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Abstract: Most of today's passenger cars are over-actuated. This over-actuation is expected to grow going towards self-driving cars. However, the necessary systems that would be needed for a safe and a comfortable autonomous driving remain uncertain. This paper aims to provide an extensible control architecture that does not depend on a particular system combination. Car manufacturers tend to develop ad hoc rule-based strategies for a specific set of integrated systems. Through several realistic scenarios, we have shown that the control architecture proposed in this paper can be adopted for different set of integrated systems. A minimal effort is required from the control designer when changing the nature of the systems integrated to adapt the control strategy. The control architecture proposed in this paper can serve as a starting point for the standardization of control architectures for future vehicles motion control.

Keywords: Control Architecture, Vehicle Motion Control, Robust Control, Control Allocation, Extensibility.

1. INTRODUCTION

At the end of the 70's, the automotive sector started switching its focus from passive safety systems towards active chassis systems. It began with the Anti-lock Braking Systems (ABS) [1], and since its huge success in terms of the number of accidents avoided, several applications have followed. Systems such as the Electronic Stability Program (ESP) have even become mandatory in new passenger cars. In addition, new systems as the Intelligent Speed Assistance (ISA), Autonomous Emergency Braking (AEB), and Lane Keeping Assist (LKA) have been approved by the European Parliament [2], and the regulation will be now submitted for approval to the EU Council of Ministers so these systems become mandatory from May 2022 for new vehicle models and from May 2024 for existing models. As Fig. 1 shows, the driving authority is taken away from the human driver, the vehicle getting more and more over-actuated until completely becoming autonomous. Even though each system is developed for a particular functionality, different systems may influence the same physical variable. For example, an Active Rear Steering (ARS) generates a yaw moment through the rear lateral tire forces, and then influences the vehicle's yaw rate. But even if an ESP depends on longitudinal tire forces, by generating forces at the right wheels different from the left wheels, another yaw moment can be induced. If both of these systems are implemented within the same vehicle, conflicts may occur. Over-actuation is adopted in order to expand the potential of the vehicle. Without any global system coordination, the concurrent actions of systems may lead to unwanted interactions that compromise the potential of each system and may impact the global vehicle safety.

When only few number of systems is implemented, one could pre-study the possible conflicted scenarios in order to develop rule-based strategies and prevent any conflict. For example, in [3], fuzzy logic has been adopted to coordinate an Active Front Steering (AFS) system and braking-based a Direct Yaw Control (DYC) system downstream their standalone controllers. Their interactions have been studied in a non-formal way to come up with ad-hoc solutions. In [4], the authors used Active Differential (AD), ESP, and Torque Vectoring (TV) for lateral motion control. Prioritization strategies have been adopted. Here, the priority has been selected according to a pre-study of the efficiency of each system when implemented apart. The yaw moment demand was then ensured first by the AD. If the yaw moment demand is too high, the request is equally shared between the ESC and the TV systems. Usually, we suppose that the systems can be superposed without an actual study of simultaneous operations.

The more numerous the systems get, which would probably be the case in self-driving cars, the more conflicts we may encounter. On one hand, in this scenario, we cannot foresee all the possible conflicted scenarios and develop rule-based strategies for each one of them. On the other hand, developing strategies specific to a particular system combination is definitely neither flexible nor extensible, and it would be hard to convince any industrial to adopt such strategies in the long term. For all these reasons, the problem should be tackled differently. The system interactions should be mathematically formalized in order to overcome this dependency on use-cases in the design stage. In this way, we can develop a high-level control to specify the motion of the car, and then an optimization-based strategy to split the control on the different implemented systems upstream the low-level controllers [5]. This control allocation strategy should be extensible so if a new system should be implemented within the same car, the control designer does not have to redesign the overall architecture of the motion control. New systems can be implemented in a

