Robust Vehicle Lane Keeping Control with Networked Proactive Adaptation

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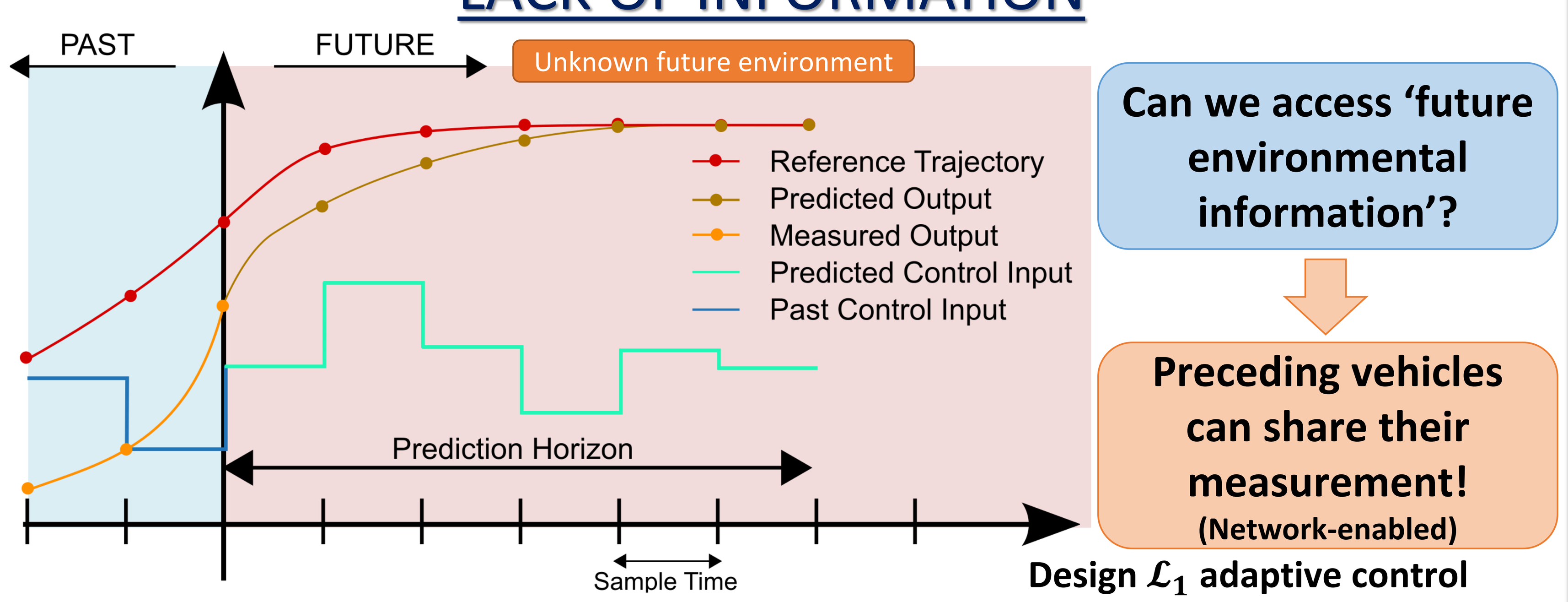
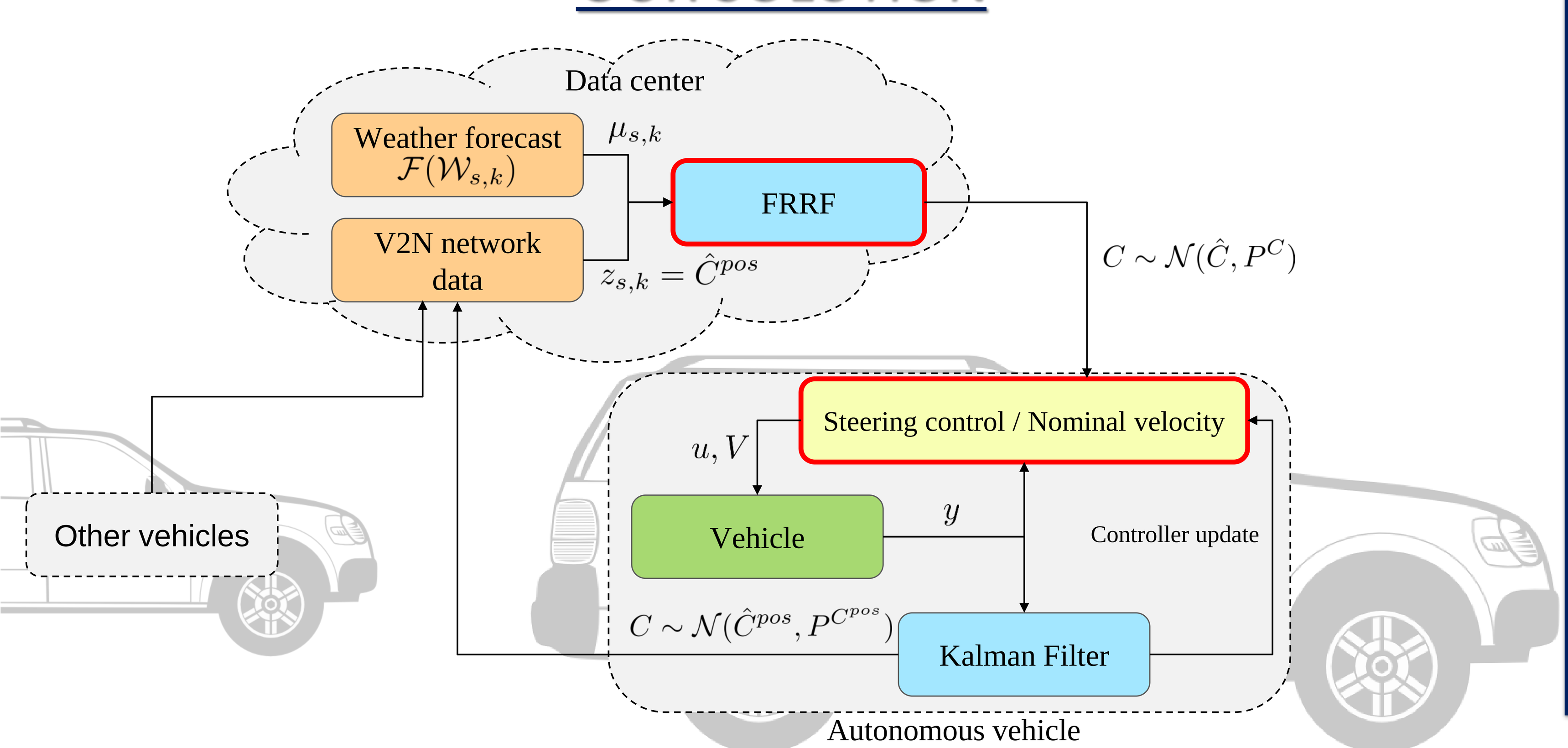
MOTIVATION

