LPV methods for fault-tolerant vehicle dynamic control

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Outline

About Vehicle Dynamics Control

The LPV approach
- Brief background and some interest of the LPV framework
- LPV tools for FTC design

The suspension control problem
- About Suspension systems
- LPV Model for faulty semi-active suspension
- The LPV fault-scheduling suspension control problem
- Simulation results on a non linear damper simulation model

LPV FTC for Vehicle Dynamics Control
- Towards global chassis control
- The LPV FTC VDC... approach
- Simulations on a full NL vehicle model

Conclusions
Road safety: an international stake

- Worldwide, 1.24 million people of road traffic deaths per year (+ 50 million of injuries)\(^a\). For people aged 5-29 years, road traffic injuries is the leading cause of death.

- Various causes: speed, alcohol, drugs, non safe driving,...

- Recognized importance of smart and safe cars: passive safety (airbags, belt..) and active (ABS, ESP....)

\(^a\)World health organization 2013
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- Various causes: speed, alcohol, drugs, non safe driving,…
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\(^a\)World health organization 2013

Among the 5 pillars towards road safety

**Safer vehicles**: Electronic Stability Control is part of the minimum standards for vehicle construction (ex European and Latin New Car Assessment Programs - NCAP)
Challenges in chassis control

Today’s vehicles . . .

- Growth of controlled organs: suspensions, ABS, ESC, ABC, braking distribution, active steering, tire pressure, TCS
- Increasing number of sensors & actuators
- Heavy networking
Challenges in chassis control

- Complexity to synchronize all the controllers to improve:
  - Driving comfort (and pleasure)
  - Active safety
- Need for fault tolerance in case of actuator/sensor malfunctions

Ferrari VDC
French National Research Agency project
INtegrated approach of Observation and control of VEhicle dynamics 2010-2014

PhD students on vehicle dynamics
Damien Sammier 98-01, Alessandro Zin 02-05, Charles Poussot-Vassal 05-08, Sébastien Aubouet 07-10, Anh-Lam Do 08-11, Soheib Fergani (11-14)
Jorge Lozoya 08-12, Juan-Carlos Tudon (11-14): TEC, PCP Mexique

Long term International supported collaboration projects
The LPV approach

Definition of an Linear Parameter Varying system

$$\Sigma(\rho): \begin{bmatrix} \dot{x} \\ z \\ y \end{bmatrix} = \begin{bmatrix} A(\rho) & B_1(\rho) & B_2(\rho) \\ C_1(\rho) & D_{11}(\rho) & D_{12}(\rho) \\ C_2(\rho) & D_{21}(\rho) & D_{22}(\rho) \end{bmatrix} \begin{bmatrix} x \\ w \\ u \end{bmatrix}$$

$x(t) \in \mathbb{R}^n$, ...., $\rho = (\rho_1(t), \rho_2(t), \ldots, \rho_N(t)) \in \Omega$, is a vector of time-varying parameters ($\Omega$ convex set)
The LPV approach

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(Scherer, ACC Tutorial 2012)

Dampened mass-spring system:

\[ \ddot{p} + c \dot{p} + k(t)p = u, \quad y = x \]

First-order state-space representation:

\[ \frac{d}{dt} \begin{pmatrix} p \\ \dot{p} \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ -k(t) & -c \end{pmatrix} \begin{pmatrix} p \\ \dot{p} \end{pmatrix} + \begin{pmatrix} 0 \\ 1 \end{pmatrix} u, \]

\[ y = \begin{pmatrix} 1 & 0 \end{pmatrix} \begin{pmatrix} p \\ \dot{p} \end{pmatrix} \]
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- If \( \rho = \rho(x(t), t) \) then the system is referred to as quasi-LPV
- An usual model is affine \( A(\rho) = A_0 + \sum_{i=1}^{N} A_i \rho_i \) .... that is usually referred to as polytopic systems.
- Take care to the confusion between LTI uncertain systems (with CONSTANT parameters) and LPV systems (with time-varying parameters), (in particular when dealing with parameter-dependent Lyapunov functions).
Towards LPV control: the "gain scheduling" approach