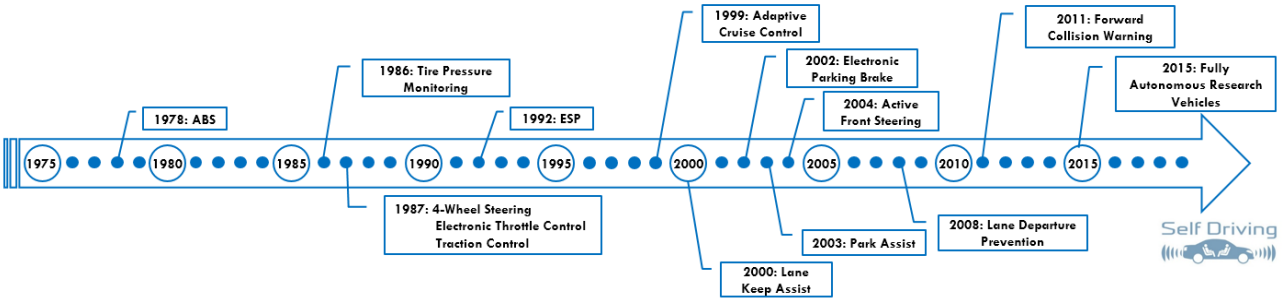

Fig. 1 Time-line of automotive embedded systems (completed from [1]).

"*plug-and-play*" style [6], and the car manufacturer can proceed in an agile way and accelerate its future vehicles development.

The purpose of this paper is to show how extensible an upstream approach could be. The aim is to convince automotive stakeholders to start adopting this optimization based coordination strategies. We show in this paper that the same control structure can be adopted for different chassis systems combination. Simulation results show the effectiveness of the control strategy even for different chassis systems combinations. Benchmarks can be inspired from the examples shown here, and standardization can be expected.

The rest of the paper is structured as follows: We start in Section 2by explaining why we think that today's vehicles are not suitable for future industrial applications. The proposed control architecture is illustrated in Section 3. In Section 4, different applications are studied in order to prove the extensibility of the control architecture proposed. Conclusions and future works are outlined in Section 5.

2. PROBLEM DEFINITION

In order to keep control of the market, car manufacturers tend to vary their equipment suppliers. Each embedded system is developed individually by a different equipment supplier. Since the equipment supplier does not know the other embedded systems that can be implemented within the same vehicle, conflicts are not studied by this latter.

It is up to the car manufacturer to harmonize the overall vehicle motion control.

The equipment supplier focus on the specific functionality of its system. In this context, simple reduced vehicle models can be adopted for control synthesis. For example, the quarter vehicle model illustrated in Fig. 2 is adopted in [7] for longitudinal tire force based control. Regarding lateral tire force based control, the bicycle model illustrated in Fig. 3 can be adopted as in [8].

These models are heterogeneous. When developing controllers based on a particular model to stabilize the vehicle, each controller, when activated alone, can indeed stabilize the vehicle. However, there is no guarantee that the overall system will be stable when more than one controller are activated at the same time. This is why the car

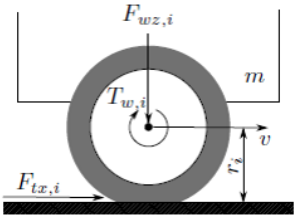

Fig. 2 Quarter vehicle model [7].

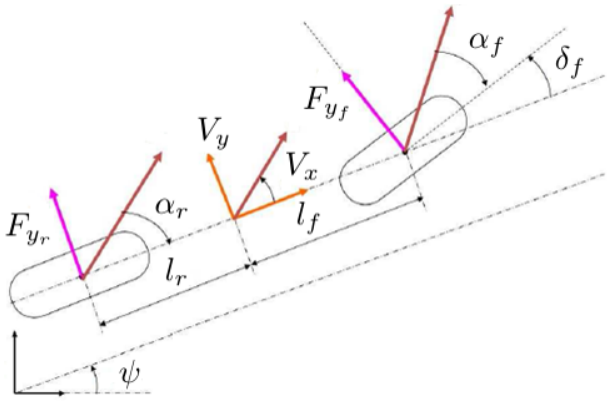

Fig. 3 Bicycle model.

manufacturer end up opting for prioritizing strategies to activate one system at a time, especially if the control logic of the equipment supplier comes in a black-box.

