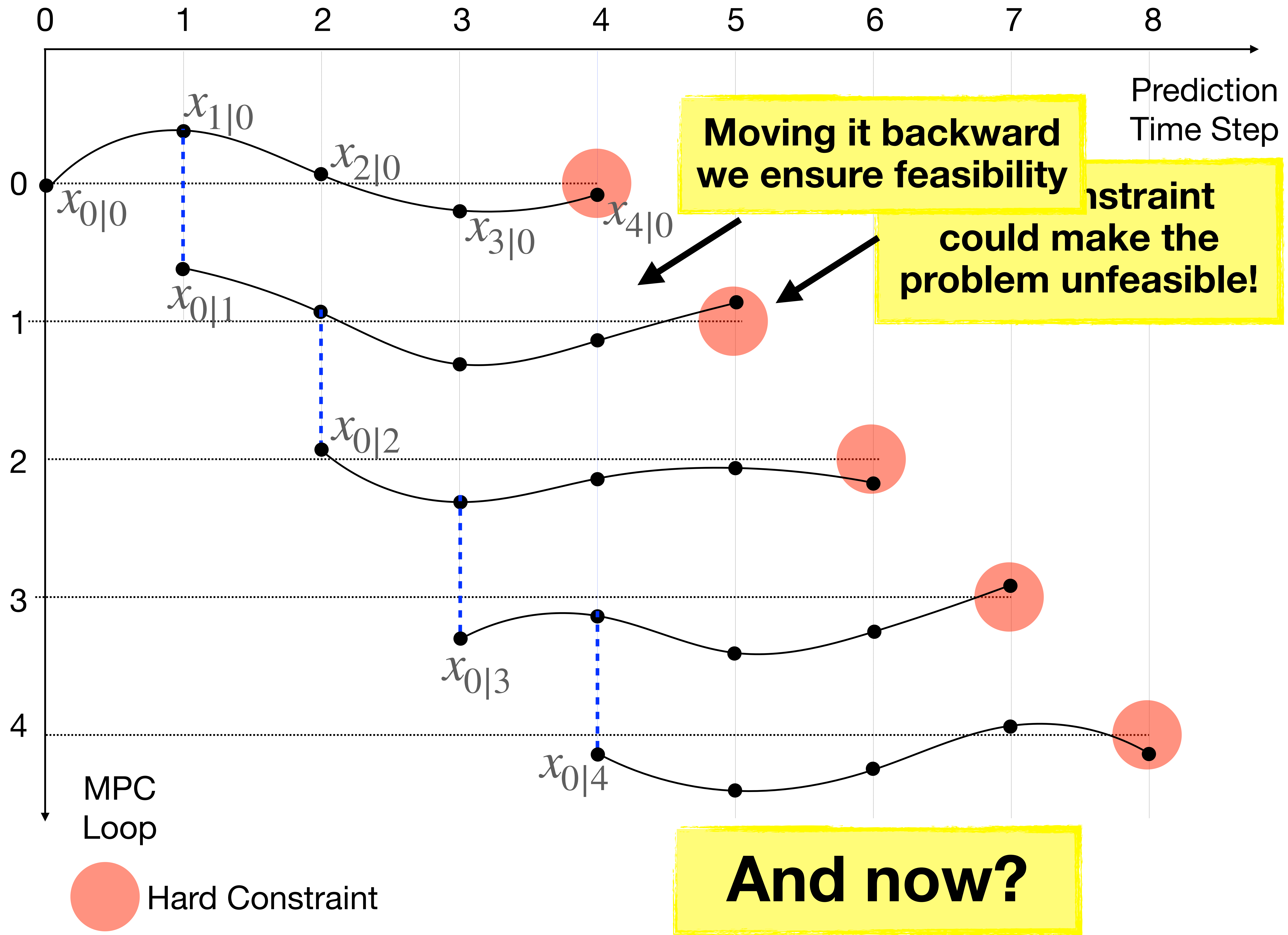
New controllers work better even with approximate CIS	New sets are easier to compute
✅	~✅