LACK OF INFORMATION



- Prediction quality is determined by limited prior knowledge

OUR SOLUTION



FIXED RANK RESILIENT FILTERING (FRRF)

$$q_{s,k} = \mu_{s,k} + \boxed{S_{s,k}\eta_k} + \xi_{s,k}$$

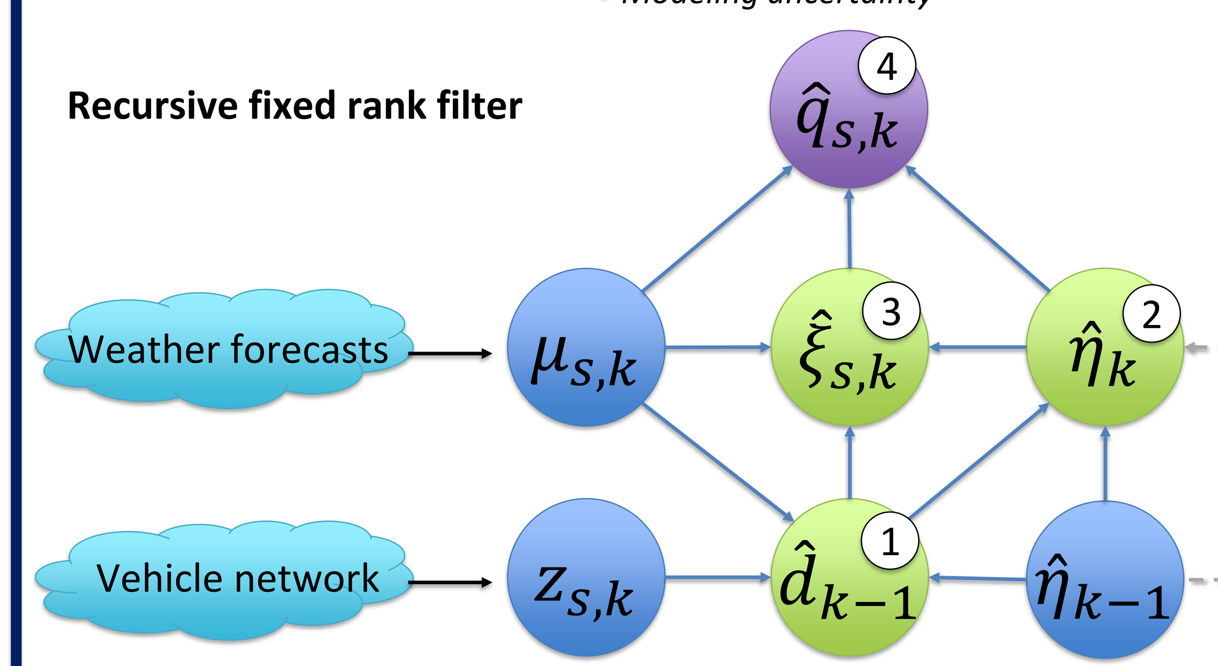
$$z_k = [z_{s_{1_k},k}, z_{s_{2_k},k}, \cdots, z_{s_{n_k},k}]^\top$$

