Intelligent Control Supervisor for Autonomous Vehicles

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Thematic School
SAUTOS: Safe AUTOnomous Systems

Université Paris-Saclay, Orsay, France

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Presenter: Hussam ATOUI

Welcome

- **Current position:** Automated Driving Systems Software Engineer at Valeo (France).
- Integrated Valeo in November 2022
- Received the PhD in October 2022
- **Previous work experiences:** RENAULT (2019 - 2022), Gipsa-lab (2019-2022)
- **Academic background:** PhD in Robotics and Control Systems, Mechatronics Engineering
- **Specialities:** Autonomous Driving, Automatic Control, Robotics, Optimization, Machine Learning, Reinforcement Learning.

→ **Introduce yourselves**

Presentation Contents

Welcome

gipsa-lab

PhD Thesis: Hussam ATOUI

Renault Group

- **Gipsa-lab (Grenoble):**
  - Supervised by Olivier Sename
- **Technocentre RENAULT (Guyancourt):**
  - Supervised by Vicente Milanes
  - using ZOE experimental platform

Valeo

SMART TECHNOLOGY
FOR SMARTER CARS

Automated Driving Software Engineer

Outline

1 Introduction

2 About LPV

3 About LPV-YK

4 LPV-YK Control Structures

5 Application to Autonomous Vehicles

6 Conclusions

Outline

1 Introduction
2 About LPV
3 About LPV-YK
4 LPV-YK Control Structures
5 Application to Autonomous Vehicles
6 Conclusions

Introduction

Automated driving at VALEO

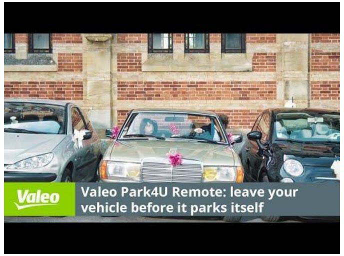
Deliver collaborative and cutting edge innovations to Valeo CDV

NEW PRODUCTS AND SYSTEMS

NEW BUSINESS MODELS

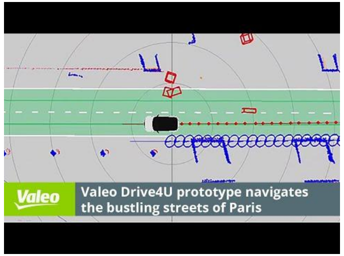
NEW TECHNO AND COMPETENCIES

Park4U®



Cruise4U

Drive4U

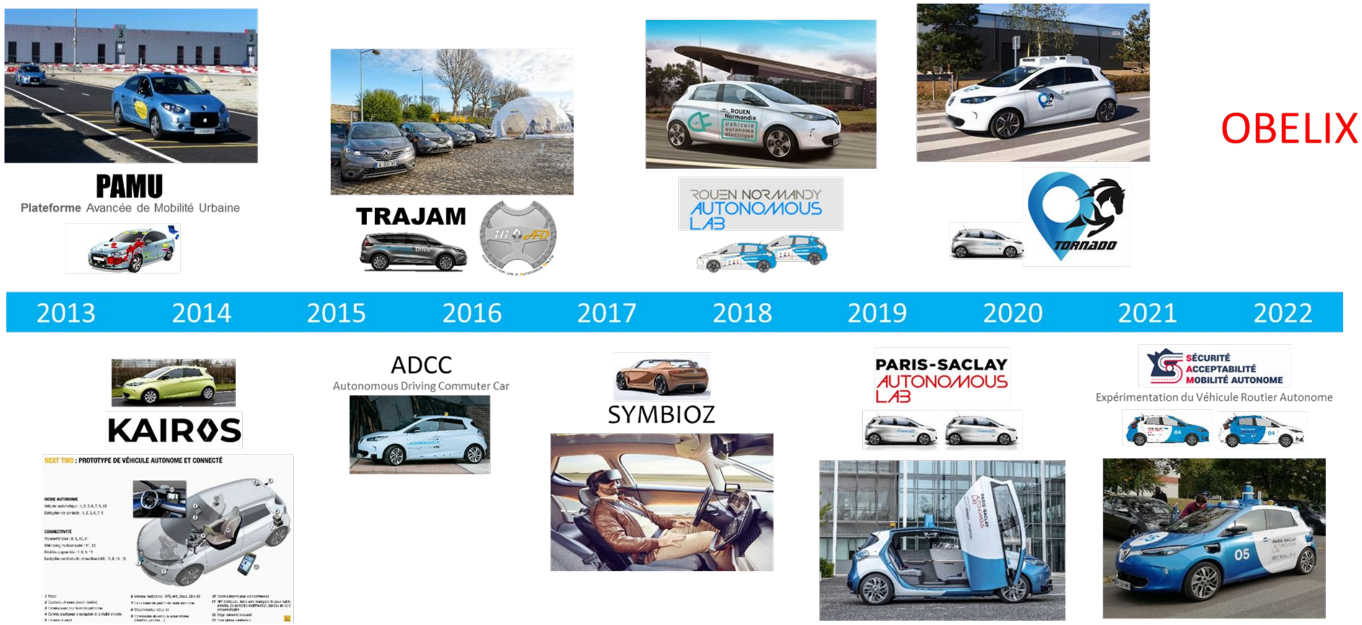


Deliver4U

Mobility kits

Introduction

RENAULT history in automated vehicles



Why to improve the existing lateral control?

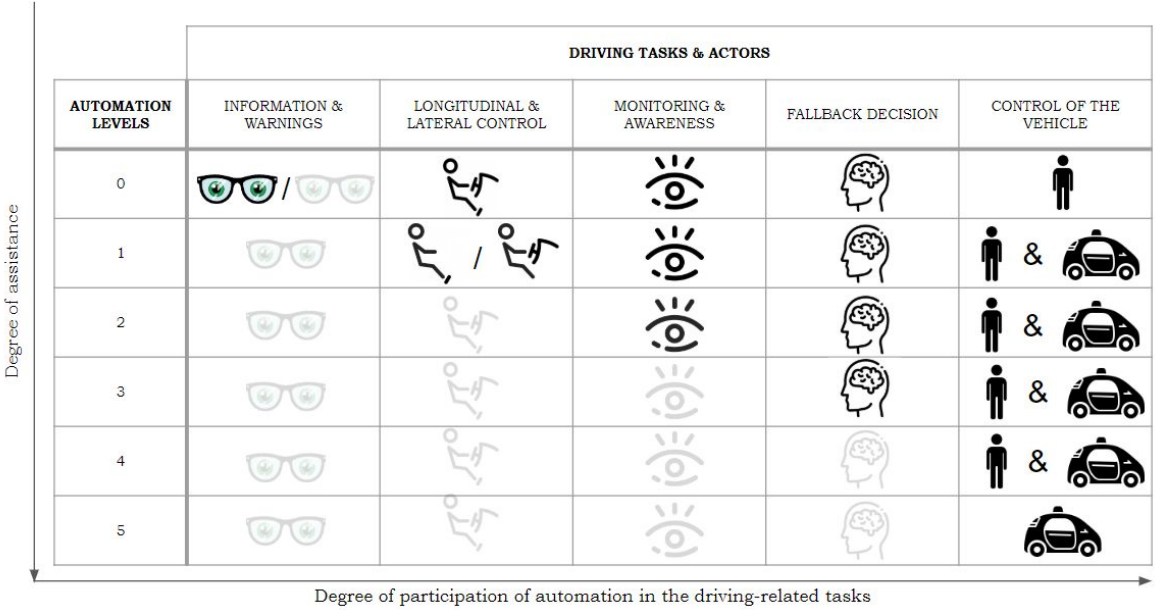
- It needs control tuning for each kind of RENAULT vehicles
- It is limited to low speeds ($< 50\ Km/h$)
- It requires time to re-tune the controller by the engineers

Introduction

Automation Levels

Driving automation divided into 6 levels [1]

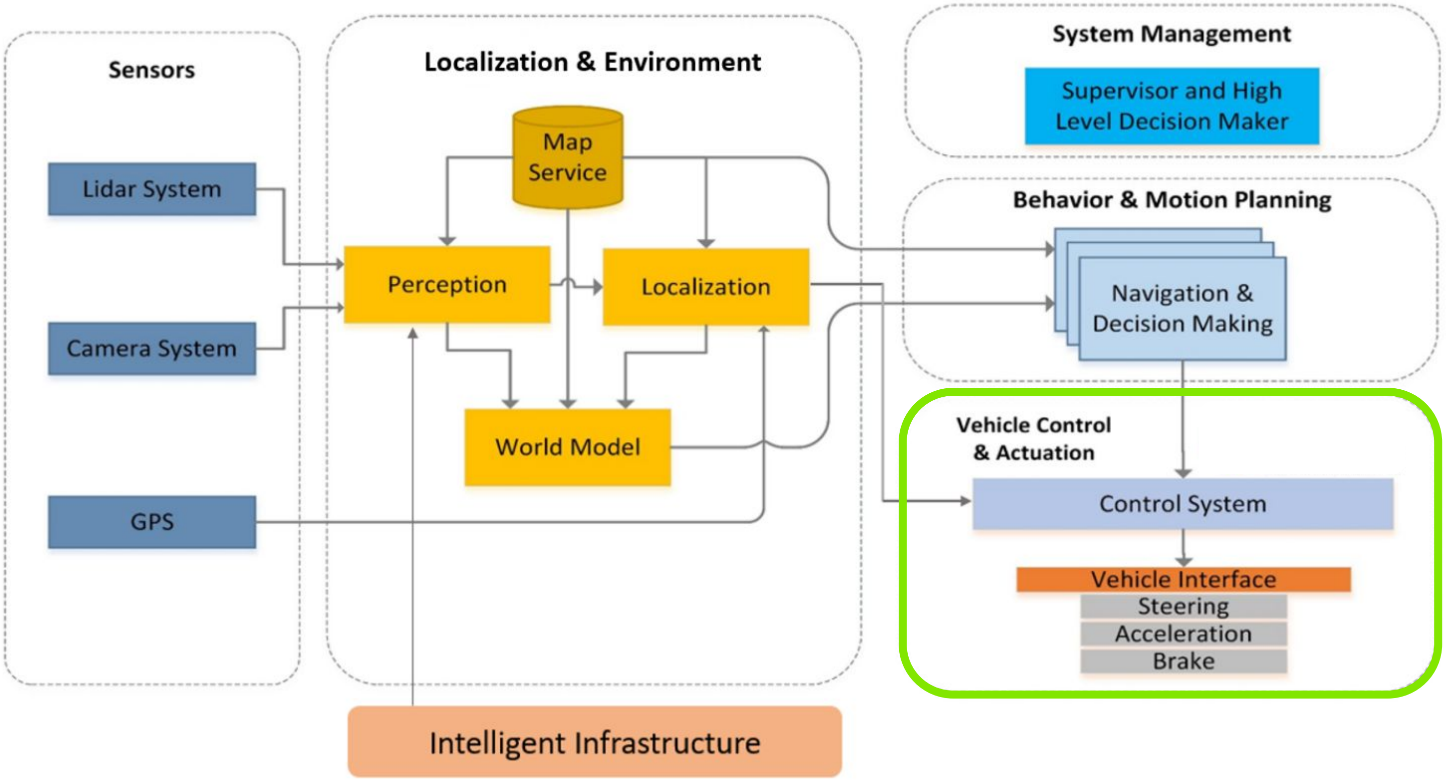
- **Automated Driving System (ADS)** perform the entire Dynamic Driving Task: levels 1-5