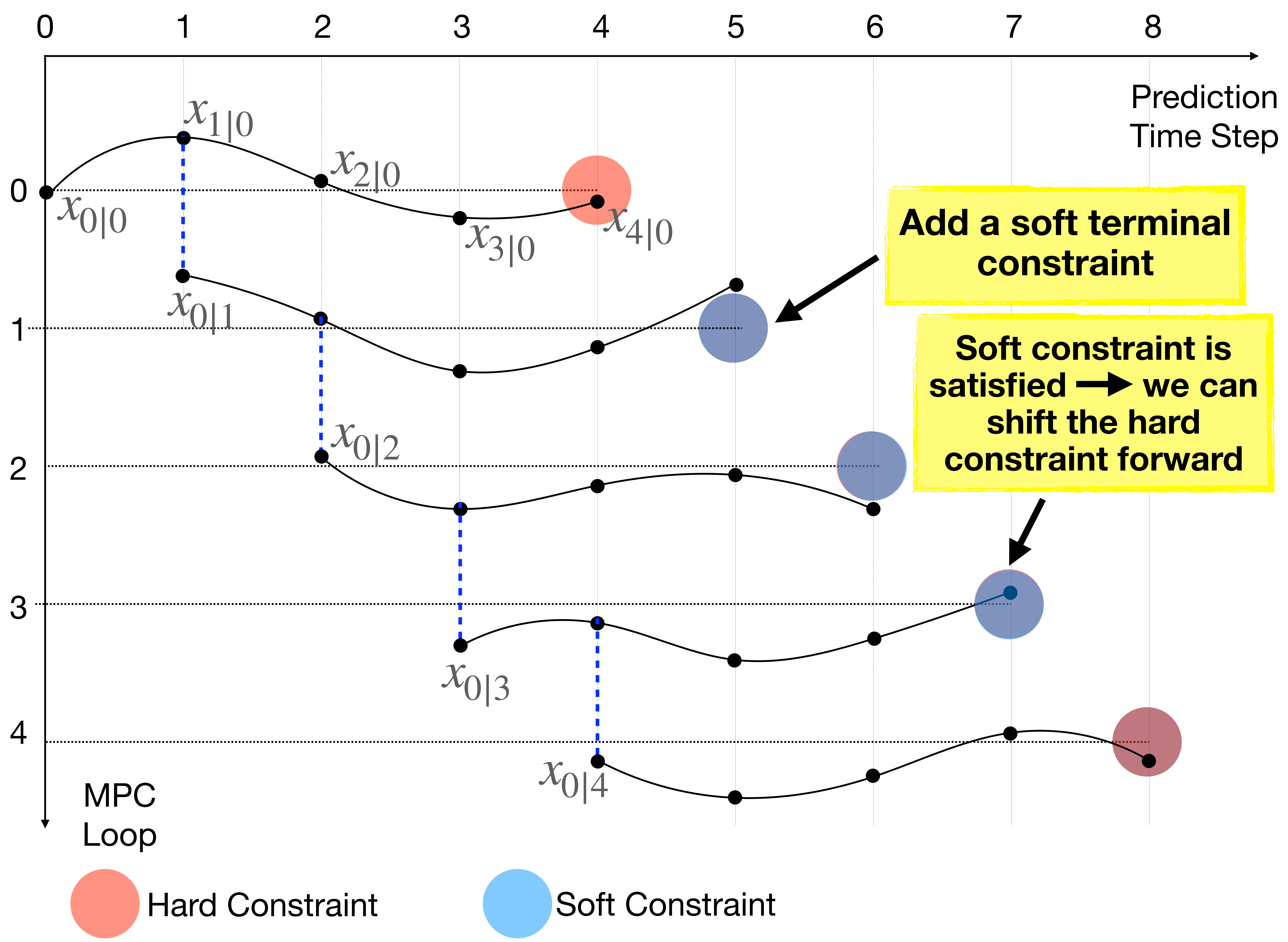
N-Step Control Invariant Set

- $\hat{\mathcal{V}}$ is an N-Step CIS iff for every $x_0 \in \hat{\mathcal{V}}$ it is possible to have:
  - $x_N \in \hat{\mathcal{V}}$
  - $x_i \in \mathcal{X} \quad \forall i \in [1, N-1]$
- Weaker condition than classic control invariance