$$z_{s,k} = q_{s,k} + \epsilon_{s,k},$$

$$\eta_{k+1} = H_k\eta_k + \boxed{G_k d_k} + \zeta_k$$

Weather forecasts · *Spatial relation between area* · *Variable of interest* · *Measurements for some areas* · *Fixed rank model* · *Modeling uncertainty*

Recursive fixed rank filter



Properties
- Best Linear Unbiased Estimate (BLUE)
- Estimation errors are practically exponentially stable

PROACTIVE CONTROLLER DESIGN

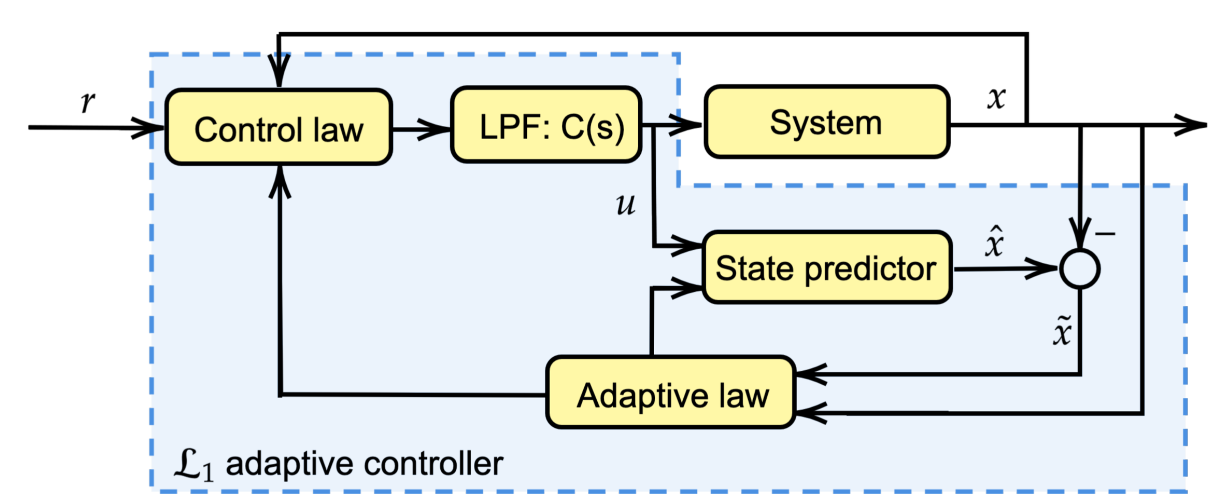
Vehicle lateral model

$$\dot{x} = A(V, C_f, C_r)x + b(C_f)u + g(V, C_f, C_r)\dot{p}^{\psi,des}$$

System matrices depend on the longitudinal velocity and cornering stiffness

Obtain the uncertainty model by propagating estimation uncertainty ($u = -Kx + u_{ad}$)

$$\dot{x}(t) = A_m x(t) + b_m(w u_{ad}(t) + \theta^\top x(t) + \sigma(t))$$
$$y(t) = c^\top x(t) \qquad x(0) = x_0,$$



- The architecture decouples adaptation from robustness. We can choose adaptation gain as large as CPU permits.
- The low pass filter design trade-offs between the performance and the robustness.