Some references

- Modelling, identification: (Bruzelius, Bamieh, Lovera, Toth)
- Control (Shamma, Apkarian & Gahinet, Adams, Packard, Beker ...)
- Stability, stabilization (Scherer, Wu, Blanchini ...)
- Geometric analysis (Bokor & Balas)
The $H_{\infty}/LPV$ control problem

**Definition**

Find a LPV controller $C(\rho)$ s.t the closed-loop system is stable, and, $\sup \|z\|_2 \|w\|_2 < \gamma_{\infty}$

- Unbounded set of LMIs (Linear Matrix Inequalities) to be solved ($\rho \in \Omega$)
- **Some approaches**: polytopic, LFT, gridding. See Arzelier [HDR, 2005], Bruzelius [Thesis, 2004], Apkarian et al. [TAC, 1995]...

**A solution: The "polytopic" approach [C. Scherer et al. 1997]**

- Problem solved off line for each vertex of a polytope (convex optimisation) (using here a single Lyapunov function i.e. quadratic stabilization).
- On-line the controller is computed as the convex combination of local linear controllers

$$C(\rho) = \sum_{k=1}^{2^i} \alpha_k(\rho) \begin{bmatrix} A_{c_k} & B_{c_k} \\ C_{c_k} & D_{c_k} \end{bmatrix}, \quad \sum_{k=1}^{2^i} \alpha_k(\rho) = 1, \quad \alpha_k(\rho) > 0$$

- Performance and stability ensured for all parameter variations and .... easy implementation !!
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- Performance and stability ensured for all parameter variations and .... easy implementation !!
Interest of the LPV approach

LPV is a key tool to the control of complex systems.

Modelling of complex systems (non linear)

- Use of a quasi-LPV representation to include non linearities in a linear state space model (even delays): \( \dot{x}(t) = \rho(t).x(t) \) with \( \rho(t) = \sin(x(t)) \)
- Transformation of constraints (e.g. saturation) into an 'external' parameter, \( \rho(t) = \text{sat}(u(t)) \)
- Modelling of LTV, hybrid (e.g. switching control): \( \rho(t) \in \{0, 1\} \).

leads to Polynomial, LFT or polytopic representations

**BUT**:

A q-LPV system is not equivalent to the non linear one:

- **stability**: \( \rho = \rho(x(t), t) \) is assumed to be bounded... so are the state trajectories
- **controllability**: some non controllable modes of a non linear system may vanish according to the LPV representation
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The LPV approach for control design: GIPSA-lab research works

LPV for non linear systems

- Account for various operating conditions using a variable "equilibrium point": (PhDs: Gauthier 2007, Roche 2011)
- Representation of non linear systems (PhDs: Zin 2008, Do 2010, Rivas 2012)
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**LPV for performance adaptation**

- Control with real-time performance adaptation using parameter dependent weighting functions from endogenous or exogenous parameters (PhDs: Poussot 2008, Aubouet 2010, Do 2011)
- Analysis and control of LPV Time-Delay Systems: delay-scheduled control Briat PhD 2008
- Control under computation constraints: $H_\infty$ variable sampling rate controller with sampling dependent performances (PhDs: Robert 2007, Roche 2011)
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Coordination of several actuators for MIMO systems

Several studies (PhDs: Poussot 2012, Fergani 2014)

- An LPV structure for control allocation
- Selection of a specific parameter for the control activation
Fault-Tolerant control and LPV approaches

Active FTCS:

Jiang (2012): The term ‘active’ represents corrective actions taken actively by the reconfiguration mechanism to adapt the control system in response to the detected system faults
LPV Fault-Tolerant control

Inherent adaptive structure of LPV controllers.
But still very few results...
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FTC for LPV systems

