Safe Dual Control through MPC

Workshop on Stochastic Planning & Control of Dynamical Systems

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64th IEEE Conference on Decision and Control

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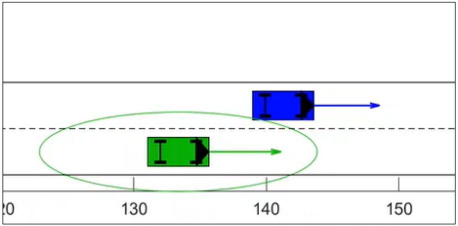
Motivation: automated driving

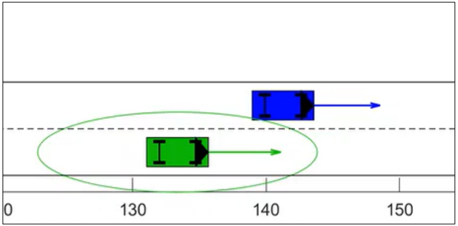
Naïve MPC

Constant Velocity Predictions



Dual MPC

Adaptive constraints & online training



[1] **T.M.J.T. Baltussen**, E. Lefeber, R. Tóth, W.P.M.H. Heemels and A. Katriniok, "Online learning of interaction dynamics with dual model predictive control for multi-agent systems using Gaussian processes," American Control Conference 2025

Dual Control

$$\mathcal{I}_k := \{x_k, \mathbf{z}_{k-1}, \ldots, \mathbf{z}_0\},$$

$$\text{where } \mathbf{z}_i^\top = [x_i^\top, u_i^\top] \in \mathbb{R}^{n_z}$$

Dual objectives

- Control vs system identification

Dual effect [2]

$$\Sigma^x_{i|k} := \mathbb{E}\left[\Sigma^x_{k+i} \mid \mathcal{I}_k, U^*_{0:i-1|k}\right] \neq \mathbb{E}\left[\Sigma^x_{k+i} \mid \mathcal{I}_k\right]$$

- Caution: conservatism under uncertainty (or lack thereof)
- Active learning: steer system to states provide information

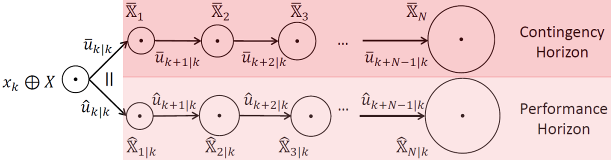
[2] Y. Bar-Shalom and E. Tse, "Dual effect, certainty equivalence, and separation in stochastic control," in *IEEE Transactions on Automatic Control*, vol. 19, no. 5, pp. 494-500, October 1974

Safety?

$$x_{k+1} = \underbrace{f(x_k, u_k)}_{\text{Nominal dynamics}} + \underbrace{g(x_k, u_k) + v_k}_{=:w_k \text{ (Unmodeled dynamics)}},$$

$$v_k \in \mathbb{V} \subset \mathbb{R}^{n_x} \quad w_k \in \mathbb{W} \subset \mathbb{R}^{n_x}$$

- Bounded uncertainties
- Given a robust MPC
- Contingency MPC inherits safety guarantees



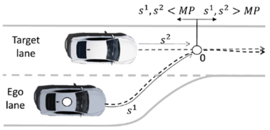
$$f(x_k, u_k)$$

$$f(x_k, u_k) + d(x_k, u_k, \mathcal{I}_k)$$

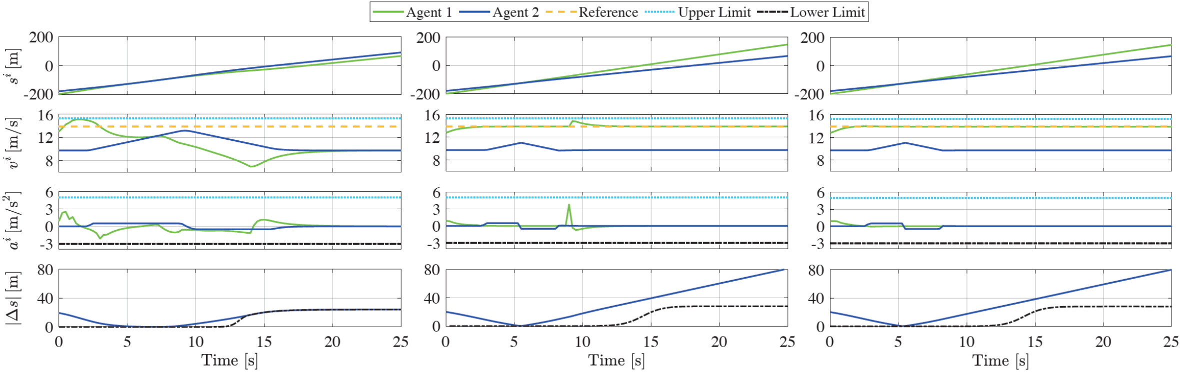
$$d(x_k, u_k, \mathcal{I}_k) \approx g(x_k, u_k)$$

[3] M. Geurts*, **T. Baltussen***, A. Katriniok and M. Heemels, "A Contingency Model Predictive Control Framework for Safe Learning," in IEEE Control Systems Letters, 2025 – Presented at CDC 2025

Lane Merging (2)



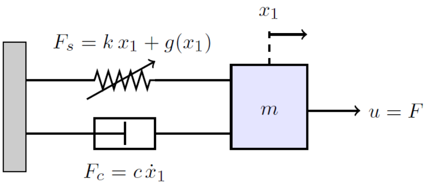
RMPC **Contingency MPC** **GP-MPC**



[3] M. Geurts*, **T. Baltussen***, A. Katriniok and M. Heemels, "A Contingency Model Predictive Control Framework for Safe Learning," in IEEE Control Systems Letters, 2025 – Presented at CDC 2025.