Stability condition:

$$A_m, A_g = \begin{bmatrix} A_m + b_m\theta^\top & b_m w \\ -k\theta^\top & -kw \end{bmatrix} \text{ Hurwitz}$$

Filter gain

Common Lyapunov approach: Stability condition for all velocity ranges. This gives a freedom to choose velocity later.

$$A_m(V)P + PA_m^\top(V) < 0$$

LONGITUDIANL VELOCITY DESIGN

$$\max_{k, V \in [V_{\min}, V_{\max}]} V$$
$$\text{s.t. } \boxed{\|G(s)\|_{\mathcal{L}_1} \le \lambda_{gp}} \text{ for } \forall w \in \Omega$$
$$\boxed{k \le \bar{k}}$$

Tracking performance constraint · *Robustness constraint*

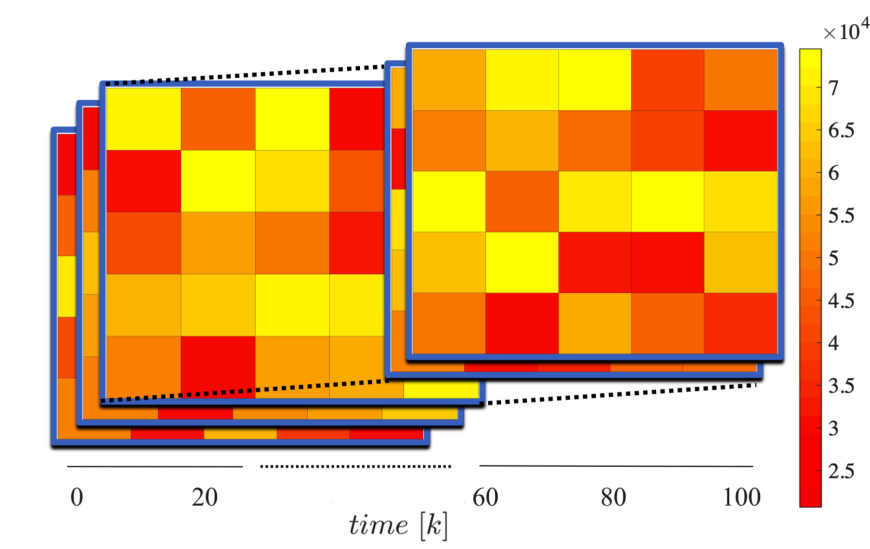
- $k\uparrow$: Better tracking performance, time-delay margin decreases.
- Lateral controller is designed for all velocities.
- The velocity determines performance.

CONTROLLER UPDATE

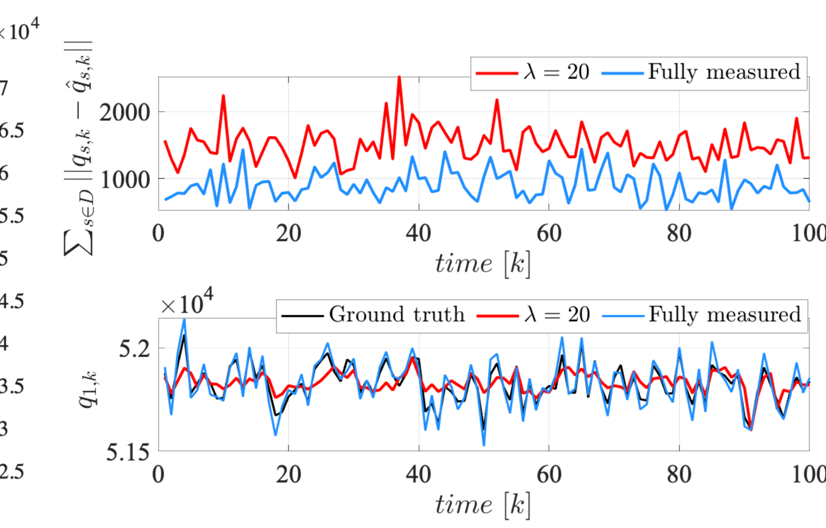
$$k = \arg\min_k |k - k_*|$$
$$\text{s.t. } A_g(V) \text{ being Hurwitz, } k \le \bar{k}$$

- Reference system A_m and A_g must be Hurwitz stable for all uncertainty ranges.
- A_m does not depends on the uncertainty bound, i.e., no tuning required.
- Given posterior distribution, we update control gain k to guarantee A_g is Hurwitz.

