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A decentralized multilayer sliding mode control architecture for vehicle's global chassis control, and comparison with a centralized architecture

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Abstract. This paper presents a decentralized Global Chassis Control (GCC) architecture. The objective of this global chassis controller is to improve the overall vehicle performance i.e maneuverability, lateral stability and rollover avoidance, by coordinating the Active Front steering, Direct Yaw Control and Active Suspensions in a decentralized architecture. The developed architecture is multilayer, and based on higher order sliding-mode control, the super-twisting algorithm. The proposed GCC is validated by simulation using Matlab/Simulink, and a comparison is done with a centralized LPV/\mathcal{H}_∞ architecture that has been developed in the laboratory, to show the difference in behavior and performance of both strategies of control.

Decentralized Multilayer Control Architecture; Global Chassis Control; Active Suspensions; Direct Yaw Control; Active Front Steering; Sliding Mode Control.

1 INTRODUCTION

Active safety is an important feature into the intelligent vehicles. According to the “National Highway Traffic Safety Administration (NHTSA)” statistics, human’s faults cause almost 90% of road accidents as explained in [1]. Advanced Driving Assistance System (ADAS) influences on the behavior of vehicle on the road, and helps the driver in the driving process in order to avoid a dangerous situation. ADAS systems are formed by several single-actuator approaches that have been proposed and marketed, such as: Electronic Stability Program (ESP) or Direct Yaw Control (DYC) to enhance the vehicle lateral stability; Active Front Steering (AFS) to mainly improve the vehicle maneuverability or lane keeping; and (Semi-) Active Suspensions (AS) to improve comfort, road holding and rollover avoidance [2].

Many advanced studies are developed in literature to improve the global performance of the vehicle in different driving situations. These studies suggest coordination between several ADAS systems known as Global Chassis Control (GCC). The GCC system deals with the complexity of control problems for Multi-Input-Multi-Output (MIMO) systems. The main idea of the GCC is the coordination between the AFS and the DYC to improve the vehicle maneuverability and lateral stability depending on the driving

situation. Many advanced control approaches have been proposed for this issue. The authors in [3] applied a decentralized approach where they developed a DYC controller for lateral stability purpose and an AFS controller for maneuverability purpose, based on sliding mode technique, and then a monitor switches between the two controllers according to the driving situations. However, the overall stability of the system is not guaranteed in the decentralized approach, but it is simple to develop, implement and tune. In [4], [5], the authors propose several robust and optimal centralized controllers for the MIMO system based on the LPV/ \mathcal{H}_∞ control technique, where the LPV/ \mathcal{H}_∞ controller penalizes or relaxes the steering and braking to enhance maneuverability and lateral stability. By using this method, the overall stability of the system is guaranteed and a polytopic approach is used to actuate the different controllers. However, these controllers were synthesized while disregarding the roll motion; the deduced rollover enhancement was a consequence of the lateral stability control. Authors in [6], [7] have presented several centralized LPV/ \mathcal{H}_∞ controllers, where AFS, DYC and AS are used to control the decoupled lateral and vertical vehicle dynamics. From the other side, authors in [8] and [9], have used the roll angle and its angular velocity to control the vehicle load transfer that leads to rollover avoidance. Moreover, authors deduced lateral stability improvement as a consequence of roll control. Centralized architectures are optimal in global performance, but are more complex to design and to implement, and could take an important amount of calculation.

All these interesting research have motivated us to study the control of the vehicle yaw rate, the side slip angle and the roll angle in order to improve the overall vehicle performance. Thus, in our present work, a decentralized multilayer control structure, based on sliding mode super-twisting control approach, is developed to improve the maneuverability, lateral stability, and rollover avoidance using steering, braking actuators and active suspension system. A comparison between the proposed controller and a centralized architecture presented in [10] is done. The paper structure is as follows: Section 2 exposes the extended bicycle model of the vehicle based on the combination of the coupled lateral (yaw and side-slip) and roll motions. In Section 3, the proposed decentralized control architecture is detailed. Simulation validation of the proposed approach is reported in Section 4. Finally, the conclusions and the perspectives of this work are given in Section 5.