- Balas (2012): special Issue on "Fault tolerant control and fault detection/isolation design for linear parameter varying systems" in *International Journal of Adaptive Control and Signal Processing*

- Main results on the application of 'known techniques" for LPV systems: FDI for LPV systems (Henry, Edwards), LPV virtual sensors (Puig 2010)
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LPV for FTC: towards Fault-scheduling control

Probably the most interesting. Some first results in:
- Puig & Theilliol, 2010: the LPV model includes parameter changes due to some fault,
- Sloth & Stoustrup 2011: a fault parameter corresponding to a loss of hydraulic pressure in an actuator is estimated using an EKF and is used to schedule the controller.
Today and ...

Two LPV Fault-scheduling FTCS are proposed

Suspension control

- damper malfunction (oil leakage): loss of damper efficiency represented as a varying parameter; performance specifications dependent on the state-of-health of the damper (parameter dependent weighting functions).
- Non linearities: MR damping model (Do, Lozoya, Aubouet)

Vehicle dynamics

- yaw control using braking, steering, and suspension control
- monitoring the braking efficiency (slipping conditions that could be due to actuator malfunction) together with a **coordinated activation** of the steering control and the **performance adaptation** of the suspension system
- monitoring the suspension efficiency (through the induced roll motion in case of damper malfunction) and fault attenuation using the **coordinated control** of the 3 healthy dampers.
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Suspension system

Characteristics

- Link between unsprung \(m_{us}\) and sprung \(m_s\) masses
- Involves vertical \(z_s, z_{us}\) dynamics
- Influences comfort / road-holding performances

Semi-active quarter vehicle model

Only energy dissipation (i.e. real-time modification of the damping factor): good performances, fast dynamics, weight comparable to passive ones, economically viable.
Performance objectives

Comfort

- linked to the road vibration isolation of the chassis
- relating to the human sensitivity (between 0.5Hz and 20 Hz): ISO 2631

.estimated using the chassis movement: \(\ddot{z}_s/z_r\) and \(z_s/z_r\)

Road holding

- concerns the wheel rebound (or tire deflection)... keep contact between the wheel and the road

.evaluated using \(z_{us}/z_r\) on [0-20]Hz

Constraints

- End-stop, damper force saturation and dissipativity
Magneto-Rheological (MR) dampers

- adaptive behaviour through the application of a magnetic field
- fast time response and a low battery voltage consumption.
- but highly non linear: bi-viscosity, temperature dependency and hysteresis

A "usual" problem: shock absorber leak that generates loss of damping in the suspension system.

Video: Damper leakage during characterization  Cause: Overpressure in the chambers by an increment of the oil temperature due to an inconsistent voltage value.
LPV/FTC paradigm for semi-active suspensions

- **Objective 1**: account for loss of damping efficiency using an additional parameter
- **Objective 2**: handle the semi-active constraint through an LPV model based approach with non-linear damper model A-L. Do [PhD thesis 2010, Springer 2012]
  - Usual "Clipped control" (design without constraint and saturation) : leads to unpredictable behaviors
  - Semi-active control: Mixed SH-ADD (Savaresi et al.) , LPV approaches (Poussot, Aubouet, Do, Dugard & Sename)
Quarter vehicle dynamics

\[
\begin{align*}
    m_s \ddot{z}_s &= -k_s z_{\text{def}} - F_{\text{damper}} \\
    m_{us} \ddot{z}_{us} &= k_s z_{\text{def}} + F_{\text{damper}} - k_t (z_{us} - z_r)
\end{align*}
\]

\( z_{\text{def}} = z_s - z_{us} \): damper deflection, \( \dot{z}_{\text{def}} = \dot{z}_s - \dot{z}_{us} \): deflection velocity.