SIMULATION: FRRF



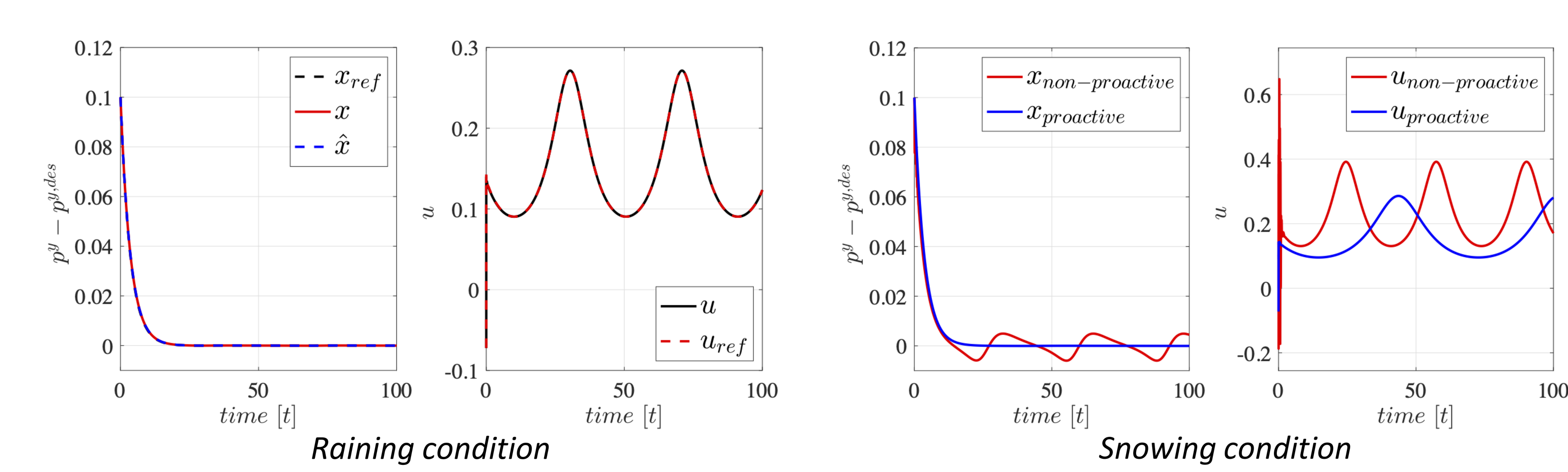
Prior estimation heat map (mean)



Prior estimation performance

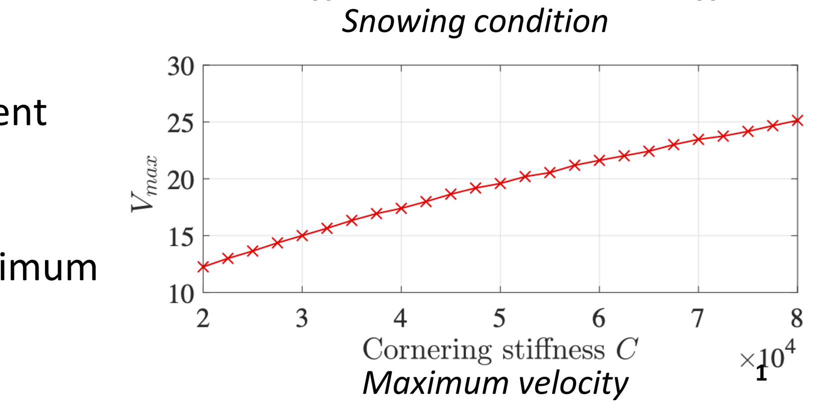
- FRRF generates prior estimation heatmap characterized by mean and variance.
- Estimation performance has been compared with full measurement and sparse measurements in the presence of modeling uncertainty.

SIMULATION: PROACTIVE ADAPTIVE CONTROL (CURVY ROAD)



Raining condition · Snowing condition

- Proactive control maintains desired transient and steady state performance for all environmental conditions.
- The velocity design program provides maximum safe velocity.



Maximum velocity

REFERNCES

- [Full version] H. Kim, W. Wan, N. Hovakimyan, L. Sha, and P. Voulgaris, "Robust Vehicle Lane Keeping Control with Networked Proactive Adaptation", arXiv e-prints, pp.arXiv-2009, 2020.
- N. Hovakimyan, and C. Cao, "$\mathcal{L}_1$ adaptive control theory: Guaranteed robustness with fast adaptation", Society for Industrial and Applied Mathematics, 2010.

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