[1] SAE International J3016_201806 - Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles, 2018

Introduction

Functional components of an automated vehicle

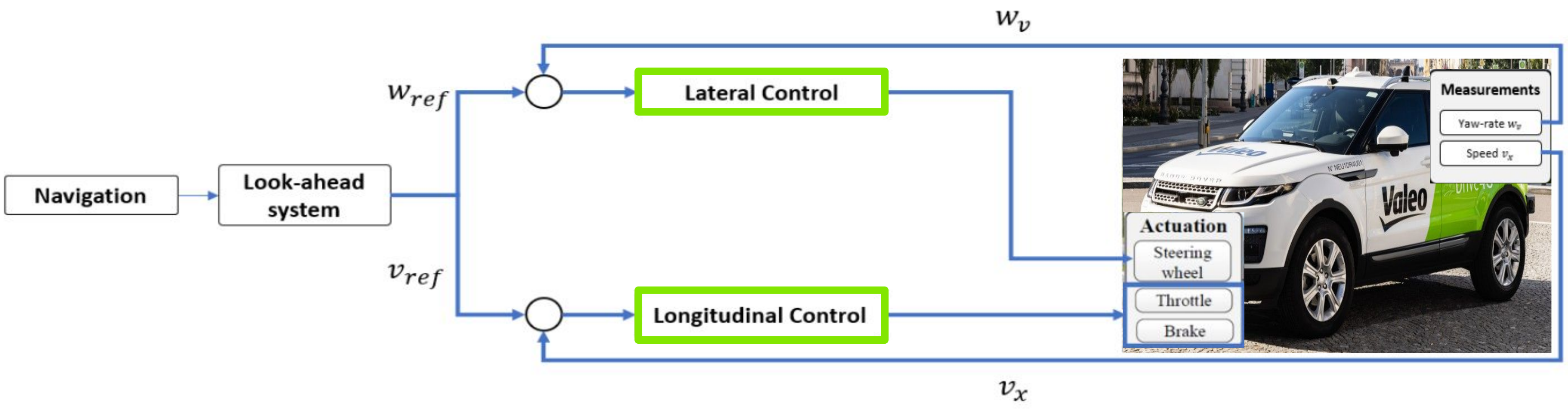


Introduction

Vehicle control & actuation

- **Longitudinal Control:** it is responsible to regulate the vehicle speed such as Adaptive Cruise Control (ACC) or vehicle following. It controls the throttle and brake actuators.

- **Lateral Control:** it is responsible for vehicle manoeuvring such as lane-keeping, lane-changing, collision avoidance, parking, etc. It controls the steering actuator.



Questions?

Outline

1 Introduction

2 About LPV

3 About LPV-YK

4 LPV-YK Control Structures

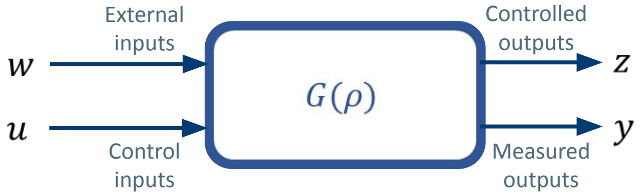
5 Application to Autonomous Vehicles

6 Conclusions

About LPV

LPV System

$$G(\rho): \begin{cases} \dot{x}(t) = A(\rho(t))\,x(t) + B_1(\rho(t))\,w(t) + B_2(\rho(t))\,u(t) \\ z(t) = C_1(\rho(t))\,x(t) + D_{11}(\rho(t))\,w(t) + D_{12}(\rho(t))\,u(t) \\ y(t) = C_2(\rho(t))\,x(t) + D_{21}(\rho(t))\,w(t) + D_{22}(\rho(t))\,u(t) \end{cases}$$



- $\rho(.)$ is assumed to be known or measurable
- The parameters ρ are always assumed to be bounded in a compact set $\mathcal{P}$ defined by their extremums

$$\rho_i(t) \in \left[\underline{\rho_i}\,, \overline{\rho_i}\right], \qquad \forall i$$

- The system matrices are continuous on $\mathcal{P}$.
- It is required sometimes that

$$\dot{\rho}_i(t) \in \left[\underline{\nu_i}\,, \overline{\nu_i}\right], \qquad \forall i$$

- The parameters can be endogenous if they are state-dependent $\rho = \rho(x(t), t)$, this leads to a quasi-LPV system

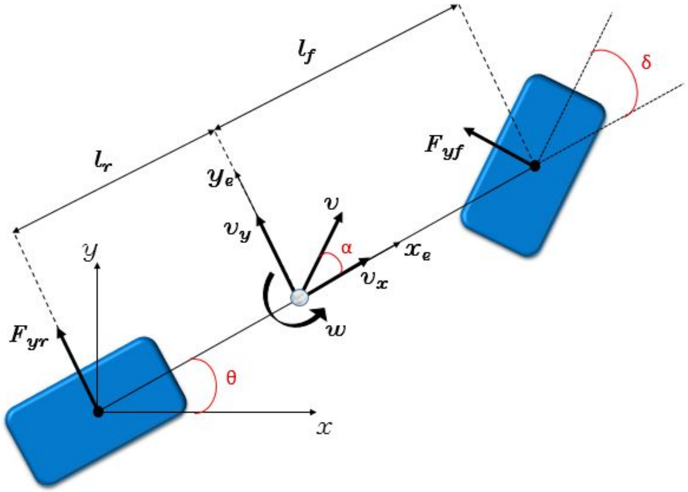
About LPV

LPV lateral bicycle model (Steering Control)

$$\Sigma(\rho): \begin{cases} \dot{x}(t) = A_\Sigma(\rho)\, x(t) + B_\Sigma\, u(t) \\ y(t) = [0 \;\; 1]\, x(t) \end{cases}$$

$$\begin{bmatrix} \dot{v}_y \\ \dot{w} \end{bmatrix} = \underbrace{\begin{bmatrix} -\frac{C_r + C_f}{m v_x} & -\frac{C_f l_f - C_r l_r}{m v_x} - v_x \\ -\frac{C_f l_f - l_r C_r}{I v_x} & -\frac{C_f l_f^2 + l_r^2 C_r}{I v_x} \end{bmatrix}}_{A_\Sigma(\rho)} \begin{bmatrix} v_y \\ w \end{bmatrix} + \underbrace{\begin{bmatrix} \frac{C_f}{m} \\ \frac{C_f l_f}{m} \end{bmatrix}}_{B_\Sigma} \delta$$

Not affine w.r.t. ρ



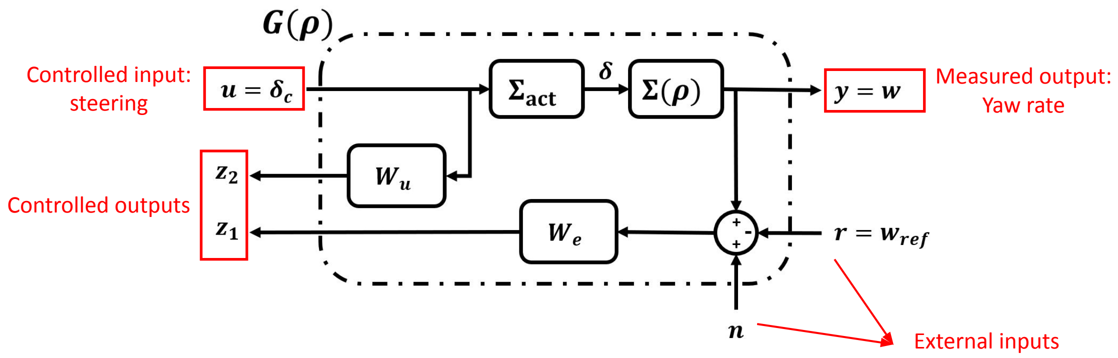
- C_r, C_f, l_r, l_f, m, I are known constants

About LPV

Generalized LPV lateral model for $\mathcal{H}\infty$ control

Steering actuator model Σ_{act}

- $\Sigma_{act} = \frac{k}{s^2+2\zeta w_n\, s+w_n^2} e^{-T_d s}$
- $e^{-T_d s} = \frac{1-\frac{T_d s}{2}+\frac{(T_d s)^2}{12}}{1+\frac{T_d s}{2}+\frac{(T_d s)^2}{12}}$



$$W_e(s) = \frac{\frac{s}{M_s} + w_b}{s + w_b \epsilon}$$

robustness (M_s)

rising time-response (w_b)

steady-state tracking error (ϵ)

$$W_u(s) = \frac{s + \frac{w_{b_u}}{M_u}}{\epsilon_u s + w_{b_u}}$$

actuator bandwidth

maximum allowed effort of the actuators

noise rejection at high frequencies

About LPV

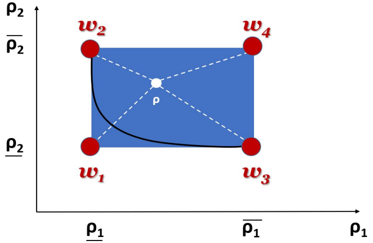
LPV system representations

LPV Control	Conditions
Polytopic	• Affine parameter-dependency • Convex parameter region
Grid-based	• General parameter-dependency • Bounded parameter variations
Linear Fractional Transformation (LFT)	• Fractional parameter-dependency

Polytopic: $A(\rho) = A_0 + \sum_{i=1}^{n_p} \rho_i A_i$

Grid-based: $A(\rho) = A_0 + \sum_{k=1}^{S} \rho^k A_k$

Polytopic

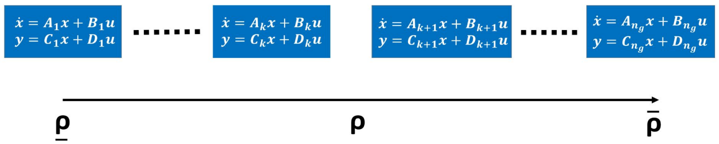


$$\left[\begin{array}{c|c} A(\rho) & B(\rho) \\ \hline C(\rho) & D(\rho) \end{array}\right] = \sum_{i=1}^{2^{n_p}} \mu_i(\rho) \left[\begin{array}{c|c} A(w_i) & B(w_i) \\ \hline C(w_i) & D(w_i) \end{array}\right]$$

$\mu_i(\rho)$ are the scheduling coefficients satisfying:

$$\sum_{i=1}^{2^{n_p}} \mu_i(\rho) = 1, \qquad \mu_i \geq 0 \; \forall i$$

Grid-based



For $\rho \in [\rho_k, \rho_{k+1}]$:

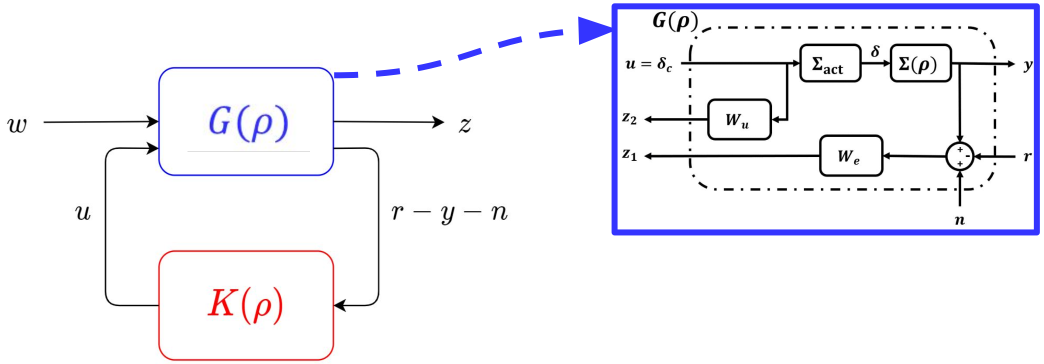
$$\left[\begin{array}{c|c} A(\rho) & B(\rho) \\ \hline C(\rho) & D(\rho) \end{array}\right] = \sum_{i=k}^{k+1} \alpha_i(\rho) \left[\begin{array}{c|c} A_i & B_i \\ \hline C_i & D_i \end{array}\right]$$

where:

$$\alpha_k = \frac{\rho_{k+1} - \rho}{\rho_{k+1} - \rho_k} \text{ and } \alpha_{k+1} = \frac{\rho - \rho_k}{\rho_{k+1} - \rho_k}$$

About LPV

LPV/$\mathcal{H}\infty$ control design



Polytopic and grid-based control design

The objective is to minimize the $\mathcal{L}_2$ induced gain from the external input w to the controlled output z. This is achieved by solving the following $\mathcal{L}_2$ induced minimization problem:

$$\|z\|_2 \leq \gamma_\infty \|w\|_2$$

and $\gamma_\infty > 0$ to be minimized, represents how much the demanded performance is achieved. If $\gamma_\infty < 1$, the demanded performance is totally achieved by the controller.