In addition, the simplified vehicle models do not take into account the couplings that exist at the vehicle level and the tire level. The tire potential is delimited by the friction ellipse concept [9]. As Fig. 4 shows, the overall potential of the tire is delimited by the friction coefficient μ and the vertical load F_z. However, the longitudinal tire force and the lateral one are competing. In other words, if the tire is solicited only the longitudinal direction, F_x may reach the maximum potential of $\mu_x F_x$. However, if the tire is solicited first laterally, than the maximum potential of the longitudinal tire force is penalized, and F_x can only reach $\sqrt{(\mu_x F_z)^2 - F_y^2}$. Not taking into account this limitation, high tire force can be requested in one direction, while the tire is saturated due to a simultaneous operation. Because of all of these limitations, the car manufacturer opt for the safest solution consisting of activating one system at a time. Ad-hoc coordination strategies are then developed. Whenever a new system

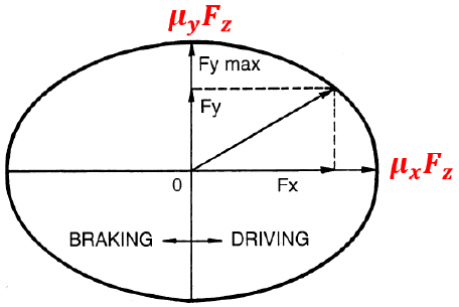

Fig. 4 Friction ellipse concept (adapted from [9]).

has to be implemented, the overall control structure has to be redesigned. Since the future systems required for autonomous vehicles are still not completely defined, the actual coordination strategy remains fragile and not suitable for future challenges.

3. EXTENSIBLE CONTROL ARCHITECTURE DEVELOPMENT

For long-term robust design, the control architecture has to be flexible and extensible. First, the vehicle and tire models should be unified. Secondly, the vehicle motion control problem should be separated from the control distribution problem. The architecture should be in addition modular.

3.1 Vehicle Motion Control Structure

To satisfy the mentioned specifications, the control architecture should follow the structure depicted in Fig. 5.

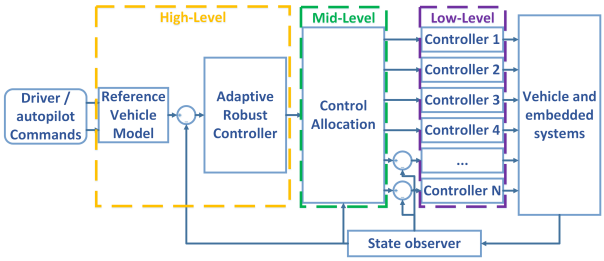

Fig. 5 Proposed upstream integrated vehicle dynamics control [6].

Four different problems are distinguished in this architecture: motion reference, high-level control, control allocation and low-level control. The reference generation can be based on an ideal vehicle motion behavior that the real vehicle has to follow. This reference can be tuned online in order to generate different behaviors depending on the driving mode as discussed in [10]. Regarding the high-level control, the goal is to generate generalized forces at the vehicle's Center of Gravity (CoG). The control allocator has to generate tire forces in order to achieve the required forces at the vehicle's CoG. The low-level controllers can then transform the required tire forces in actuators' requests to be fed to the different embedded systems.

The high-level controller depends on the directions desired to be controlled. A Single-Input Single-Output (SISO) control would differ from a Multiple-Inputs Multiple-Outputs (MIMO) control. A control synthesis suitable for both SISO and MIMO control should be adopted. The low-level controllers depend from the embedded system. However, the control allocator should be based on the relationship between vehicle dynamics and tire dynamics. Through the right optimization solver, we can show that this problem can be generalized to make the overall design extensible.

3.2 Vehicle and Tire Modeling

This structure aims to take into account the different couplings to avoid the problems encountered in a downstream approach design. The vehicle model and the tire model should at the same time depict the dynamic couplings and stay simple enough for control synthesis.