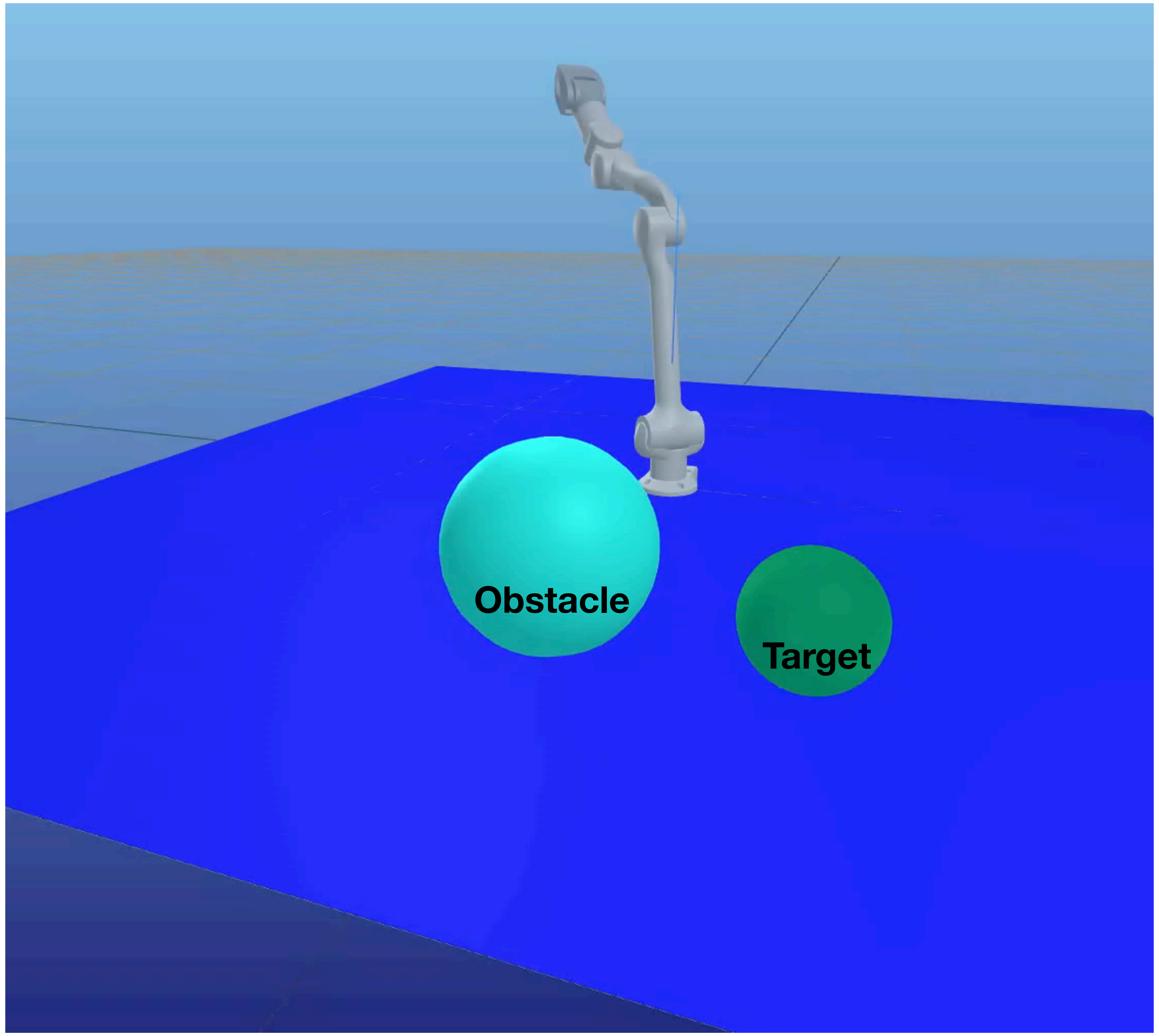
Beyond Control Invariant Sets


0 1 2 3 4 5 6 7 8
Prediction
Time Step
MPC
Loop
0
1
2
3
4
$x_{0|0}$
$x_{1|0}$
$x_{2|0}$
$x_{3|0}$
$x_{4|0}$
$x_{0|1}$
$x_{0|2}$
$x_{0|3}$
$x_{0|4}$
Moving it backward
we ensure feasibility
nstraint
could make the
problem unfeasible!
And now?
Hard Constraint