❖ **Note:**

Polytopic control design → **Constant Lyapunov function P**

Grid-based control design → **Parameter-dependent Lyapunov function $P(\rho)$**

Questions?

Outline

1 Introduction

2 About LPV

3 About LPV-YK

4 LPV-YK Control Structures

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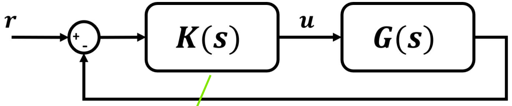
6 Conclusions

About LPV-YK

LTI-YK case

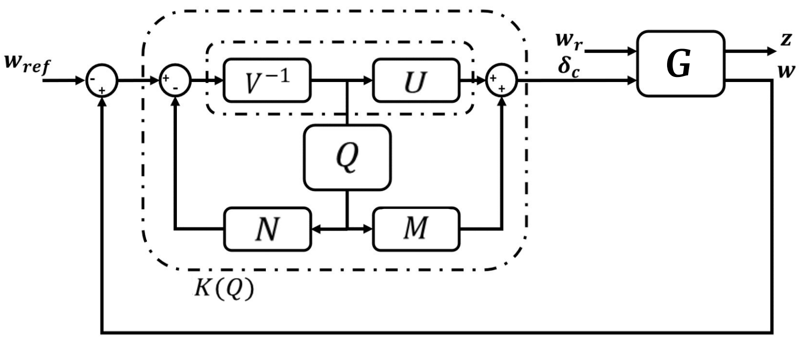
- **SISO LTI-YK definition**



$$CL(s) = \frac{G(s)K(s)}{1 + G(s)K(s)}, \qquad Q(s) = \frac{K(s)}{1 + G(s)K(s)}, \qquad then, CL(s) = G(s)Q(s)$$

- **Coprime factorization**

$G = NM^{-1}$, $K = UV^{-1}$ satisfying the Bezout Identity



- **Parameterized controller**

$K(Q) = (U + MQ)(V + NQ)^{-1}$

- **Proved theorem in the literature**

If K(s) stabilizes G(s), then Q(s) is stable and K(Q) stabilizes G(s) where M, N and U, $V \in RH_\infty$ are the coprime factorizations of G and K respectively.

About LPV-YK

LPV-YK parameterization

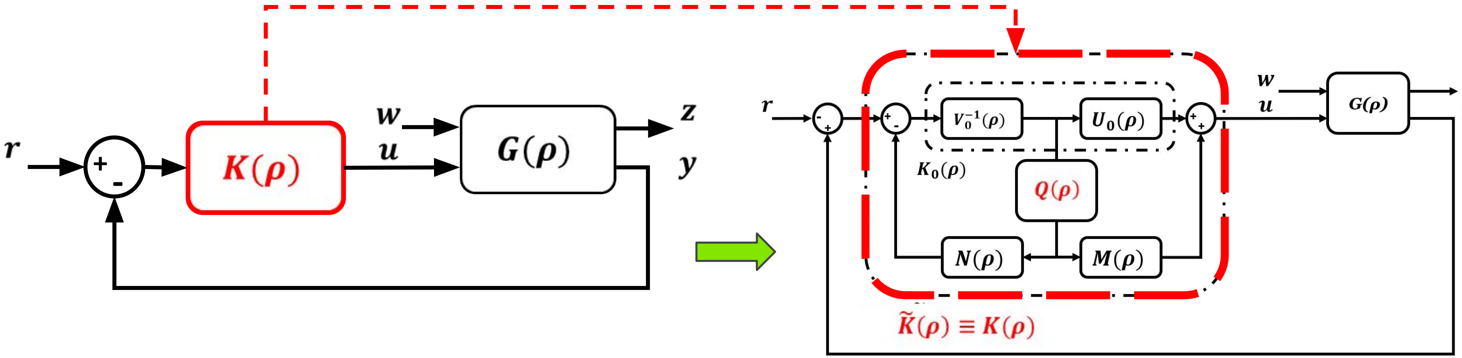
- The plant and the controllers can be factorized (from left and right) as a product of stable transfer function matrices with stable inverse, as follows:

$$G(\rho) = N(\rho)M^{-1}(\rho) = \tilde{M}^{-1}(\rho)\,\tilde{N}(\rho)$$
$$K(\rho) = U(\rho)V^{-1}(\rho) = \tilde{V}^{-1}(\rho)\tilde{U}(\rho)$$

- Satisfying the following *Bezout Identity*:

$$\begin{bmatrix} \tilde{V}(\rho) & -\tilde{U}(\rho) \\ -\tilde{N}(\rho) & \tilde{M}(\rho) \end{bmatrix} \begin{bmatrix} M(\rho) & U(\rho) \\ N(\rho) & V(\rho) \end{bmatrix} = \begin{bmatrix} M(\rho) & U(\rho) \\ N(\rho) & V(\rho) \end{bmatrix} \begin{bmatrix} \tilde{V}(\rho) & -\tilde{U}(\rho) \\ -\tilde{N}(\rho) & \tilde{M}(\rho) \end{bmatrix} = \begin{bmatrix} I & 0 \\ 0 & I \end{bmatrix}$$

- **LPV-YK Parameterization**



About LPV-YK

LPV-YK parameterization

Multiple LPV-YK Parameterizations

Assume multiple LPV controllers $K_i(\rho) = U_i(\rho)V_i^{-1}(\rho) = \tilde{V}_i^{-1}(\rho)\tilde{U}_i(\rho)$ that can be parameterized with respect to a chosen nominal LPV controller $K_0(\rho) = U_0(\rho)V_0^{-1}(\rho) = \tilde{V}_0^{-1}(\rho)\tilde{U}_0(\rho)$ as:

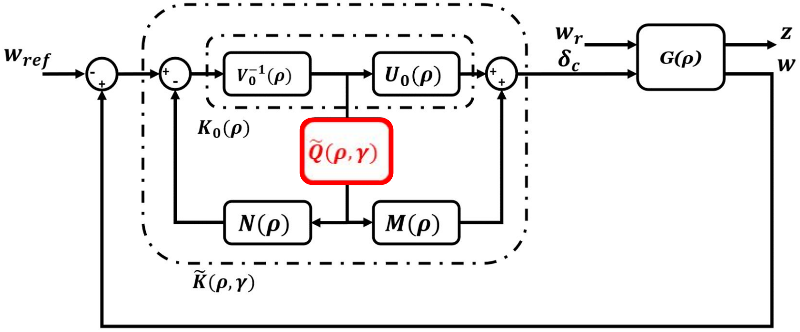
$$\begin{aligned}\tilde{K}_i(\rho) = K(Q_i) &= \big(U_0(\rho) + M(\rho)Q_i(\rho)\big)\big(V_0(\rho) + N(\rho)Q_i(\rho)\big)^{-1} \\ &= \big(\tilde{V}_0(\rho) + Q_i(\rho)\tilde{N}(\rho)\big)^{-1}\big(\tilde{U}_0(\rho) + Q_i(\rho)\tilde{M}(\rho)\big) \\ &\equiv U_i(\rho)V_i^{-1}(\rho) = K_i(\rho)\end{aligned}$$

Interpolation of multiple LPV-YK Controllers

$$\begin{aligned}\tilde{K}(\rho,\gamma) = K(\tilde{Q}) &= \big(U_0(\rho) + M(\rho)\tilde{Q}(\rho,\gamma)\big)\big(V_0(\rho) + N(\rho)\tilde{Q}(\rho,\gamma)\big)^{-1} \\ = K(\tilde{Q}) &= \big(\tilde{V}_0(\rho) + \tilde{Q}(\rho,\gamma)\tilde{N}(\rho)\big)^{-1}\big(\tilde{U}_0(\rho) + \tilde{Q}(\rho,\gamma)\tilde{M}(\rho)\big)\end{aligned}$$

Where $\tilde{Q}(\rho,\gamma) = \sum_{i=1}^{\zeta} \gamma_i Q_i(\rho)$

- if $\gamma_i = 0\ \forall i$, $\tilde{K}(\rho,\gamma) \equiv K_0(\rho)$
- if $\gamma_i = 1$ for $i = c \in \mathbb{I}[1,\zeta]$ and $\gamma_i = 0\ \forall i \neq c$, $\tilde{K}(\rho,\gamma) \equiv K_c(\rho)$
- else, the performance of $\tilde{K}(\rho,\gamma)$ is interpolated among $K_i(\rho)$ according to the chosen γ_i's.



Questions?