3.2.1 Unified Vehicle Model

In this case, we use the vehicle model developed in [11] as illustrated in Fig. 6. Using Newton's laws of

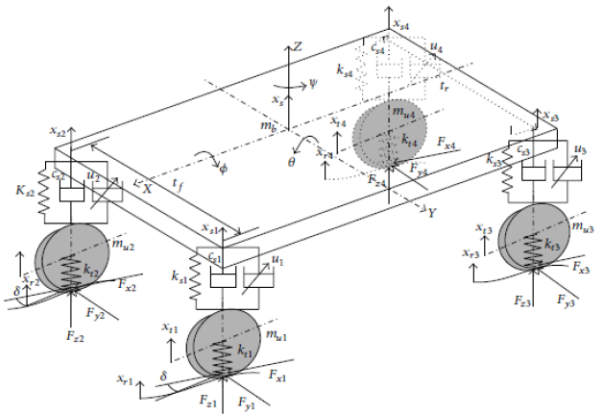

Fig. 6 Unified vehicle model [12].

motion, and simplifying cross-multiplied low angles and angular velocities, e.g., multiplication of the roll velocity and the pitch velocity, we find the following state-space representation:

$$\dot{V}_x = \frac{F_{x_{tot}}}{M} + \frac{M_s}{M} g V_x + V_y \dot{\psi} \tag{1}$$

$$\dot{V}_y = \frac{F_{y_{tot}}}{M} - V_x \dot{\psi} \tag{2}$$

$$\dot{V}_z = \frac{F_{z_{tot}}}{M} \tag{3}$$

$$\ddot{\phi} = \frac{M_{x_{tot}}}{I_{s_{xx}}} - \frac{K_r}{I_{s_{xx}}}\phi - \frac{C_{s_r}}{I_{s_{xx}}}\dot{\phi} \tag{4}$$

$$\ddot{\theta} = -\frac{M_s h_s}{M I_{s_{yy}}} F_{x_{tot}} + \frac{M_{y_{tot}}}{I_{s_{yy}}} - \frac{M K_p + M_s^2 h_s g}{M I_{s_{yy}}}\theta - \frac{C_{s_p}}{I_{s_{yy}}}\dot{\theta} \tag{5}$$

$$\ddot{\psi} = -\frac{M_s h_s}{M I_{zz}} \phi F_{x_{tot}} + \frac{M_{z_{tot}}}{I_{zz}} \tag{6}$$

With V_x, V_y, V_z are the longitudinal, lateral, and vertical velocities of the vehicle, respectively. ϕ, θ, ψ are the roll,

pitch, and yaw angles of the vehicle. M_s and M are the vehicle's sprung and overall masses, h_s is the height of the vehicle's CoG, g is the gravitational acceleration, K_r is the equivalent overall antiroll bar stiffness, C_{s_r} is the equivalent overall roll suspension damping, and K_p and C_{s_p} are the equivalent overall pitch suspension stiffness and damping. $I_{s_{xx}}$ and $I_{s_{yy}}$ are the sprung mass's roll and pitch moment of inertia and I_{zz} is the vehicle's yaw moment of inertia. $F_{i_{tot}}$ and $M_{i_{tot}}$ are the combination of tire forces and moments projected at the axis "i".

3.2.2 Unified Tire Model

For the same reasons, a unified tire model is adopted. In order to take into account tire couplings but still keep a simple structure for control synthesis, the linear tire model with varying parameters developed in [13] is adopted. This model keep the same structure as the one used for the bicycle model, but depend on a varying stiffness that varies according to simultaneous operations:

$$F_x(\kappa) = C_s^* \kappa \tag{7}$$

$$F_y(\alpha) = C_\alpha^* \alpha \tag{8}$$

With:

$$C_s^* = \frac{4\sqrt{C_s^2 \kappa^{*^2} + C_\alpha^2 \tan^2(\alpha)} - (1-\kappa^*)\mu F_z}{4\left(C_s^2 \kappa^{*^2} + C_\alpha^2 \tan^2(\alpha)\right)} \mu F_z \tag{9}$$

$$C_\alpha^* = \frac{4\sqrt{C_s^2 \kappa^2 + C_\alpha^2 \alpha^{*^2}} - (1-\kappa)\mu F_z}{4\left(C_s^2 \kappa^2 + C_\alpha^2 \alpha^{*^2}\right)} \mu F_z C_\alpha \tag{10}$$

Where:
- κ : longitudinal slip,
- α : side-slip angle,
- C_s : longitudinal stiffness of the tire,
- C_α : cornering stiffness of the tire,
- C_s^* : varying longitudinal stiffness of the tire,
- C_α^* : varying cornering stiffness of the tire.