0
1
2
3
4
5
6
7
8
Prediction Time Step
$x_{1|0}$
$x_{2|0}$
$x_{0|0}$
$x_{3|0}$
$x_{4|0}$
Add a soft terminal constraint
$x_{0|1}$
Soft constraint is satisfied → we can shift the hard constraint forward
$x_{0|2}$
$x_{0|3}$
$x_{0|4}$
MPC Loop
Hard Constraint
Soft Constraint

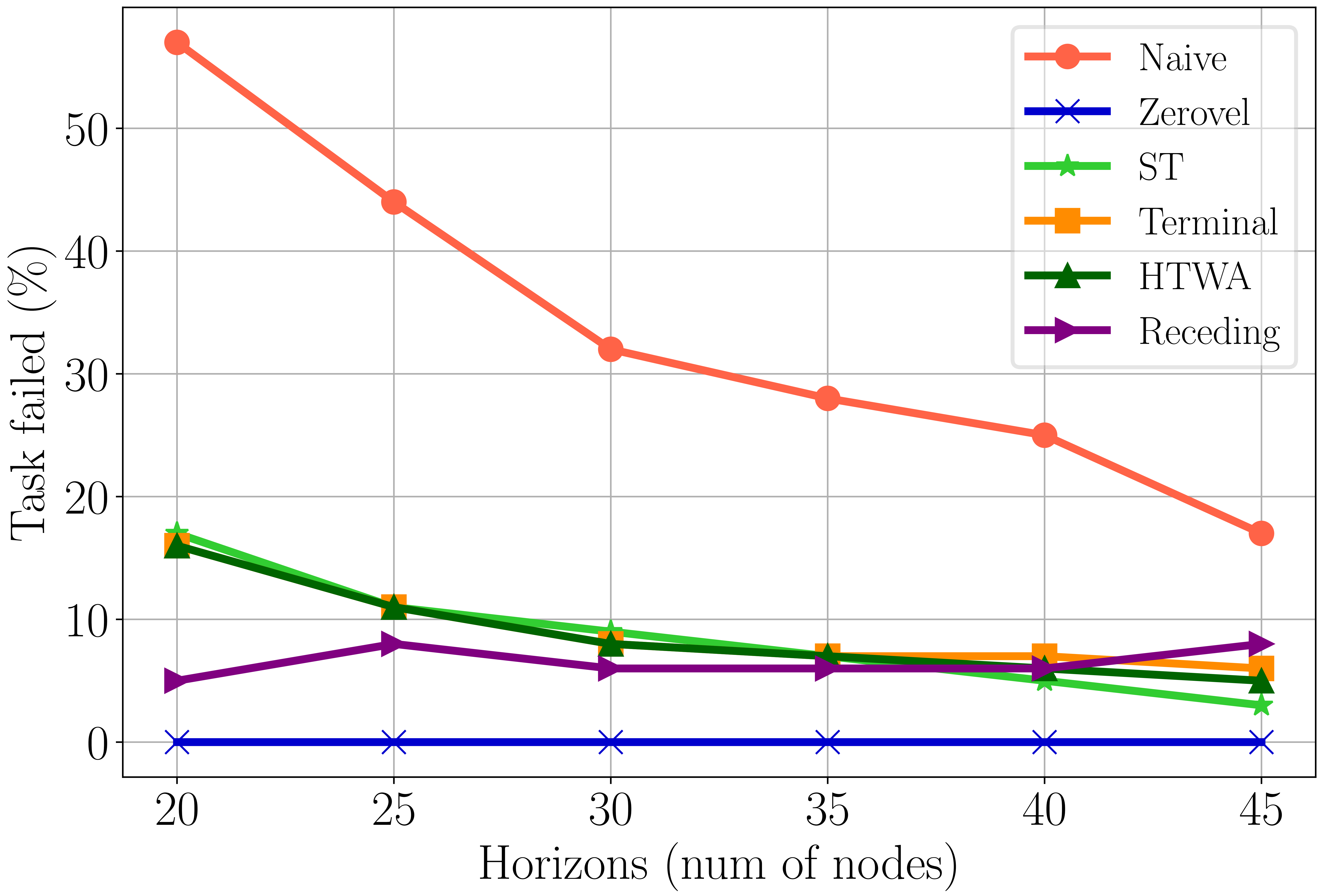
Simulation Results

- 4 DoF Z1 robot manipulator
- Acados software library
- Safe set $\hat{\mathscr{V}}$ represented with neural network
- 500 simulations
- Random initial configurations
- Max horizon N=45
- Computation time < dt (5 ms)
- https://github.com/idra-lab/safe-mpc