Outline

1 Introduction

2 About LPV

3 About LPV-YK

4 **LPV-YK Control Structures**

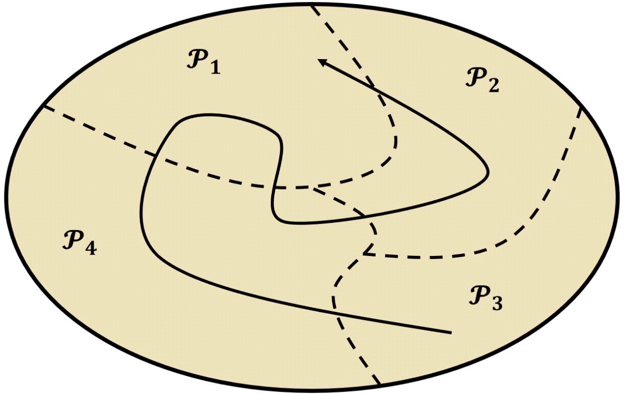
5 Application to Autonomous Vehicles

6 Conclusions

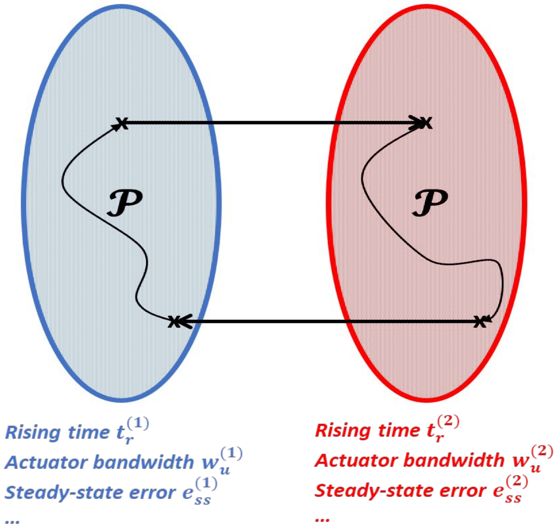
LPV-YK Control Structures

Objectives

1. Switching between partitioned parameter regions (e.g. partition vehicle speed region)



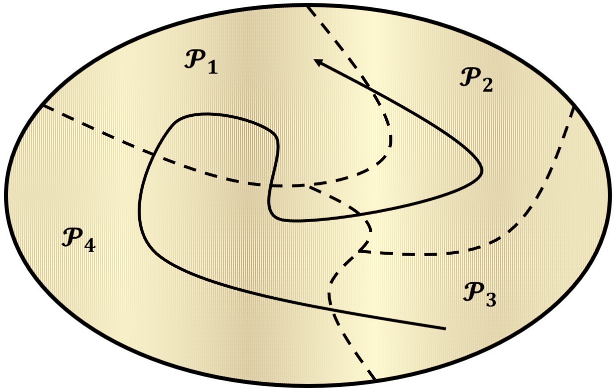
2. Interpolation of control performances (e.g. multiple lateral control tasks)



LPV-YK Control Structures

1. Partitioned parameter regions

- Design multiple LPV controllers, each one corresponds to a certain parameter region $\mathcal{P}_i$
- The aim is to maintain a closed-loop robust performance over a wide parameter variations
- Switch between the multiple LPV controllers with smooth transient response at the switching instants



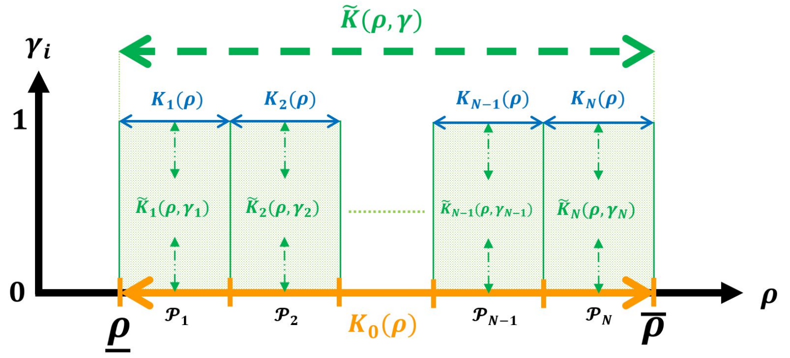
LPV-YK Control Structures

1.1 Grid-based LPV-YK control *

1. Design multiple LPV controllers $K_i(\rho), i \in \mathbb{I}[1, N]$

All $K_i(\rho)$ are designed based on the standard **grid-based** approach with similar performance.

2. An overall switching is obtained with switching signal vector $\gamma(\rho) = [\gamma_1(\rho), \ldots, \gamma_N(\rho)]$.



- **Stability Conditions**

  1. Each $K_i(\rho)$ must **exponentially** stabilize $G(\rho)$ over $\mathcal{P}_i$.
  2. The following LMIs are satisfied:

$$A(\rho)X_g(\rho) + X_g(\rho)A^T(\rho) + \sum_{j=1}^{s} \pm\left\{\underline{\nu_j}, \overline{\nu_j}\right\}\frac{\partial X_g}{\partial \rho_j} + B_2 W(\rho) + W^T(\rho)B_2^T < 0$$

$$A_{k,0}(\rho)X_{k,0}(\rho) + X_{k,0}(\rho)A_{k,0}^T(\rho) + \sum_{j=1}^{s} \pm\left\{\underline{\nu_j}, \overline{\nu_j}\right\}\frac{\partial X_{k,0}}{\partial \rho_j} + B_{k,0}(\rho)V(\rho) + V^T(\rho)B_{k,0}^T(\rho) < 0$$

** [Atoui et al, (2022)] Advanced LPV-YK Control Design with Experimental Validation on Autonomous Vehicles, under revision in Automatica*

LPV-YK Control Structures

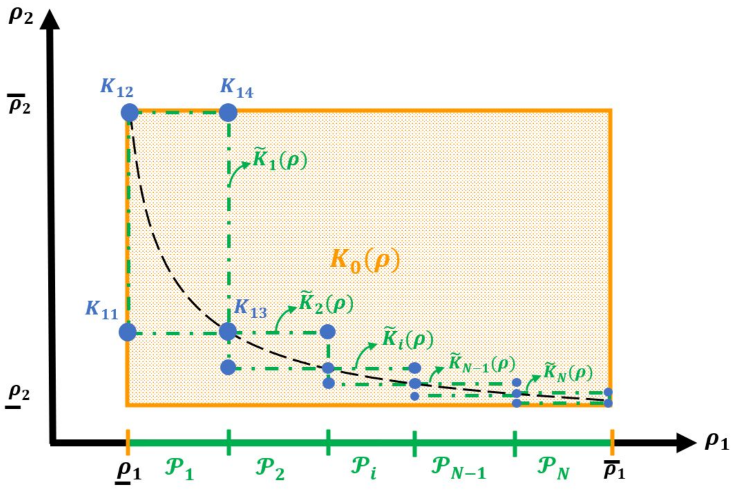
1.2 Partitioned gain-scheduled control *

1. Design multiple YK-based gain-scheduled controllers

   $\widetilde{K}_i(\rho),\ i \in \mathbb{I}[1, N]$.

Each $\widetilde{K}_i(\rho)$ is designed by interpolating its corresponding K_{ij} ($j \in \mathbb{I}[1,2^{n_p}]$) based on **LTI-YK** concept.

2. Create an overall switched LPV-YK controller $\widetilde{K}_\sigma(\rho)$.



- **Stability Conditions**
  1. $G(\rho)$ must have **affine** parameter-dependency.
  2. **Only** $K_0(\rho)$ must **quadratically** stabilize $G(\rho)$. The other K_{ij} must **stabilize** the local systems G_{ij}.
  3. The following LMIs are satisfied:

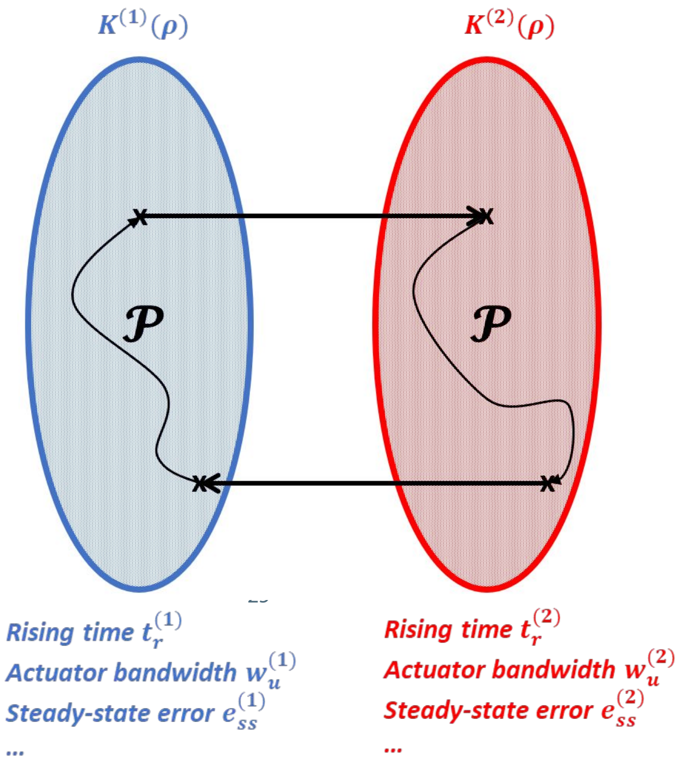
$$A(\rho)X_g + X_g A^T(\rho) + B_2 W(\rho) + W^T(\rho) B_2^T < 0$$
$$A_{k,0}(w_{ij}) X_{k,ij} + X_{k,ij} A_{k,0}^T(w_{ij}) + B_{k,0}(w_{ij}) V_{ij} + V_{ij}^T B_{k,0}^T(w_{ij}) < 0, \qquad \forall w_{ij}$$

* *[Atoui et al, (2022)] Advanced LPV-YK Control Design with Experimental Validation on Autonomous Vehicles, under revision in Automatica*

LPV-YK Control Structures

2. Multiple closed-loop performances

- Design multiple LPV controllers over the same parameter convex region
- Each LPV controller achieves a specific required closed-loop performance, i.e. rising time, steady-state error, etc.
- Interpolate between the multiple LPV controllers to adapt the system performance according to the situation



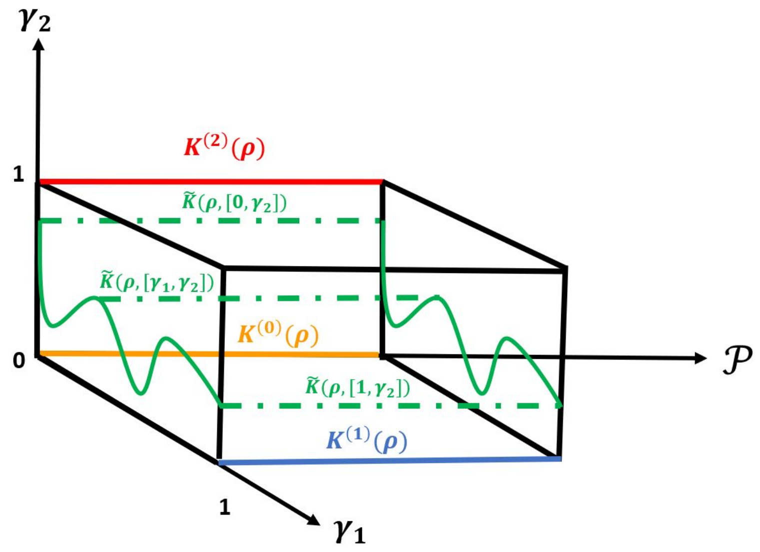
LPV-YK Control Structures

2.1 Polytopic-based LPV control interpolation *

1. Design multiple LPV controllers $K^{(j)}(\rho), j \in \mathbb{I}[0, \zeta]$.

All $K^{(j)}(\rho)$ are designed based on the standard **polytopic** approach.