3.3 Control Synthesis

Since the most inner controllers may be provided as black-boxes, the high-level controllers should be robust. Moreover, as mentioned before, the control synthesis should be suitable for both SISO and MIMO problems. For these reasons, we recommend a Gain-Scheduled $\mathcal{H}_\infty$. A guideline on how to synthesize a Gain-Scheduled $\mathcal{H}_\infty$ as a high-level controller for vehicle motion control is detailed in [11]. Since this goes beyond the scope of this paper, and because this method can be actually adopted for both a downstream and an upstream approach, no further development is provided.

3.4 Control Allocation

The problem here is how to generate the tire forces required to satisfy the generalized forces computed by the high-level controller. The control allocation problem can be defined as follows [14]: find the control vector, $\vec{u} \in \mathbb{R}^n$ such that

$$\mathbf{B}\vec{u} = \vec{v} \tag{11}$$

subject to

$$\vec{u}_{min} \leq \vec{u} \leq \vec{u}_{max} \tag{12}$$

$$\dot{\vec{u}} \leq \dot{\vec{u}}_{max} \tag{13}$$

where $\mathbf{B} \in \mathbb{R}^{m \times n}$ is a control effectiveness matrix, $\vec{u}_{min} \in \mathbb{R}^n$ and $\vec{u}_{max} \in \mathbb{R}^n$ are the lower and upper position limits, respectively, $\dot{\vec{u}} \in \mathbb{R}^n$ is the control rate, $\dot{\vec{u}}_{max} \in \mathbb{R}^n$ is the maximum control rate, $\vec{v} \in \mathbb{R}^m$ are the desired accelerations, n is the number of control effectors, and m is the number of axes to control with $n > m$.

By considering equation (11) as a cost function, and taking into account the friction ellipse as the main constraint, the problem can be tackled as an optimization problem that can be solved in two different ways. For single objective problems, an explicit solution can be obtained by means of a Weighted Pseudo-Inverse (WPI) method [15]. However, for multiple-objectives problem, it would be hard, if not impossible to find an explicit solution to be used as a pre-computed law. In this case, online optimization should be adopted. Different optimization algorithms have been compared in [16]. The Fixed-Point Iteration (FPI) algorithm and the Active Set Algorithm (ASA), especially in a one-stage weighted Least Squares (WLS) ([17]) have been found to be the fastest ones, which is substantial in case of vehicle motion control in severe maneuvers. In our studies, we privilege the ASA algorithm as it produces solutions with better accuracy and gives more flexibility and extensibility in programming [17].

Indeed, the control designer has only to reformulate the problem as a WLS problem, and then use the same ASA presented in [17]. Consequently, the first step consists on formulating the multiple objectives control allocation problem as a WLS problem:

$$\min_{\vec{u}_{min} \leq \vec{u} \leq \vec{u}_{max}} \sum_l \gamma_i \left\| \mathbf{W_i} \left(\mathbf{B_i} \vec{u} - \vec{v}_\mathbf{i} \right) \right\|^2 \tag{14}$$

Where:
- l : number of objectives,
- γ_i : weight of the i^{th} objective,
- $\mathbf{W_i}$: non-singular weighting matrices,
- $\vec{v_i}$: desired vector of the i^{th} objective,
- $\mathbf{B_i}$: effectiveness matrix relating the control vector to the desired i^{th} objective.

The second step consists on rewriting the cost function (14) as:

$$\left\| \mathbf{A}\vec{u} - \vec{b} \right\| \tag{15}$$

Where:
- $\mathbf{A} = \begin{pmatrix} \sqrt{\gamma_i}\mathbf{W_i}\mathbf{B_i} \\ . \\ . \end{pmatrix}$,
- $\vec{b} : \begin{pmatrix} \sqrt{\gamma_i}\mathbf{W_i}\vec{v_i} \\ . \\ . \end{pmatrix}$.

At this stage, the same ASA algorithm presented in [17] can be used. This means, if the over-actuation problem

changes, the control designer has to reformulate the problem only to take into account the new number of inputs and outputs. The same ASA algorithm can be used for different combinations, which offers the extensibility feature. More specifically, it is the modularity of the control architecture that gives the possibility of using control allocation algorithms, and with the right algorithm, the control architecture becomes extensible.