2 Vehicle model

The vehicle is a group of interconnected mechanical and electrical systems that make the vehicle behavior nonlinear. The ADAS systems such as AFS (Active Front Steering), active suspensions, differential braking, etc, improve the vehicle's performance (lateral motion, yaw motion, rolling motion, etc.). A complete nonlinear vehicle model has been developed in [11]. However, this model is a nonlinear model that does not respond to the formulation of control problems. For this reason, a linear simplified LTI vehicle model is used to develop the GCC controller. It is an extended bicycle model, with coupled lateral/vertical dynamics. For vertical dynamics, the rolling motion is considered, for being the most critical for stabilization problems and rollover avoidance. Hence, this LTI model is a coupled yaw-lateral-roll linear vehicle model, inspired from

literature [8], and is given by the following equations of “Plant P”:

$$Plant P: \begin{cases} I_z \ddot{\psi} = F_{yf} l_f + F_{yr} l_r + I_{xz} \ddot{\theta} + M_z + M_{d,\psi}, \\ MV(\dot{\beta} + \dot{\psi}) = F_{yf} + F_{yr} + M_s h_\theta \ddot{\theta} + F_{d,y}, \\ (I_x + M_s h_\theta^2) \ddot{\theta} = M_s h_\theta V(\dot{\beta} + \dot{\psi}) + (M_s g h_\theta - K_\theta) \theta \\ \quad - C_\theta \dot{\theta} + M_{d,\theta}, \end{cases} \quad (1)$$

where the vehicle parameters and variables are given in Table 1. F_{yf} represents the lateral force of the front left and right tires merged together at the center of the front axle. Similarly, F_{yr} is noted for the rear axle. F_{yf} and F_{yr} are given as:

$$\begin{aligned} F_{yf} &= \mu C_f \alpha_f, \\ F_{yr} &= \mu C_r \alpha_r, \end{aligned} \quad (2)$$

and the tires slip angles as:

$$\begin{aligned} \alpha_f &= -\beta - \frac{l_f \dot{\psi}}{V} + \delta_f, \\ \alpha_r &= -\beta + \frac{l_r \dot{\psi}}{V}. \end{aligned} \quad (3)$$

The reference “bicycle model” used in the control layer is presented in [1] and is given in (4):

$$\begin{pmatrix} \dot{\psi}_{ref} \\ \dot{\beta}_{ref} \end{pmatrix} = \begin{bmatrix} -\mu \frac{l_f^2 c_f + l_r^2 c_r}{I_z V_x} & \mu \frac{l_r c_r - l_f c_f}{I_z} \\ -1 + \mu \frac{l_r c_r - l_f c_f}{MV_x^2} & -\mu \frac{c_f + c_r}{MV_x} \end{bmatrix} \begin{pmatrix} \psi_{ref} \\ \beta_{ref} \end{pmatrix} + \begin{bmatrix} \mu \frac{l_f c_f}{I_z} \\ \mu \frac{c_f}{MV_x} \end{bmatrix} \delta_d, \quad (4)$$

where δ_d is the driver steer angle on the front wheels, ψ_{ref} is the desired reference yaw rate, β_{ref} is the corresponding side slip angle, and V_x is the vehicle longitudinal speed. For security reasons, the authors in [1] propose to saturate β_{ref} and ψ_{ref} below a threshold, as described in (5):

$$\begin{aligned} |\dot{\psi}_{ref}| &\leq \left| \frac{0.85 \mu g}{V_x} \right| \\ \beta_{ref} &= \arctan(0.02 \mu g) \end{aligned} \quad (5)$$

3 DECENTRALIZED GLOBAL CHASSIS CONTROL ARCHITECTURE

The global decentralized multilayer control architecture of Fig. 1 is presented in this section. The output variables i.e the vehicle yaw rate $\dot{\psi}$, the side-slip angle β , and the suspended mass roll θ are controlled independently by using the single-input, single-output controller based on the Super-Twisting Sliding Mode (STSM) technique. Let us introduce an overview of the theory of Super-Twisting Sliding Mode. The STSM is a robust control technique that forces the states of the system to reach a sliding surface during a finite time (convergence phase) and to stay on this surface (sliding phase) in presence of perturbations.