Semi-active nonlinear MR damper model [J. Lozoya (PhD thesis 2012)]

\[
F_{\text{damper}} = c_0 \dot{z}_{\text{def}} + k_0 z_{\text{def}} + I \cdot f_c \cdot \tanh (c_1 \dot{z}_{\text{def}} + k_1 z_{\text{def}})
\]

- \( \tanh \): allows to model the bi-viscous behavior.
- \( I \): controllable input current. Constraint: \( 0 \leq I_{\text{min}} \leq I \leq I_{\text{max}} \) - passivity constraint.
MR damper and oil leakage effects

An oil leakage on a semi-active damper is modelled as:

\[
\overline{F}_{\text{damper}} = \alpha F_{\text{damper}}
\]  

(3)

\(\alpha \in [0, 1]\) is the oil leakage degree.

**Figure**: Force-Velocity map of a semi-active damper (low and high damping) subject to different leakages

**Figure**: Semi-active suspension performances at different manipulations, by considering a fault \(\alpha = 0.5\).
An LPV state space model of a faulty quarter vehicle model

Define two new scheduling parameters

- \( \tanh ( c_1 \dot{z}_{def} + k_1 z_{def} ) \rightarrow \rho_1 \)
- \( I \in [I_{min}, I_{max}] \rightarrow \rho_2 \)

The LPV model for the semi-active suspension FTC problem is:

\[
\Sigma \left\{ \begin{array}{l}
\dot{x} = A(\rho_1, \rho_2, \alpha) x + B_u c + B_1 w \\
y = C x 
\end{array} \right.
\]

where the 3 varying parameters are bounded (\( \alpha \in [0, 1], \rho_1 \in [-1, 1] \) and \( \rho_2 \in [0, 1] \))

FTC objectives

Assuming that \( \alpha \) is estimated using a FDD strategy:

- Use of parity space equation to estimate \( F_{damper} \) (LTI formulation)
- \( \alpha \) is evaluated through:

\[
\alpha \approx \sqrt{\frac{\sum_{i=1}^{N} \hat{F}_{sai}^2}{\sum_{i=1}^{N} F_{sai}^2}} \in [0, 1],
\]

then design a Fault-scheduled LPV controller that ensures the performances of the suspension controller in terms of comfort and road holding, while satisfying the dissipativity constraints of the semi-active damper.
**$\mathcal{H}_\infty$ /LPV fault-scheduling suspension control strategy**

- Uses a varying parameter ($\alpha$) associated to the fault to schedule the suspension actuator work according to new damping characteristics.
- Parameter dependent weighting functions allowing to modify on-line the performance specifications according to the state of health of the damper.
- Solution obtained solving the $\mathcal{H}_\infty$ control problem for polytopic systems: the global LPV-FTC is a convex combination of 8 local controllers.
Time domain analysis

Simulations performed on a non linear suspension model validated on real data. **Scenario:** 3cm bump on the wheel from $t = 1s$ to $t = 1.5s$; and damper leakage: 50% of reduction of the nominal damping force ($\alpha = 0.5$) from $t = 0$.

Comfort performance: sprung mass displacement. By using the RMS value, the comfort is improved 16.3% with the LPV-FTC.

Road holding performance: suspension deflection. By using the RMS value, the suspension deflection is lower 27.7% with the LPV-FTC, consequently the road holding.
Time domain analysis (cont..)

Controller output analysis (MR damper input current)

- In the case free of faults, the LPV controller only acts when the vehicle passes on the bump.
- In the faulty case, the “LPV nominal” controller cannot schedule the malfunction, the manipulation only appears in presence of the bump.
- The LPV-FTC input current changes for long to schedule the damper leakage and achieve the best possible performances at every moment.
Frequency domain analysis

- The transmission of the road vibration to the car is increased in the faulty car (orange), specially close to the resonance frequency of the chassis (around 1.7 Hz that occurs in the video at $t = 5\text{ s}$). For different faults, the transmissibility is:

- At the end of the test (high frequencies), the car performs like a filter, both cars have slight vibrations; but the faulty car has a greater considerable settling time once the frequency of resonance of the chassis is passed.
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Towards global chassis control approaches (GCC)

Some facts

- Vehicle-dynamics **sub-systems** control (suspension, steering, stability, traction ....) are traditionally designed and implemented as **independent** (or weakly interleaved) systems.