Simulation Results - Receding

- Naive: standard MPC formulation
- Zerovel: terminal constraint imposing zero velocity
- ST: soft terminal constraint $\hat{\mathscr{V}}$
- Terminal: hard terminal constraint $\hat{\mathscr{V}}$
- HTWA: hard terminal constraint $\hat{\mathscr{V}}$ with safe abort strategy



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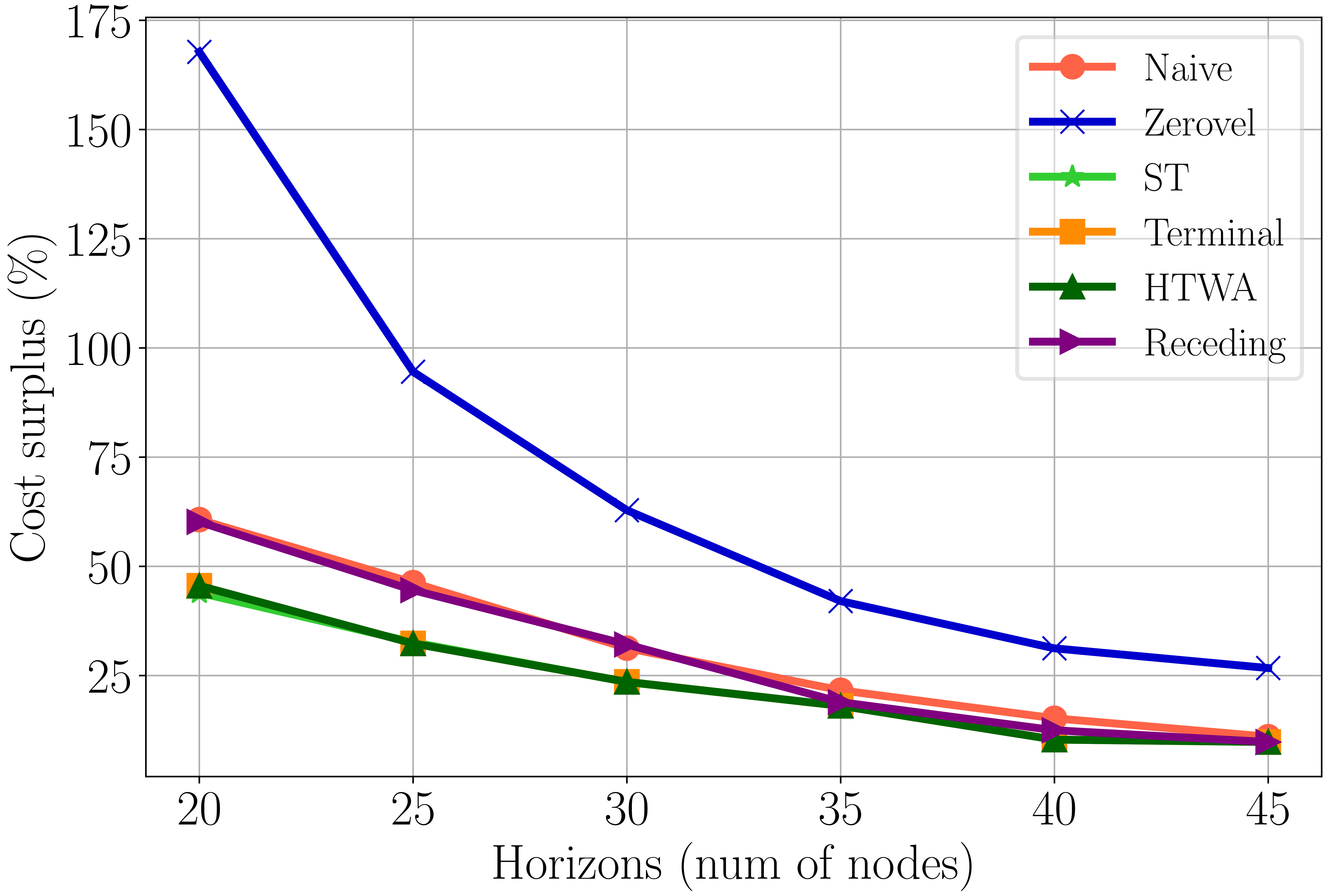