Consider the second order system given as:

$$\ddot{x} = f(X, t) + g(X, t)u(t) \quad (6)$$

Table 1. Parameters Values for Simulation

Symbols	Description	Parameters values
$\dot{\psi}$	Vehicle yaw rate	$[rad/s]$
β	Vehicle side slip angle at CG	$[rad]$
θ	Sprung mass roll angle	$[rad]$
F_{y_i}	Lateral forces at the i axle	$[N]$
δ_d	Driver steering angle	$[rad]$
V	Vehicle speed	$[m/s]$
I_x	Roll moment of inertia of sprung mass	534 $[kg.m^2]$
I_z	Vehicle yaw moment of inertia	1970 $[kg.m^2]$
I_{xz}	Vehicle yaw-roll product of inertia	743 $[kg.m^2]$
l_f	Half front track	0.773 $[m]$
l_r	Half rear track	0.773 $[m]$
l_f	Wheelbase to the front	1.0385 $[m]$
l_r	Wheelbase to the rear	1.6015 $[m]$
h_θ	Sprung mass roll arm	0.27 $[m]$
M_s	Sprung mass	1126.4 $[kg]$
C_f, C_r	Front, rear tire cornering stiffness	76776 $[N/rad]$
K_θ	Rolling suspension angular stiffness	30000 $[N.m/s]$
C_θ	Rolling suspension angular damper	10000 $[N.m/s]$
g	Gravity constant	9.81 $[m/s^2]$
μ	Road adherence coefficient	dry surface= 1 $[-]$

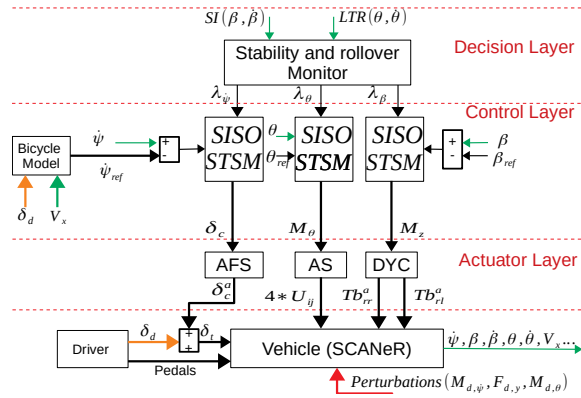


Fig. 1. Decentralized global chassis control architecture

where $X = [x, \dot{x}]^T \in \mathfrak{R}^2$ is the state vector, u is the control input, and f, g are continuous functions. X_{des} is the desired state of X with $X_{des} = [x_{des}, \dot{x}_{des}]^T \in \mathfrak{R}^2$. The error vector is given by $E = X - X_{des} = [e, \dot{e}]^T \in \mathfrak{R}^2$ where $e = x - x_{des}$ and $\dot{e} = \dot{x} - \dot{x}_{des}$. Therefore, a sliding variable s with relative degree $r = 1$ w.r.t the control input, is defined as:

$$s = \dot{e} + k e, \quad (7)$$

The second order derivative of s is:

$$\ddot{s}(s, t) = \Phi(s, t) + \xi(s, t)\dot{u}(t) \quad (8)$$

where $\Phi(s, t)$ and $\xi(s, t)$ are the unknown bounded signals.

The goal of the Super-Twisting algorithm is to enforce the sliding variable s to converge to zero ($s = 0$) in finite time. Assume that there exist positive constants $S_0, b_{min}, b_{max}, C_0, U_{max}$ verifying for all $x \in \mathfrak{R}^n$ and $|s(x, t)| < S_0$:

$$\begin{cases} |u(t)| \leq U_{max} \\ |\Phi(s, t)| < C_0 \\ 0 < b_{min} \leq |\xi(s, t)| \leq b_{max} \end{cases} \quad (9)$$

Thus, the control input based on the Super-Twisting Sliding Mode algorithm, is given as:

$$u(t) = u_1 + u_2 \begin{cases} u_1 = -\alpha_1 |s|^\tau \text{sign}(s), \quad \tau \in]0, 0.5] \\ \dot{u}_2 = -\alpha_2 \text{sign}(s) \end{cases} \quad (10)$$

α_1 and α_2 are positive gains. The following conditions guarantee the finite time convergence:

$$\begin{cases} \alpha_1 \geq \sqrt{\frac{4C_0(b_{max}\alpha_2 + C_0)}{b_{min}^2(b_{min}\alpha_2 - C_0)}} \\ \alpha_2 > \frac{C_0}{b_{min}} \end{cases} \quad (11)$$

The analysis of convergence is presented in [12]. An approximation function $\frac{s}{|s|+\varepsilon}$ is used to smooth the $\text{sign}(s)$ function, where $\varepsilon > 0$.