4. APPLICATION

The goal of this section is to prove the flexibility and extensibility of the control architecture through several chassis systems combinations. Therefore, we start with only two chassis control systems, and then we add supplementary systems to show that with a minimum effort, the control designer can adapt the architecture to the new configuration.

4.1 Case of ARS-VDC coordination

The first case is the coordination of the ARS system and the braking-based Vehicle Dynamics Control (VDC) system. These systems can already be found in commercial passenger cars such as Renault Talisman. What makes it interesting is the fact that both systems can act on the vehicle's yaw rate. The vehicle is then over-actuated. In this case, the architecture presented in Fig. 5 is adapted to suit this configuration, which results in Fig. 7.

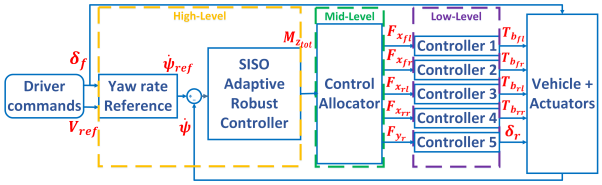

Fig. 7 Upstream control architecture in case of ARS-VDC coordination.

Where δ_f is the front steering angle, V_{ref} and $\dot{\psi}_{ref}$ the speed and yaw rate targets respectively, $F_{x_{ij}}$ the longitudinal tire forces with $i = f$ for front wheels or $i = r$ for rear wheels and $j = l$ for left wheels or $j = r$ for right wheels, F_{y_r} the rear lateral tire force[1], $T_{b_{ij}}$ braking torques and δ_r the rear steering angle. The yaw rate target is generated using the static response of a bicycle model for a fast computation [3]. The front steering angle is then an input of the control strategy generated by the driver himself.

The objective here is to control the yaw rate of the vehicle. Only a SISO high-level controller is needed. This latter generates the total yaw moment $M_{z_{tot}}$ required the move the vehicle's CoG through a Gain-Scheduled $\mathcal{H}_\infty$ controller. The control is then robust to the vehicle's parameters uncertainties as the mass, inertia and so on, and adaptive to the vehicle's speed. The control allocator ensures an optimal distribution of $M_{z_{tot}}$ into the tire forces $F_{x_{ij}}$ and F_{y_r}. The effectiveness matrix in this case is $\mathbf{B} \in \mathbb{R}^{1\times 5}$:

$$\mathbf{B} = \begin{bmatrix} l_f \sin(\delta_f) - \frac{t}{2}\cos(\delta_f) \\ l_f \sin(\delta_f) + \frac{t}{2}\cos(\delta_f) \\ -l_r \sin(\delta_r) - \frac{t}{2}\cos(\delta_r) \\ -l_r \sin(\delta_r) + \frac{t}{2}\cos(\delta_r) \\ -l_r \cos(\delta_r) \end{bmatrix}^{\mathbf{t}} \tag{16}$$

With l_f and l_r are the distance from the vehicle's CoG to the front or the rear axle respectively, t is the vehicle's track and the superscript "t" means the matrix's transpose.

Multiple objectives can be targeted. The reader can refer to [16] for precision and command moderation objectives formalization and for details on how to modify the effectiveness matrix to enable fault-tolerance capabilities between both systems. For energy consumption optimization, the works in [18] and [19] provide good guidelines. Motion feelings objectives are discussed in [10] and [20]. The control designer can select the corresponding objectives to the control specifications, formalize the problem as shown in equation (15), and finally use the ASA algorithm.

To test the effectiveness of the proposed control architecture, we select the same standardized maneuver for all cases. We choose the ISO 3888-1:1999(E) Double Lane-Change. This severe double lane-change maneuver consists in driving a vehicle from its initial lane to another parallel lane at $V = 80km/h$, and returning to the initial lane, without exceeding lane boundaries. We adopt a co-simulation procedure in order to provide realistic results [16]. The control logic is then implemented in Matlab/Simulink®, and a high-fidelity vehicle model with 15 degrees of freedom provided by Simcenter Amesim® is used. Fig. 8 shows the yaw rate tracking performance.