- Global collaboration between these systems is done through empirical rules and may lead to inappropriate or conflicting control objectives.

What is GCC ?

- combine several (at least 2) subsystems in order to improve the vehicle **global behavior** Shibahata (2004)

- tends to make **collaborate** the different subsystems in view of the **same objectives**, according to the situation (constraints, environment, ...)

- is develop to improve comfort and **safety**, according to the driving situation, accounting for actuator constraints and to the eventual knowledge of the vehicle environment
Towards Global chassis control approaches

Some examples

- **braking/suspension**: non linear approach (Chou & d’Andréa Novel), LPV for heavy vehicles (Gaspar, Szabo & Bokor), for cars (Poussot et al.)
- **braking / steering**: optimal control [Yang et al.], predictive [Di Cairano & Tseng or control allocation [Tjonnas & Johansen]
- **braking /suspension/ steering**: [Fergani, Sename, Dugard]

LPV interest: on-line Adaption of the vehicle performances

- to various **road** conditions/types (measured, estimated)
- to the **driver** actions
- to the dangers identified thanks to some measurements of the **vehicle** dynamical behavior
- to actuators/sensors **malfunctions** or failures
Active safety using LPV FTC VDC coordinated control

Key points

Yaw is one of the most complex dynamics to handle on a ground vehicle. FTC LPV control:

- Prevents vehicle from skidding and spinning out
- Improves lateral vehicle dynamics face to critical situations
- Handle Braking and suspension actuator malfunctions and Steering activation

The LPV FTC strategy

Monitoring Parameters

- **Braking efficiency**: torque transmission
- **Steering activation** during emergency situation (low slip)
- **LTR**: roll induced load transfer by damper malfunctions

Control Issues

- Lateral coordinated steering/braking control: parameter dependent weighting functions for braking torque limitation and activation of the steering action
- Full car vertical suspension control: fixed control structure for suspension force distribution, parameter dependent weighting functions for roll attenuation in critical situations and comfort improvement in normal ones.
Global chassis control implementation scheme

Supervision strategy

LPV/$H_{\infty}$ Controllers

Non Linear Full Vehicle Model

Steering + Braking Monitor 2

Load Transfer Distribution Monitor 1

Steering Controller

Braking Controller

Suspension Controller

Driving scenario

Monitor 1

Monitor 2

ρ$_s$

ρ$_{ij}$

ρ$_b$

ρ$_{ij}$

ρ$_b$

ρ$_b$

δ$^+$

$u_{ij}$

$T_{brj}$

δ$^d$

$z_r$

O. Sename [GIPSA-lab / SLR team] www.gipsa-lab.fr/~o.sename
Coordinated steering/braking control

Vehicle model : Single track model (dry road).

Inputs/Ouputs:

\[
\begin{align*}
    w(t) &= [\dot{\psi}_{\text{ref}}(v)(t), M_{dz}(t)] \\
    u(t) &= [\delta^+(t), T_{brj}^+(t), T_{brj}^-(t)] \\
    y(t) &= e_{\dot{\psi}}(t) \\
    z(t) &= [z_1(t), z_2(t), z_3(t)]
\end{align*}
\]

Weighting functions for performance requirements

\( W_{e_{\dot{\psi}}} \) and \( W_{\dot{v}_y} \) are 1st order systems.