2. An overall interpolation scheme is obtained with $\gamma = [\gamma_1, \dots, \gamma_\zeta]$.



- **Stability Conditions**
  1. $G(\rho)$ must have **affine** parameter-dependency.
  2. **All** $K^{(j)}(\rho)$ must **quadratically** stabilize $G(\rho)$.
  3. The following LMIs are satisfied:

$$A(\rho)X_g + X_g A^T(\rho) + B_2 W(\rho) + W^T(\rho) B_2^T < 0$$

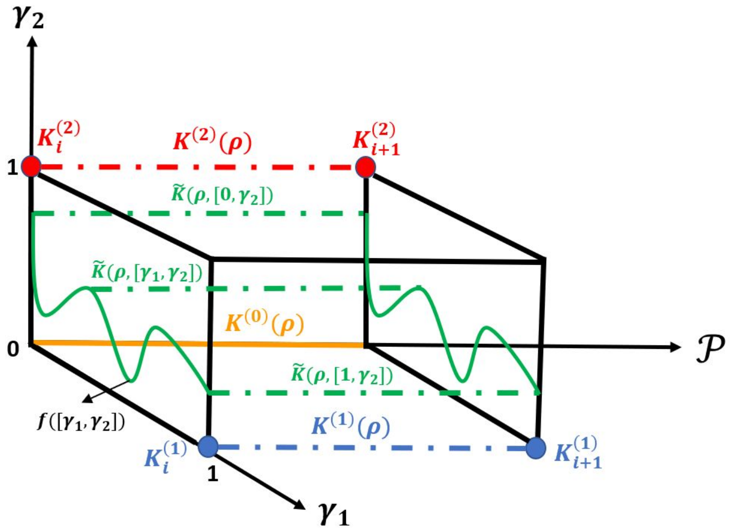
$$A_k^{(0)}(\rho)X_k + X_k A_k^{(0)T}(\rho) + B_k^{(0)}(\rho)V(\rho) + V^T(\rho)B_k^{(0)T}(\rho) < 0$$

** [Atoui et al, (2021)] Interpolation of Multi-LPV Control Systems Based on Youla–Kucera Parameterization, **published** in Automatica*

LPV-YK Control Structures

2.2 YK-based LPV control interpolation *

1. The LPV controllers $K^{(j)}(\rho), j \in \mathbb{I}[1,\zeta]$ are designed based on YK parameterization.
2. Only $K^{(0)}(\rho)$ is designed based on polytopic approach
3. An overall interpolation scheme is obtained with $\gamma = [\gamma_1, \dots, \gamma_\zeta]$.



- **Stability Conditions**
  1. $G(\rho)$ must have affine parameter-dependency.
  2. Only $K^{(0)}(\rho)$ must **quadratically** stabilize $G(\rho)$.
  3. $K_i^{(j)}$ must stabilize the local LTI systems G_i.
  4. The following LMIs are satisfied:

$$A(\rho)X_q + X_q A^T(\rho) + B_2 W(\rho) + W^T(\rho) B_2^T < 0$$

$$A_{k,i}^{(0)} X_{k,i} + X_{k,i} A_{k,i}^{(0)T} + B_{k,i}^{(0)} V_i + V_i^T B_{k,i}^{(0)T} < 0, \qquad \forall i$$

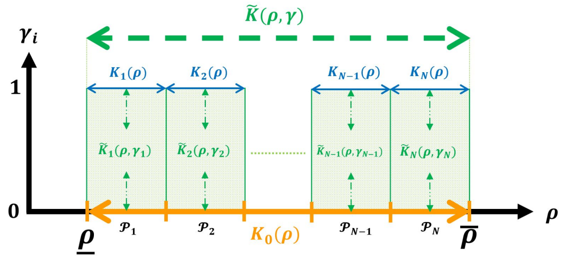
** [Atoui et al, (2022)] Multi-Variable and Multi-Objective Gain Scheduled Control Based on Youla-Kucera Parameterization: Application to Autonomous Vehicles, **under review** in International Journal on Robust and Nonlinear Control (IJRNC)*

Summary

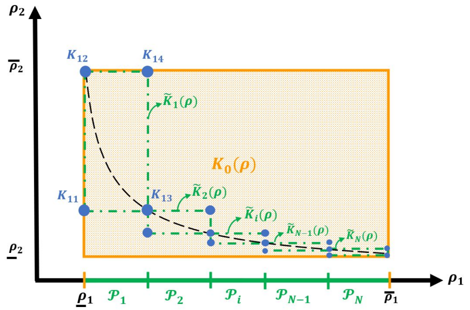
1. Parameter region partitioning

e.g. longitudinal speed range partitioning

Grid-based LPV-YK

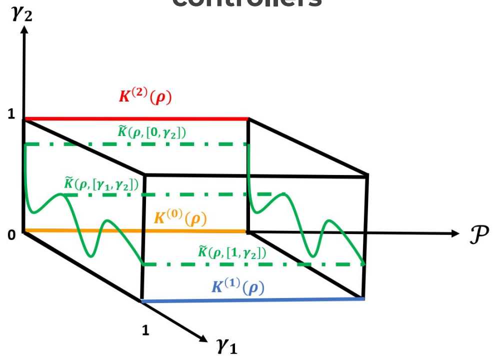


Polytopic-based LPV-YK

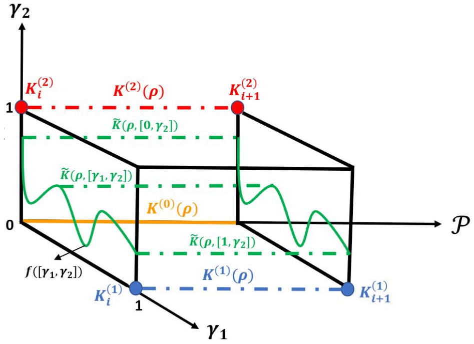


2. Interpolation of control performances for different lateral control tasks

Interpolation of polytopic LPV controllers



Interpolation of YK-based LPV controllers



Questions?