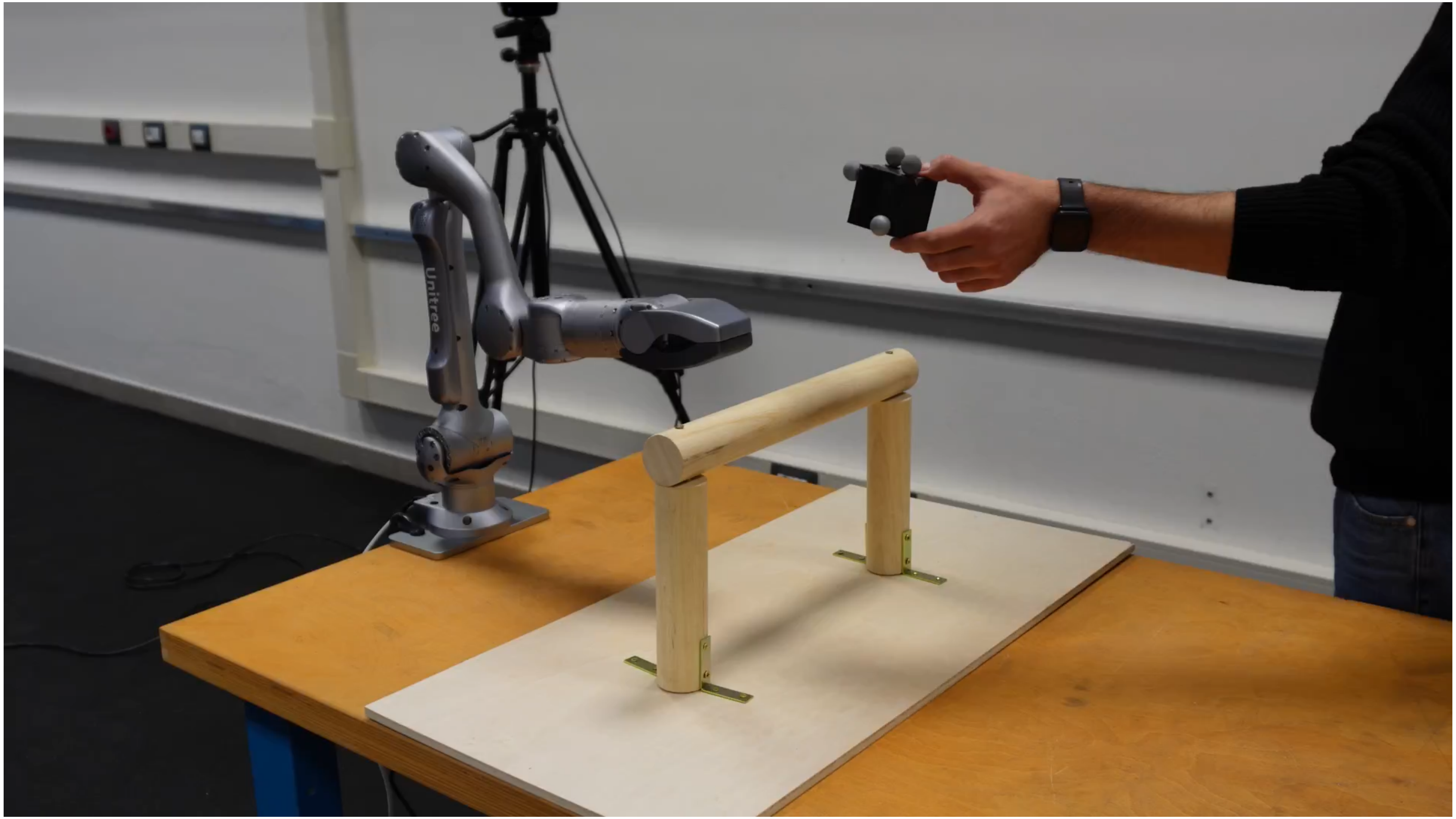


Tracking Experiment - Side View



Conclusions

- Novel MPC formulations:
  - Safe under weaker conditions (multi-step CIS)
  - Empirically superior when using approximate CIS

On-going/future work

- Computation/certification of novel Multi-Step CIS
- Dynamics uncertainties, moving obstacles

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