Weighting functions for actuator coordination

- \( W_{\delta}(\rho_s) = (1 - \rho_s) \times \) 4th order \( \rightarrow \) braking (and steering) penalized if \( \rho = \bar{\rho} \)
- \( W_{T_{b_{rj}}}(\rho_b) = (1 - \rho_b) \times \) 1st order \( \rightarrow \) braking (and steering) allowed if \( \rho = \rho \)

When a high slip ratio is detected (critical situation), the tire may lock, so \( \rho_b \to 0 \) and the gain of the weighting function is set to be high. This allows to release the braking action leading to a natural stabilisation of the slip dynamic.
A new partly fixed control structure: manage the suspension control distribution in case of damper malfunction.

\[
K_s(\rho_l) := \begin{cases} 
\dot{x}_c(t) &= A_c(\rho_s, \rho_l)x_c(t) + B_c(\rho_s, \rho_l)y(t) \\
\begin{pmatrix} u_{Hl}^\infty(t) \\
u_{Hr}^\infty(t) \\
u_{fr}^\infty(t) \\
u_{fr}^\infty(t) \\
\end{pmatrix} &= \begin{pmatrix} 1 - \rho_l & 0 & 0 & 0 \\
0 & \rho_l & 0 & 0 \\
0 & 0 & 1 - \rho_l & 0 \\
0 & 0 & 0 & \rho_l \\
\end{pmatrix} C_c^0(\rho_s)x_c(t) 
\end{cases}
\]

\(\rho_l\) allows to generate the adequate suspension forces in the 4 corners of the vehicle depending on the load transfer (left \(\leftrightarrow\) right) caused by the performed driving scenario.
Simulations on a full NL vehicle model

Simulation results

- Vehicle Automotive 'GIPSA-lab' toolbox
  - Full nonlinear vehicle model
  - Validated in a real car "Renault Mégane Coupé" coll. MIAM lab [Basset, Pouly and Lamy]
    see C. Poussot-Vassal PhD. thesis

The stabilizing torques $T_b^*$ provided by the controller is then handled by a local ABS strategy Tanelli et al. (2008)

Simulation scenario

Double lane-change maneuver at 100 km/h on a WET road (from $t = 2s$ to $t = 6s$)

- Faulty left rear braking actuator: saturation = $75N$
- 5cm Road bump from $t = 0.5s$ to $t = 1.5s$ and from $t = 4s$ to $t = 5s$)
- Faulty front left damper: force limitation of 70%
- Lateral wind occurs at vehicle’s front generating an undesirable yaw moment (from $t = 2.5s$ to $t = 3s$).
Monitoring parameters

- $\rho_b$ handles the braking efficiency
- $\rho_s$: activation of the steering actuator
- $\rho_l$ (LTR): Coordination of suspension control and on-line modification of the suspension performances
Braking/Steering actuators - stability analysis

Fault Tolerant Yaw control through an efficient coordination of braking/steering actuators.
Braking/Steering actuators - stability analysis

Fault Tolerant Yaw control through an efficient coordination of braking/steering actuators.
Suspension control distribution

Suspension Forces

Roll displacement

With Damper Fault
Without Damper Fault

Fixed structure LPV control for suspension force coordination in case of damper malfunction

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Outline

About Vehicle Dynamics Control

The LPV approach
  Brief background and some interest of the LPV framework
  LPV tools for FTC design

The suspension control problem
  About Suspension systems
  LPV Model for faulty semi-active suspension
  The LPV fault-scheduling suspension control problem
  Simulation results on a non linear damper simulation model

LPV FTC for Vehicle Dynamics Control
  Towards global chassis control
  The LPV FTC VDC... approach
  Simulations on a full NL vehicle model

Conclusions
Conclusions

Many interests of the LPV approach

+ Modelling of complex systems (but still less than nonlinear formulation)
+ Control design with varying performances, ensuring internal stability and robust-like performances
+ LPV Observer/Filter design... for FDI
+ A tool to design adaptive FTCS
+ Can be extended to mixed-objectives problems (e.g. $\mathcal{H}_\infty$, $\mathcal{H}_2$...) through LMI (and/or nonsmooth) tools

INOVE Test-bed
With my grateful thanks to ...

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