Outline

1 Introduction

2 About LPV

3 About LPV-YK

4 LPV-YK Control Structures

5 Application to Autonomous Vehicles

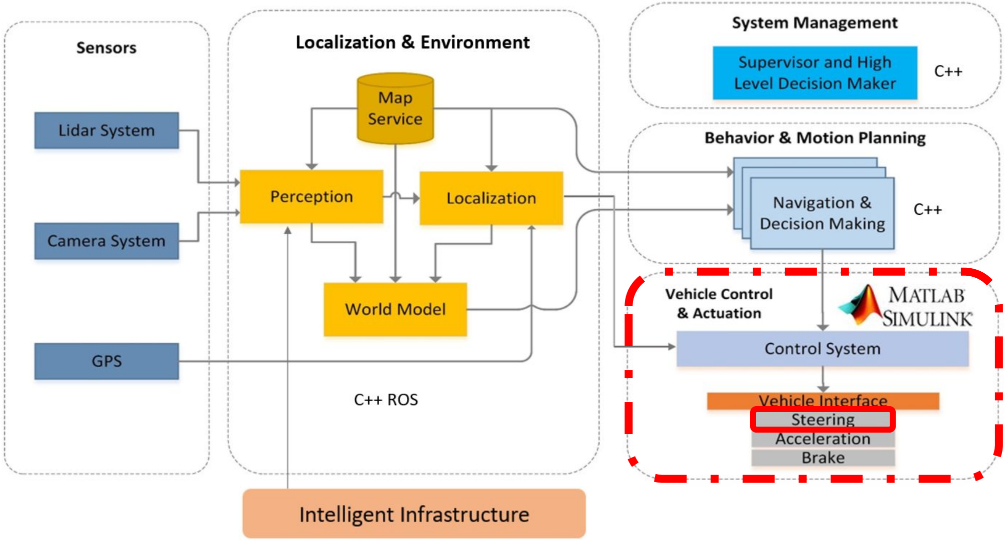
6 Conclusions

Application to Autonomous Vehicles

Experimental Architecture

Robotized Renault ZOE

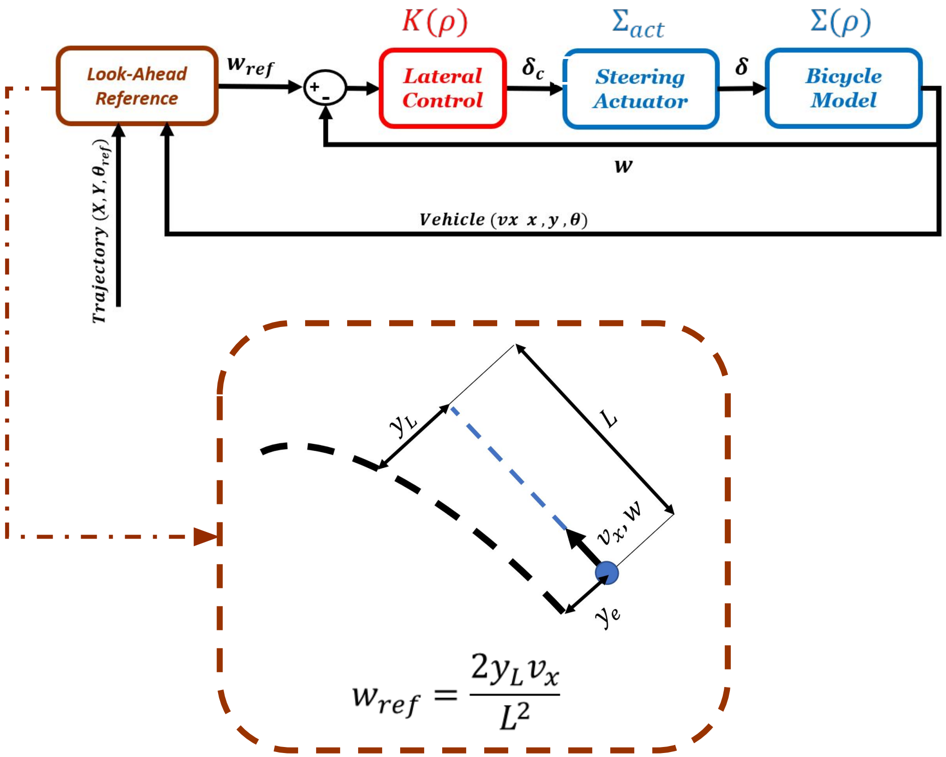
Platform architecture



Valeo

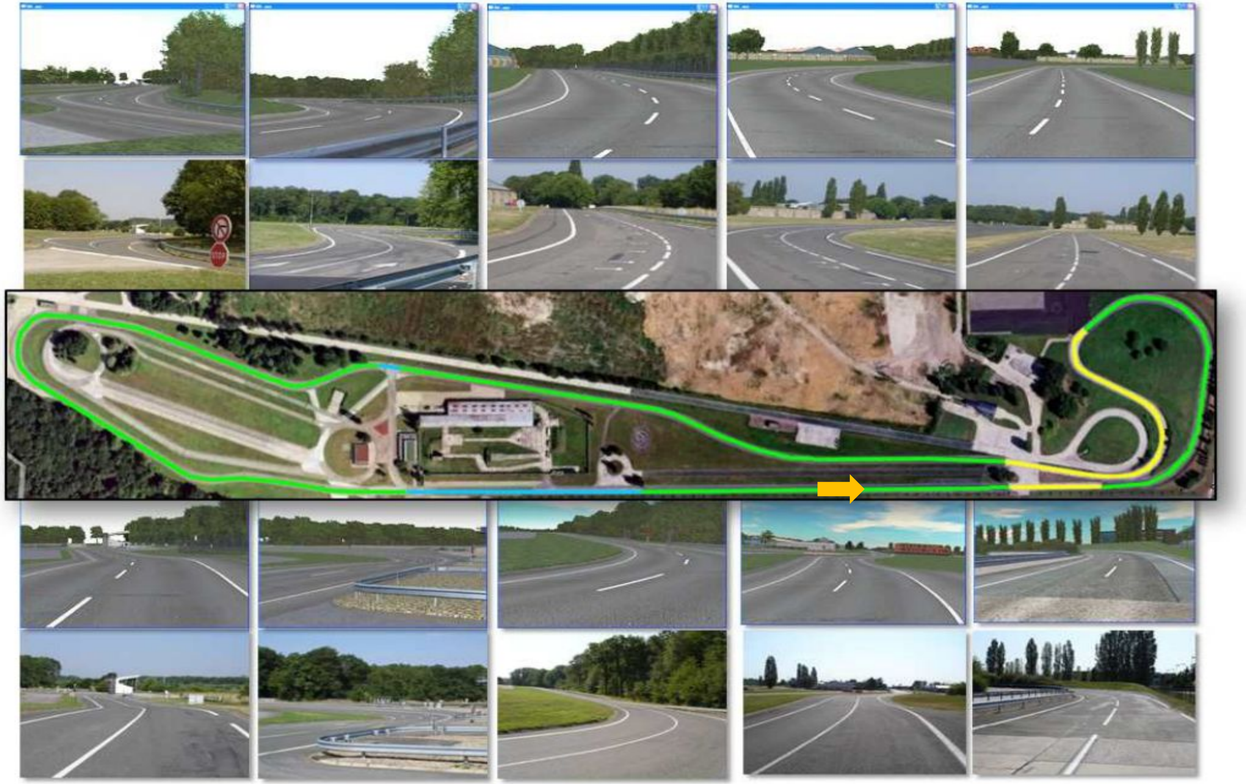
Application to Autonomous Vehicles

Lateral control: closed-loop scheme



Application to Autonomous Vehicles

Satory private test-track



Autonomous Vehicles Lateral Control

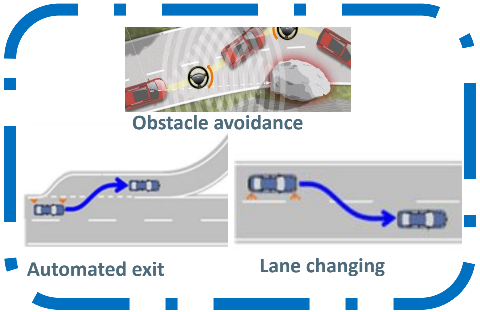
Challenges and Motivation

1. Design a controller for vehicle lateral motion achieving comfort at low and high-speed ranges.
    - LPV-YK parameterization facilitates parameter region partitioning and attain robust performance over the whole parameter region.

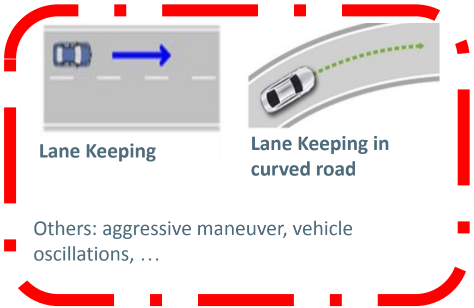
< 50 km/h

> 50 km/h

2. Design a multi-objective switching controller that can handle various lateral motion tasks.
    - LPV-YK switching control can handle multiple control objectives under any arbitrary switching signal.



Use controller $\boldsymbol{K_1}$

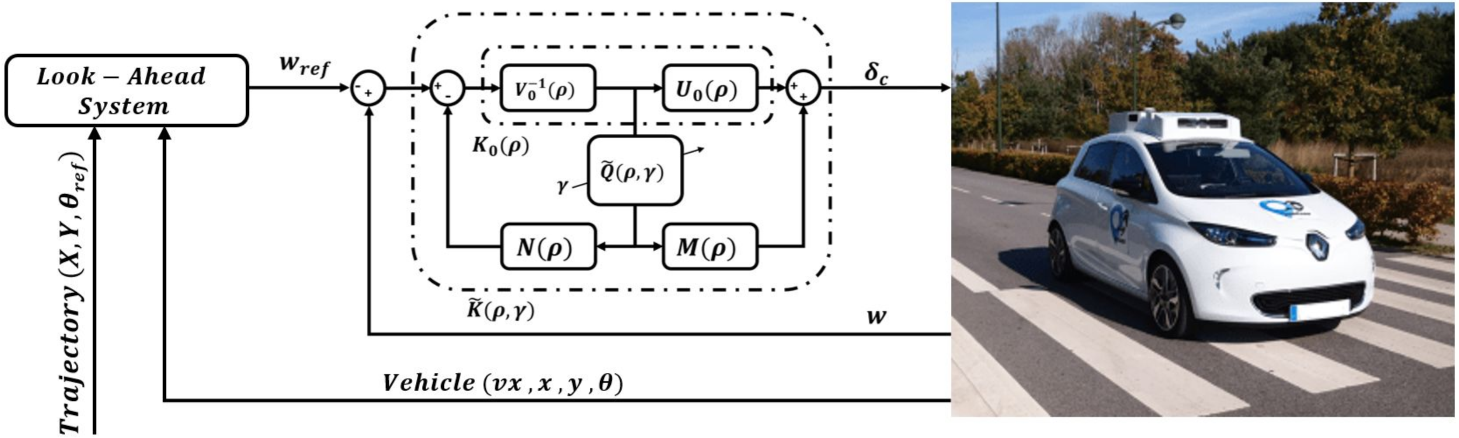


Use controller $\boldsymbol{K_2}$

Autonomous Vehicles Lateral Control

Global Objectives

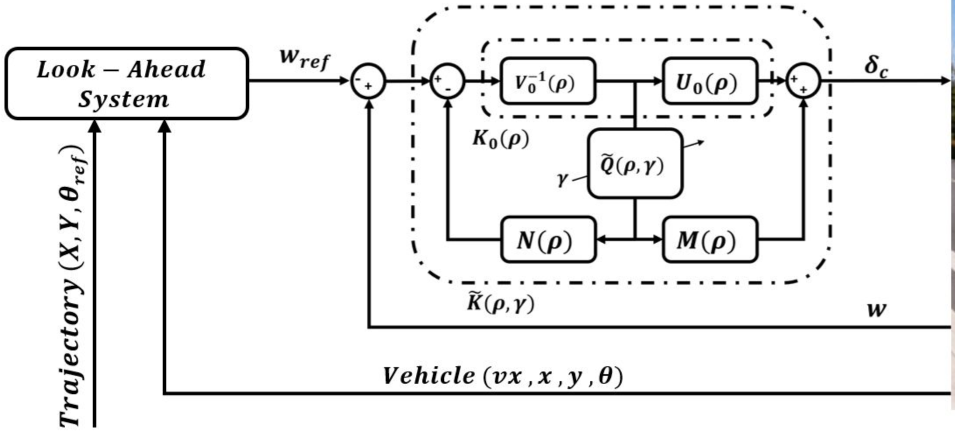
- **Reject noises on steering wheel at high vehicle speed**
- **Perform control switching with smooth transient response at the switching instants.**
- **Achieve different lateral control tasks; e.g. lane change, obstacle avoidance, etc.**



Autonomous Vehicles Lateral Control

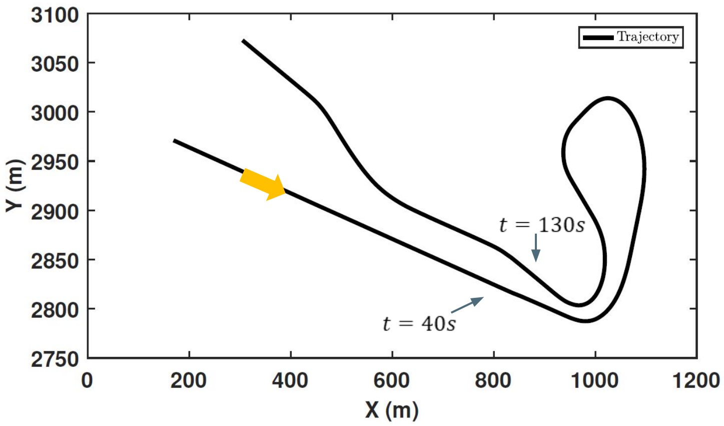
Challenge 1

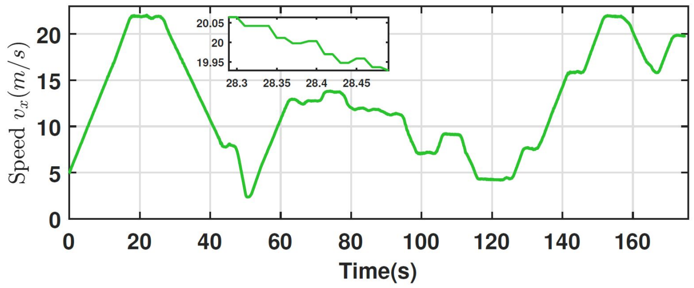
- **Reject noises on steering wheel at high vehicle speed**
- **Perform control switching with smooth transient response at the switching instants.**
- Achieve different lateral control tasks; e.g. lane change, obstacle avoidance, etc.