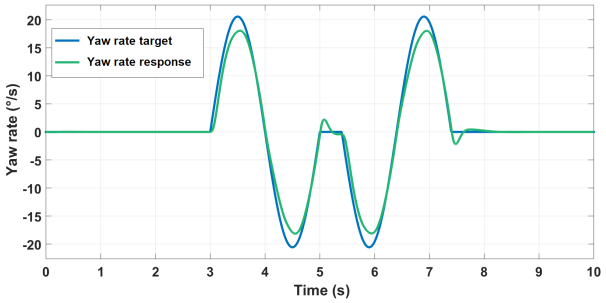

Fig. 8 Yaw rate tracking performance in case of ARS-VDC coordination.

The control strategy provides good yaw rate tracking performance while coordinating both the ARS and the VDC systems as Fig. 9 and 10 show.

4.2 Case of ARS-VDC-TV coordination

To evaluate the extensibility of the proposed control architecture, we add the Torque Vectoring (TV) system to the system. The high-fidelity vehicle model is modified

[1] Since we have only one actuator to generate the same steering angle at the wheels of the same axle: $F_{y_r} = F_{y_{rl}} + F_{y_{rr}}$.

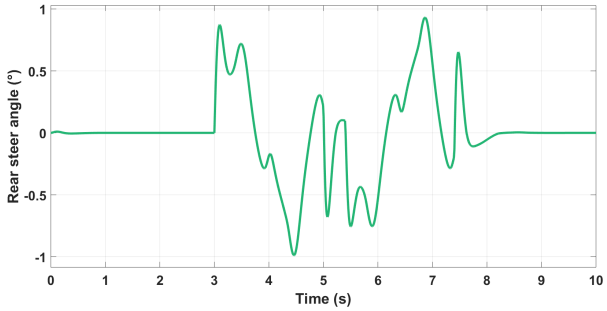

Fig. 9 Rear steering angle in case of ARS-VDC coordination.

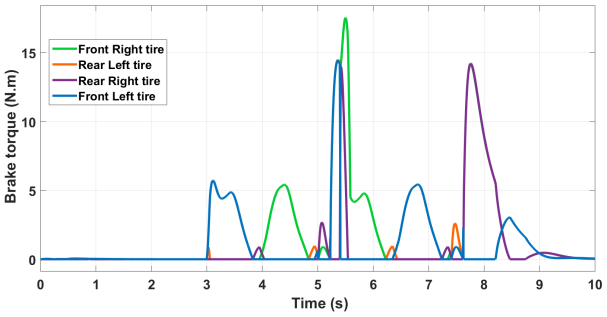

Fig. 10 Braking torques in case of ARS-VDC coordination.

to enable TV capabilities. The Control architecture in adapted as Fig. 11 shows.

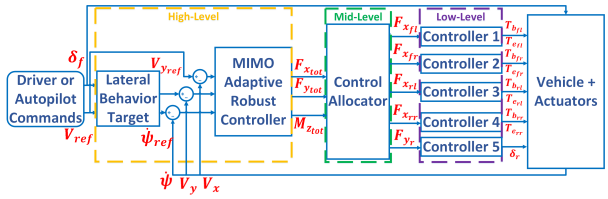

Fig. 11 Upstream control architecture in case of ARS-VDC-TV coordination.

Since the longitudinal speed can be controlled, a MIMO high-level controller should be adopted, hence the use of Gain-Scheduled $\mathcal{H}_\infty$ that can be used in both SISO or MIMO control. The design of this controller in this case can be found in [11]. The low-level controllers should always be updated when changing the actuators. However, at the control allocator level, only the matrix effectiveness $\mathbf{B} \in \mathbb{R}^{3\times 5}$ is updated as follows:

$$\mathbf{B} = \begin{bmatrix} \cos(\delta_f) & \sin(\delta_f) & l_f \sin(\delta_f) - \frac{t}{2}\cos(\delta_f) \\ \cos(\delta_f) & \sin(\delta_f) & l_f \sin(\delta_f) + \frac{t}{2}\cos(\delta_f) \\ \cos(\delta_r) & \sin(\delta_r) & -l_r \sin(\delta_r) - \frac{t}{2}\cos(\delta_r) \\ \cos(\delta_r) & \sin(\delta_r) & -l_r \sin(\delta_r) + \frac{t}{2}\cos(\delta_r) \\ -\sin(\delta_r) & \cos(\delta_r) & -l_r \cos(\delta_r) \end{bmatrix}^{\mathbf{t}} \tag{17}$$