Let us define the three sliding variables for the three decentralized controllers as follows:

$$\begin{aligned} s_{\psi} &= e_{\psi} = \dot{\psi} - \dot{\psi}_{ref}, \\ s_{\beta} &= e_{\beta} = \beta - \beta_{ref}, \\ s_{\theta} &= \dot{\theta} + k_{\theta} e_{\theta} = (\dot{\theta} - \dot{\theta}_{ref}) + k_{\theta}(\theta - \theta_{ref}), \end{aligned} \quad (12)$$

The sliding variables s_{ψ}, s_{β} and s_{θ} have a relative degree equal to one w.r.t δ_c, M_z and M_{θ} respectively. Thus, in order to converge these variables to zero and the controlled states follow the desired ones, and based on the above discussion, the control inputs of AFS, DYC and AS applied to the system, are given by:

$$\begin{aligned} \delta_c &= -\alpha_{\delta,1} |s_{\psi}|^{\tau_{\delta}} \text{sign}(s_{\psi}) - \alpha_{\delta,2} \int_0^t \text{sign}(s_{\psi}) d\tau, \\ M_z &= -\alpha_{M_z,1} |s_{\beta}|^{\tau_{M_z}} \text{sign}(s_{\beta}) - \alpha_{M_z,2} \int_0^t \text{sign}(s_{\beta}) d\tau \\ M_{\theta} &= -\alpha_{M_{\theta},1} |s_{\theta}|^{\tau_{M_{\theta}}} \text{sign}(s_{\theta}) - \alpha_{M_{\theta},2} \int_0^t \text{sign}(s_{\theta}) d\tau, \end{aligned} \quad (13)$$

where $\alpha_{\delta,i}, \alpha_{M_z,i}$ and $\alpha_{M_{\theta},i}$ with $i = [1, 2]$, are positive constants satisfying the conditions in (11). $\tau_{\delta}, \tau_{M_z}$ and $\tau_{M_{\theta}}$ are constants between $]0, 0.5]$.

The decision layer monitors the driving situation based on SI (lateral stability index) and LTR (load transfer ratio) criteria, then it delivers the different gains λ_i in order to activate or deactivate the different actuators. These gains are given as follows:

$$\lambda_\beta = \frac{1}{1 + e^{-\frac{8}{SI - \underline{SI}}(SI - \frac{\underline{SI} + \overline{SI}}{2})}}, \quad (14)$$

$$\lambda_\psi = 1 - \lambda_\beta.$$

$$\lambda_\theta = \frac{1}{1 + e^{-\frac{8}{LTR - \underline{LTR}}(LTR - \frac{\underline{LTR} + \overline{LTR}}{2})}}, \quad (15)$$

4 SIMULATION RESULTS

In this section, the developed controller will be validated with a double lane change test at 110 km/h as initial speed. All simulations are done using Matlab/Simulink with a complete nonlinear model of the vehicle [11], validated on “SCANeR Studio” (OK-tal)³[13]. Then, a comparison is done between an uncontrolled vehicle, where no controller is used (“OL” as Open Loop) and controlled vehicle equipped with two different controllers, i.e, the decentralized controller (“STSM” as Super-Twisting Sliding Mode) and a centralized controller (“LPV/ \mathcal{H}_∞ ”) developed in the laboratory Heudiasyc, and presented in [10]. During this test, The driver’s intention is to change the lane in a short time and then return to the same lane. Noting that in the two techniques of control, the active suspensions system AS aims to avoid rollover by decreasing the angle θ .

Fig. 2, 3 and 4 show the different control variables such as the yaw rate, the side-slip

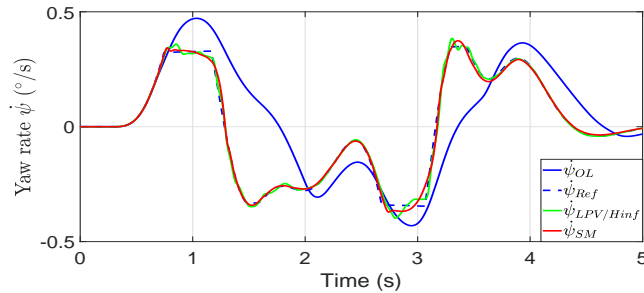


Fig. 2. Yaw rate comparison

angle and the roll angle respectively. Fig. 2 shows that the yaw rate tracks the reference yaw rate delivered by the bicycle model, and both controllers have almost the same behavior compared with the uncontrolled vehicle. Thus, the maneuverability objective is achieved. In order to improve the lateral stability and to prevent an undesirable driver

³ “SCANeR Studio” is a simulator dedicated to vehicle dynamics simulations.