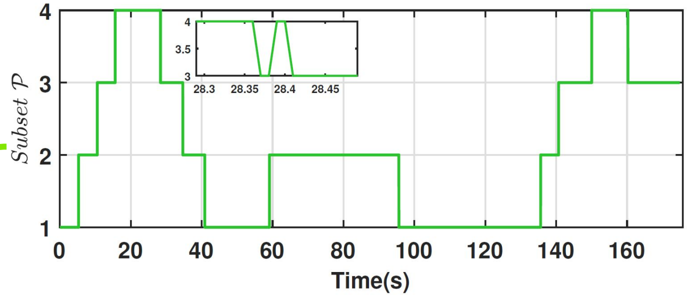


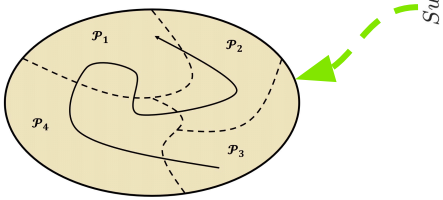
Autonomous Vehicles Lateral Control

Challenge 1



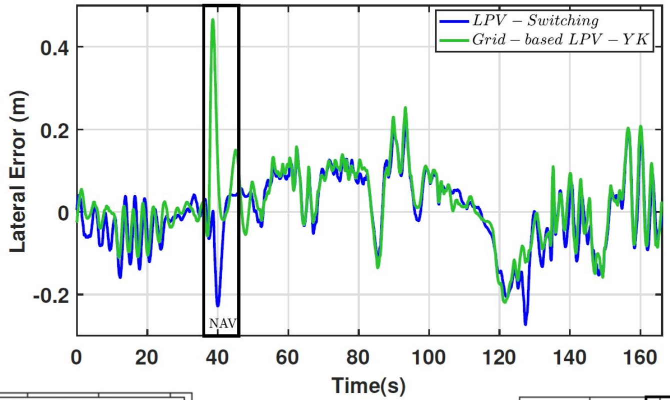




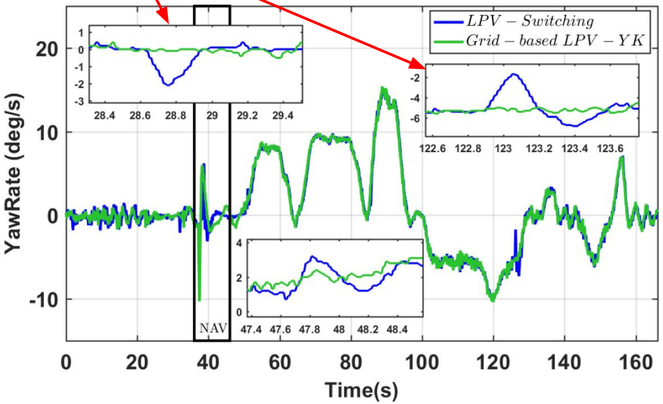


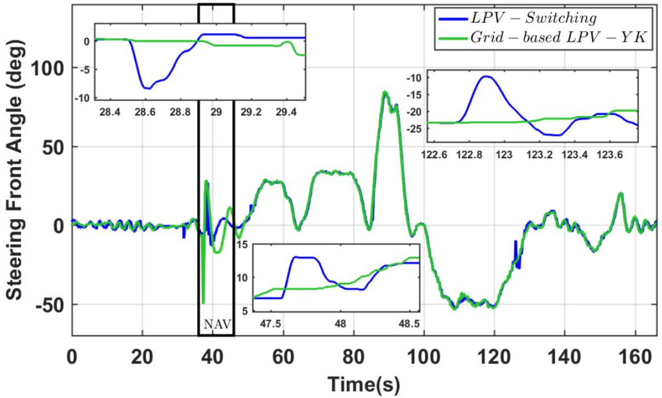
Autonomous Vehicles Lateral Control

Challenge 1: Grid-based LPV-YK



Switching Transitions

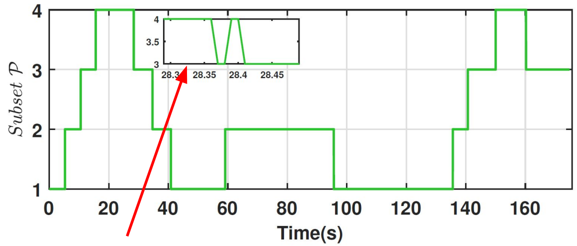


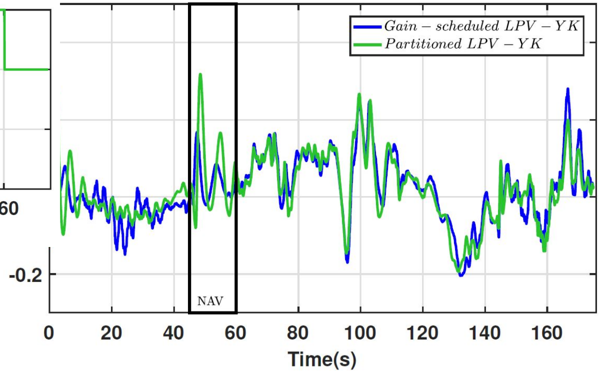


LPV-Switching: [Bei Lu and Fen Wu, (2004)] Switching LPV control designs using multiple parameter-dependent Lyapunov functions, Automatica 2004

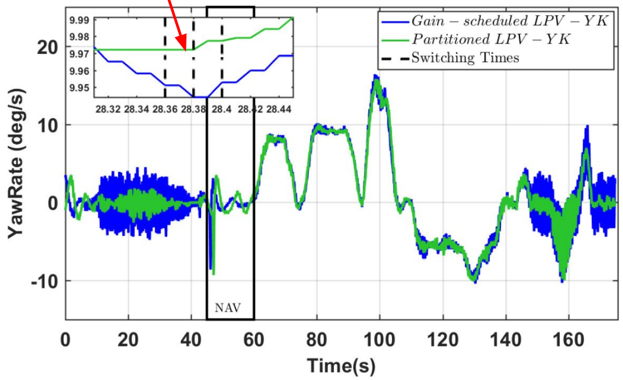
Autonomous Vehicles Lateral Control

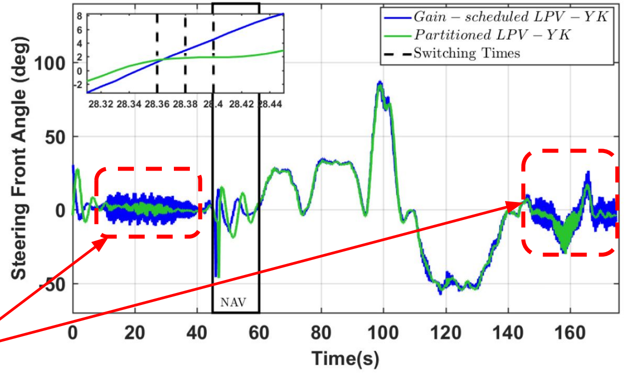
Challenge 1: Polytopic-based LPV-YK





Switching back-and-forth





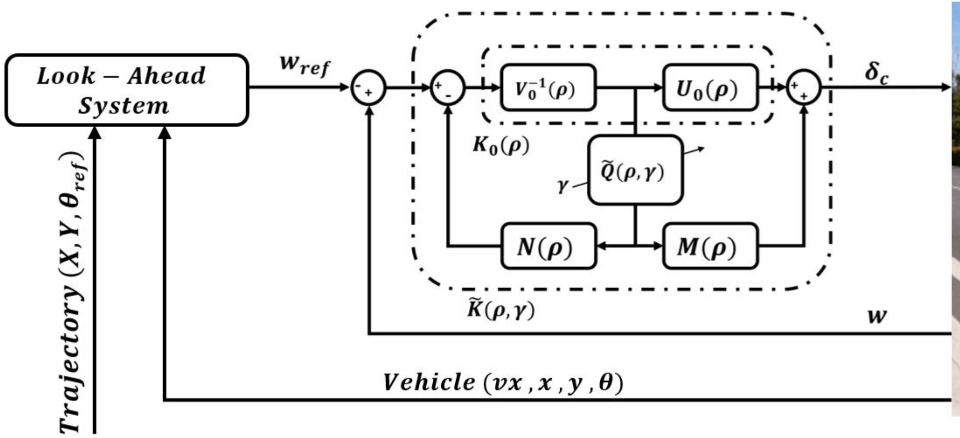
Steering noises

Gain-scheduled LPV-YK: [F. Bianchi and R. Pena, (2010)] Interpolation for gain-scheduled control with guarantees, Automatica 2010

Autonomous Vehicles Lateral Control

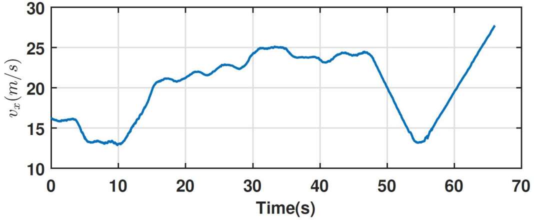
Challenge 2

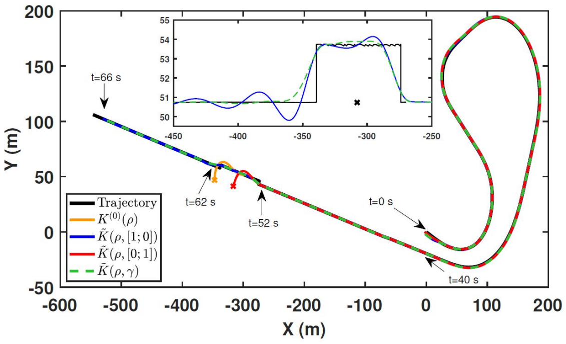
- Reject noises on steering wheel at high vehicle speed
- Perform control switching with smooth transient response at the switching instants.
- **Achieve different lateral control tasks; e.g. lane change, obstacle avoidance, etc.**

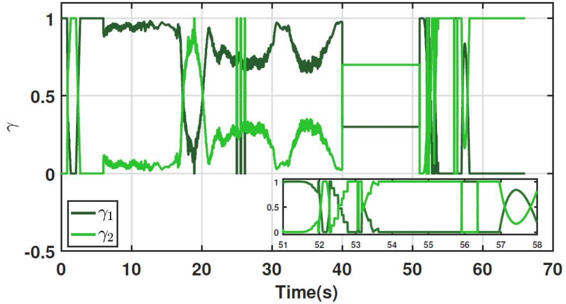


Autonomous Vehicles Lateral Control

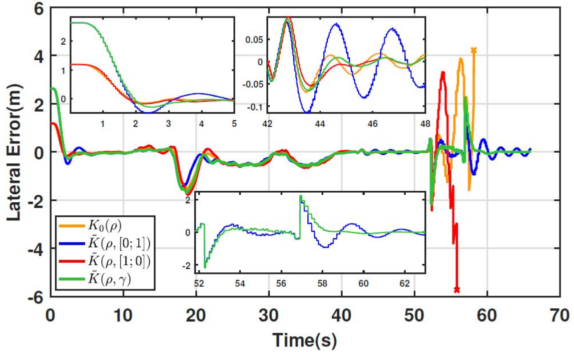
Challenge 2: Interpolation of YK-based LPV controllers (Simulation)

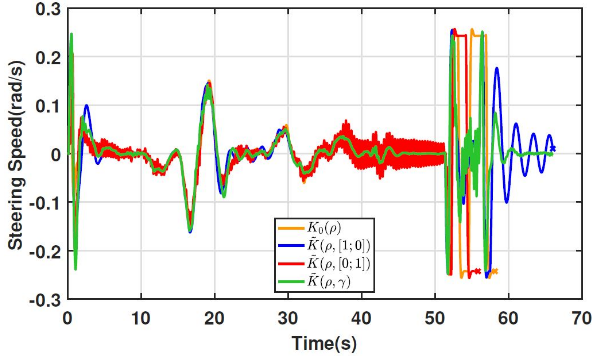






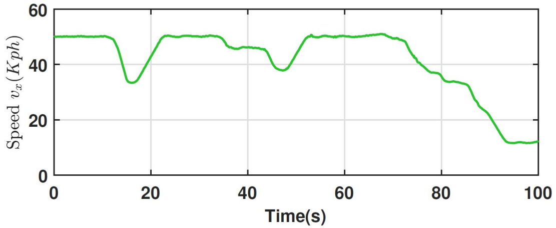
- If $\theta_e \leq 0.1, \gamma_2(t) = sat\left(-y_L + 1.4 + 0.1\dot{\delta}, [0,1]\right)$
- If $\theta_e > 1, \gamma_2(t) = sat(-0.7y_e + 1.4, [0,1])$
- $\gamma_1(t) = 1 - \gamma_2(t)$

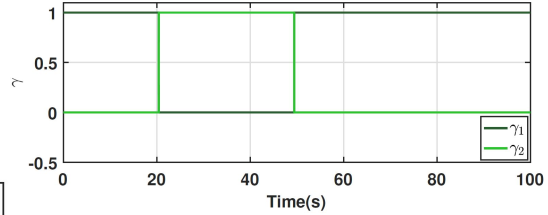


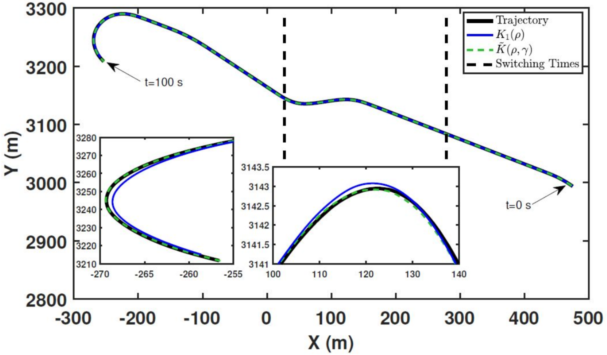


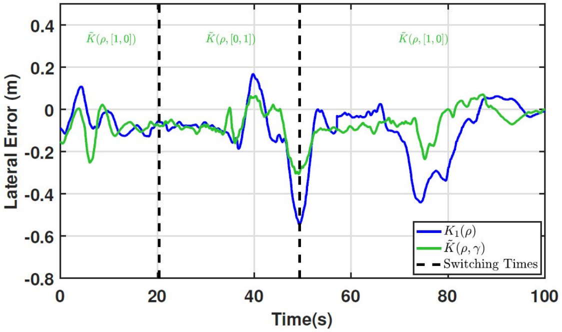
Autonomous Vehicles Lateral Control

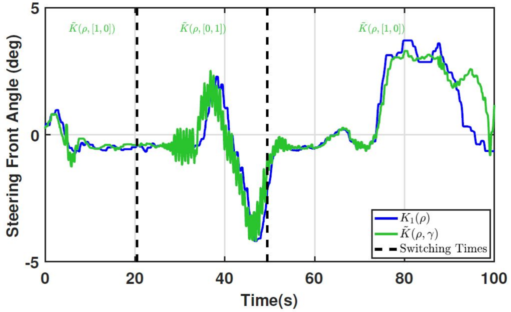
Challenge 2: Interpolation of YK-based LPV controllers (Experiment)