Active Learning

- Active learning framework [5]
- Safety guarantees



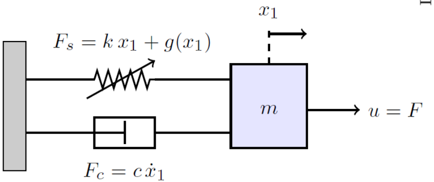
$$
\begin{aligned}
\min_{\hat{x}_{0|k}, \bar{U}_k, \hat{U}_k, \Delta J_k} \quad & H\left(x_k, \hat{x}_{0|k}, \hat{U}_k\right) \\
\text{s.t.} \quad & J\left(x_k, u_{k-1}, \hat{U}_k\right) = J_k^B + \Delta_k, \\
& \Delta_k \leq \bar{\beta} \max\{J_k^+, 0\} + \bar{\gamma} + Y_{k-1}, \\
& \Delta_k \leq \beta^{\max} \max\{J_k^+, 0\} + \gamma^{\max}, \\
& \vdots \\
& \bar{x}_{k+j|k} \in \bar{\mathbb{X}}_j, \quad j = 0, 1, \ldots, N, \\
& \hat{x}_{k+j|k} \in \hat{\mathbb{X}}_{j|k}, \quad j = 0, 1, \ldots, N.
\end{aligned}
$$

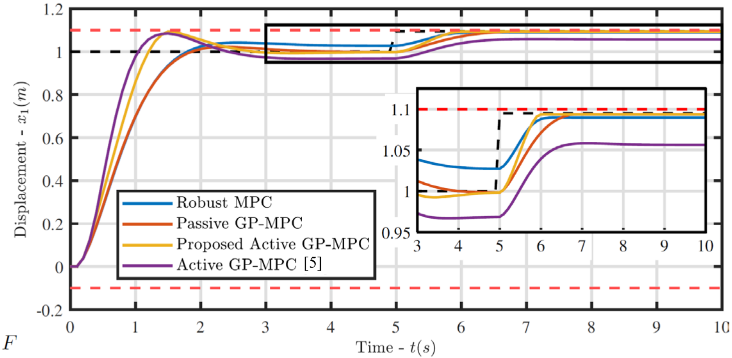
[4] **T. Baltussen**, M. Heemels & A. Katriniok, "Dual MPC for Active Learning of Nonparametric Uncertainties," preprint on arXiv 2511.08542.

[5] Soloperto, R., Köhler, J., & Allgöwer, F., Augmenting MPC schemes with active learning: Intuitive tuning and guaranteed performance. IEEE Control Systems Letters, pp. 713-718, 2020.

Active Learning

- Safe exploration
- Reduced conservatism
- Simple example



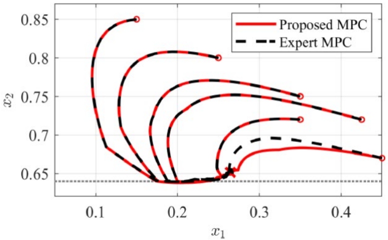


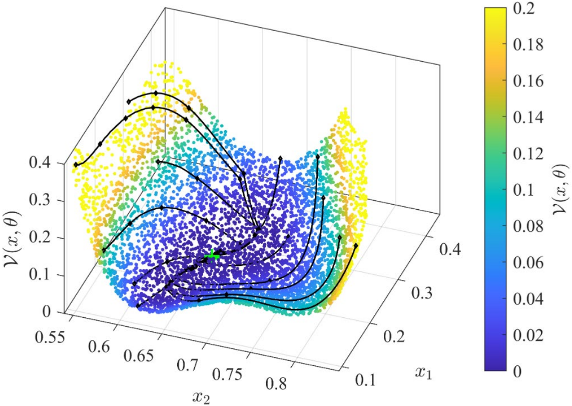
[4] **T. Baltussen**, M. Heemels & A. Katriniok, "Dual MPC for Active Learning of Nonparametric Uncertainties," preprint on arXiv 2511.08542.

[5] Soloperto, R., Köhler, J., & Allgöwer, F., Augmenting MPC schemes with active learning: Intuitive tuning and guaranteed performance. IEEE Control Systems Letters, pp. 713-718, 2020.

Value Function Approximation for MPC

- Synthesize terminal cost function
- Descent constraint
- Scenario optimization





[6] **T.M.J.T. Baltussen**, C.A. Orrico, A. Katriniok, W.P.M.H. Heemels and D. Krishnamoorthy, Value Function Approximation for Nonlinear MPC: Learning a Terminal Cost Function with a Descent Property, 2025, preprint on arXiv 2508.05804 – Presented at CDC 2025.

Let's connect

Conference on Decision and Control
CDC2025
Rio de Janeiro, Brazil. Dec. 09 - 12

Value Function Approximation for Nonlinear MPC: Learning a Terminal Cost Function with a Descent Property, 16:30-16:45 (ThC16.1)

A Contingency Model Predictive Control Framework for Safe Learning, 17:00-17:15 (ThC16.3)

Both on Thursday, Regular Session, Capri III

Link to webpage