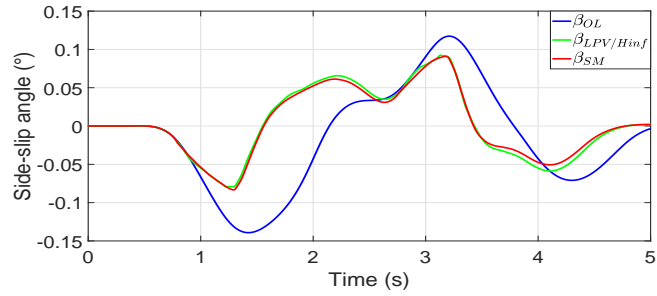


Fig. 3. Side-slip angle comparison

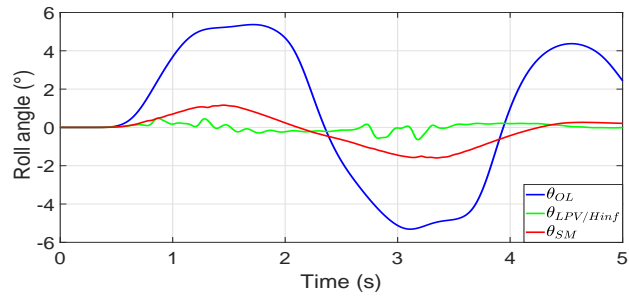


Fig. 4. Roll angle comparison

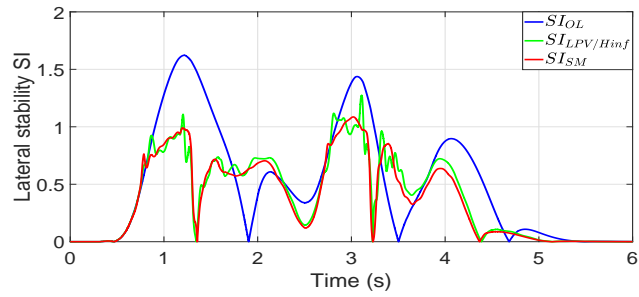


Fig. 5. Lateral stability index comparison

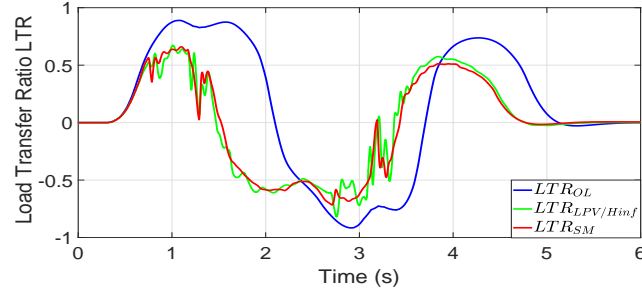


Fig. 6. Load Transfer Ratio comparison

situation, the side-slip angle should be reduced as shown in Fig. 3. Both control architectures have similar influence on this angle. On the other hand, the convergence of roll angle to zero allows the avoidance of rollover risk, by reducing the load transfer ratio LTR . The Fig. 4 shows that the LPV/\mathcal{H}_∞ controller is capable to diminish more the roll angle to zero compared to the STSM controller.

Fig. 5 shows the lateral stability index (SI), and Fig. 6 presents the lateral load transfer ratio (LTR). Both SI and LTR are improved with both GCC architectures. Hence, lateral stability and rollover avoidance are enhanced.

5 CONCLUSION AND PERSPECTIVES

To conclude, a decentralized multilayer sliding mode control architecture has been developed to improve the overall vehicle performance. This enhancement is done by coordination of the Active Front Steering, Direct Yaw Control and Active Suspensions in a decentralized controller. The proposed controller is validated by using Matlab/Simulink and a comparison is done with a centralized approach based on the LPV/\mathcal{H}_∞ technique, presented in [10]. Results show an almost similar performance of the decentralized scheme with its centralized equivalent. However, decentralized architecture is simpler and easier to tune and implement than centralized controller. Hence, the decentralized architecture could be much more interesting. In future works, we will work on the proof of the global stability of the system with the decentralized global chassis controller, a Lyapunov-based analysis will be done to show the convergence and boundedness of the solution. Validation on the Scanner Studio simulator and on a real vehicle platform will also be investigated. In addition, other performance index will be also used to do the benchmark comparing against the other conventional control approaches.

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