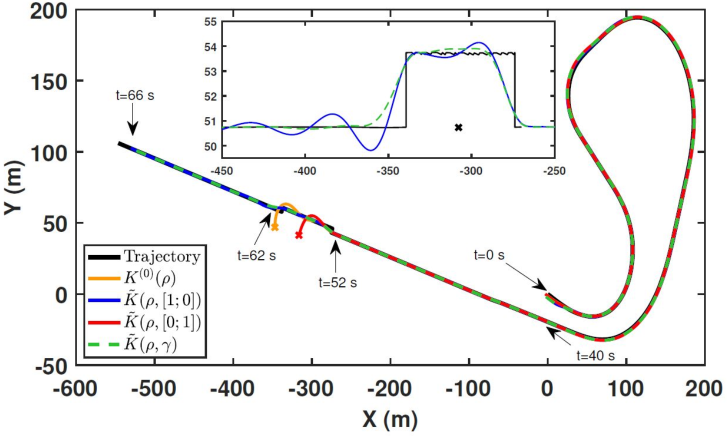






Autonomous Vehicles Lateral Control

Challenge 2: Interpolation of YK-based LPV controllers (Summary)



Controller	Value of interpolating vector γ	Control objective	Advantages	Disadvantages
$\tilde{K}(\rho,[0,0]) \equiv K^{(0)}(\rho)$	[0,0]	Highly robust	High noise rejection due to bad environment conditions, sensor faults, etc.	Inaccurate tracking performance and conservative
$\tilde{K}(\rho,[1,0]) \equiv K^{(1)}(\rho)$	[1,0]	Smooth tracker	Good tracking performance with smooth steering	Oscillatory and cannot perform well at high lateral accelerations
$\tilde{K}(\rho,[0,1]) \equiv K^{(2)}(\rho)$	[0,1]	Aggressive tracker	Fast tracking performance and could achieve high lateral accelerations	Too sensitive to noises
$\tilde{K}(\rho,\gamma)$	variant as in Fig. 7d	Multiple objectives by varying the interpolating vector γ.	All the mentioned advantages and even more by choosing the optimal combination of controllers by γ	No bad performance is observed

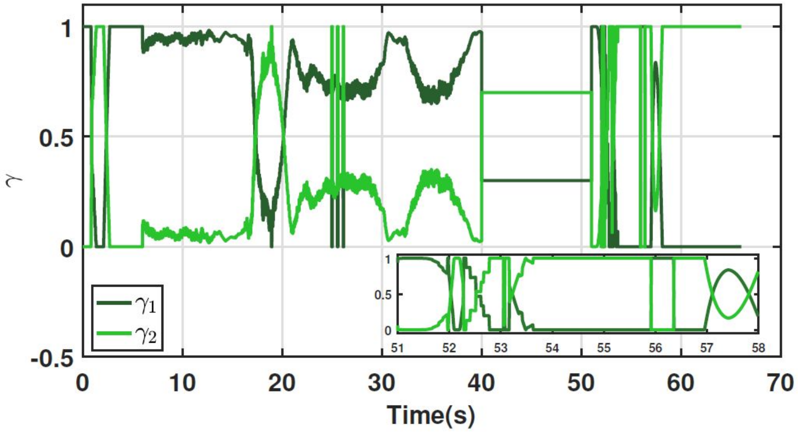
Questions?

Autonomous Vehicles Lateral Control

How to choose an optimal interpolation logic?

Heuristic Rule

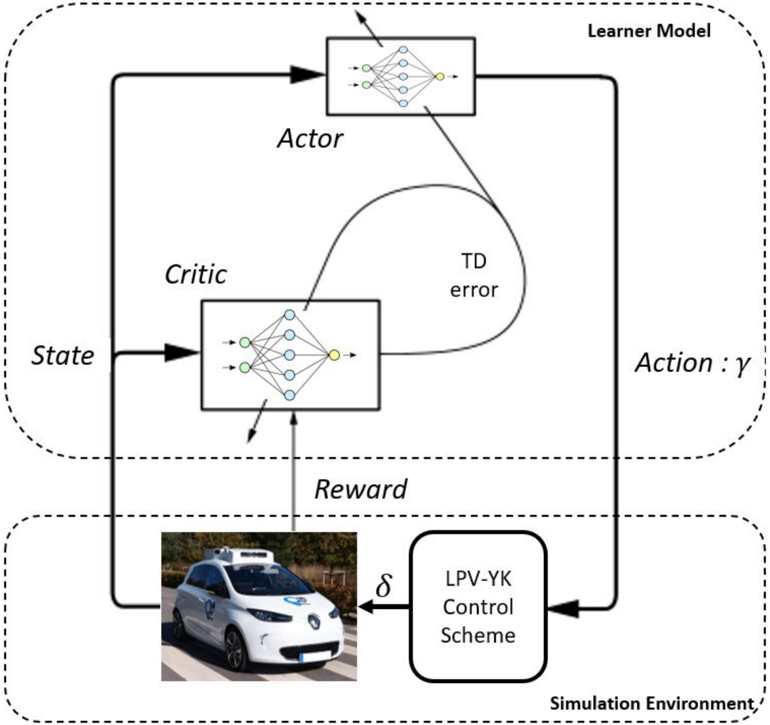
- If $\theta_e \leq 0.1, \gamma_2(t) = sat\left(-y_L + 1.4 + 0.1\dot{\delta}, [0,1]\right)$
- If $\theta_e > 1, \gamma_2(t) = sat(-0.7y_e + 1.4, [0,1])$
- $\gamma_1(t) = 1 - \gamma_2(t)$



Learning-based methods

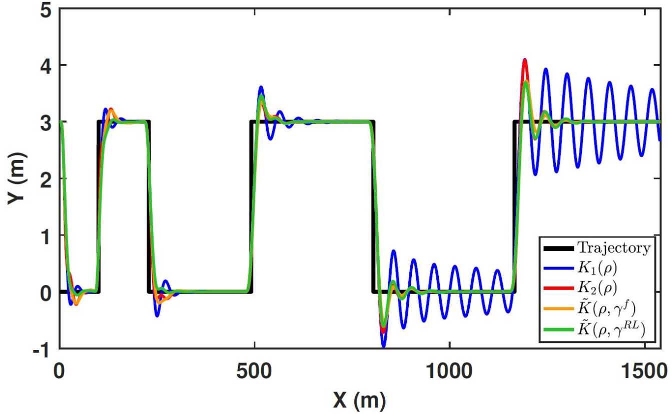
Autonomous Vehicles Lateral Control

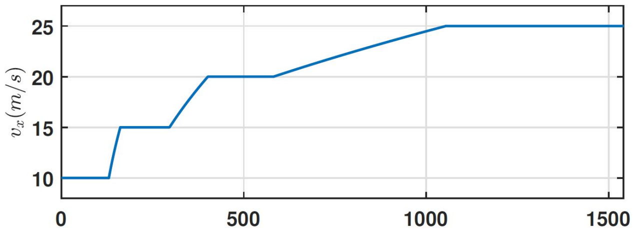
LPV-YK interpolation based on RL

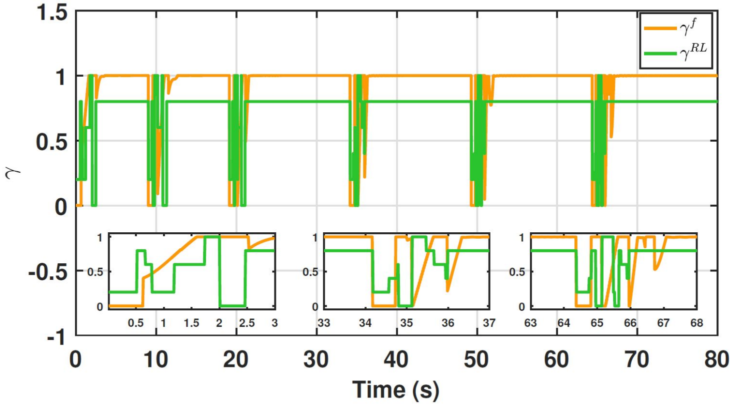


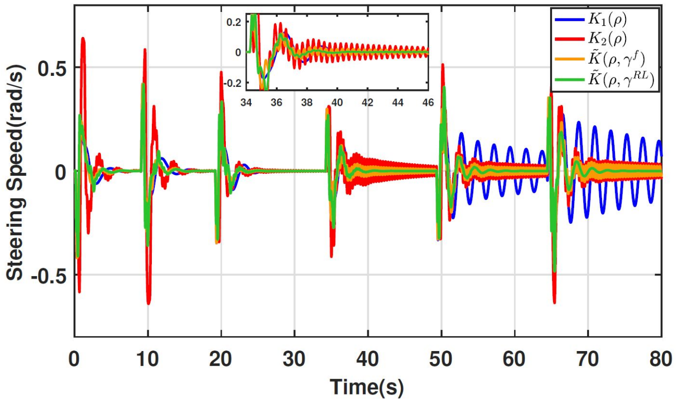
Autonomous Vehicles Lateral Control

RL-based Interpolation: Simulation









Questions?

Outline

1 Introduction

2 About LPV

3 About YK

4 About LPV-YK

5 Application to Autonomous Vehicles

6 Conclusions

Conclusions

Final words

LPV-YK Flexibility

- ✓ Ensures stability from its parameterization structure
- ✓ No limitations on the interpolating/switching signals
- ✓ Switched controllers can be designed separately, even with different dynamics and design concepts
- ✓ Achieves smooth transitions at the switching instants
- ✓ It works on real time implementations

LPV-YK Complexities

- ➢ It may reach to a very high order (>22 states)
- ➢ The dynamics of YK parameter Q affect the whole closed-loop performance
- ➢ The design of an optimal Q is not solved yet

Conclusions

Conclusions and Future Perspectives

Conclusion	Suggested Extension
LPV-YK control switching ensures closed-loop stability: 1. without requiring an instantaneous design of the local LPV controllers. 2. for any continuous/discontinuous switching signals 3. with smooth state and control input transitions	
The LPV-YK control structures have shown interesting results at high vehicle speed.	A next step can be done by testing them in more complex environments, i.e. friction drop, gust wind, higher lateral accelerations.
The multi-objective LPV-YK control structures are needed to handle different driving situations.	
The RL-based LPV-YK interpolation has achieved better efficiency, and comfort.	Improve the link between the decision-making and the control systems which leads to higher vehicle performance.

Questions?

SMART TECHNOLOGY
FOR SMARTER MOBILITY