The same procedure can then be adopted by using the ASA algorithm. Care should be however given to the fact that in a MIMO control, the choice of the crossover frequency should be done in a way to decouple the controlled physical variables [11] as Fig. 12 shows.

The rest of the results can be found in [21].

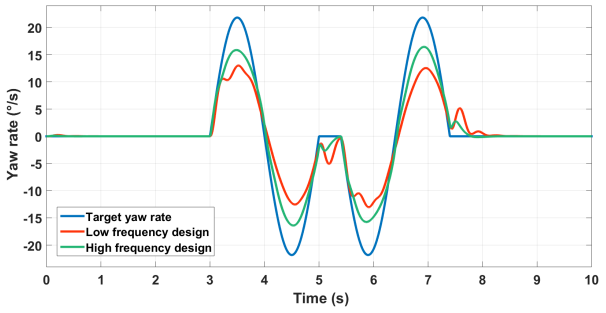

Fig. 12 Yaw rate tracking performance in case of ARS-VDC-TV coordination [11].

4.3 Case of ARS-VDC-TV-SBW coordination

Along the same lines, we add the Steer-By-Wire (SBW) system. This system can be used as an assisting system. Here, we project ourselves into future self-driving cars. The front steering angle should be therefore an output of the control strategy as Fig. 13 shows.

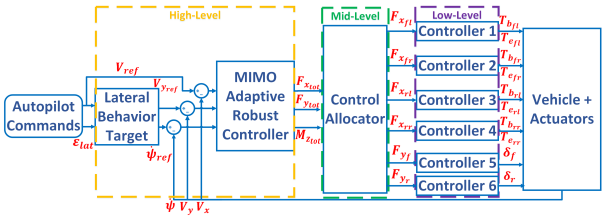

Fig. 13 Upstream control architecture in case of ARS-VDC-TV-SBW coordination.

The same procedure can be adopted, keeping the same high-level controller and adding an additional low-level controller for front steering. An additional column is then added in the effectiveness matrix $\mathbf{B} \in \mathbb{R}^{3\times 6}$:

$$\mathbf{B} = \begin{bmatrix} \cos(\delta_f) & \sin(\delta_f) & l_f \sin(\delta_f) - \frac{t}{2}\cos(\delta_f) \\ \cos(\delta_f) & \sin(\delta_f) & l_f \sin(\delta_f) + \frac{t}{2}\cos(\delta_f) \\ \cos(\delta_r) & \sin(\delta_r) & -l_r \sin(\delta_r) - \frac{t}{2}\cos(\delta_r) \\ \cos(\delta_r) & \sin(\delta_r) & -l_r \sin(\delta_r) + \frac{t}{2}\cos(\delta_r) \\ -\sin(\delta_f) & \cos(\delta_f) & l_f \cos(\delta_f) \\ -\sin(\delta_r) & \cos(\delta_r) & -l_r \cos(\delta_r) \end{bmatrix}^{\mathbf{t}} \tag{18}$$

The same ASA algorithm can then be used. The total required efforts are then optimally distributed into the corresponding systems. The weighting matrices $\mathbf{W_i}$ can be tuned to favor one system over another in a dynamic way according to the driving mode [20].

5. CONCLUSION

In this paper, we presented an extensible motion control architecture for over-actuated vehicles. The extensibility of the architecture has been demonstrated through three examples where the over-actuation increases from an example to another. Unlike the downstream coordination approach where the control architecture should be redesigned for every configuration, the presented upstream coordination approach can be easily adapted thanks to the

optimal control allocation algorithms. Since the systems required for future vehicles development are uncertain, any control architecture adopted should be flexible and extensible. In this way, if a new system is required for the vehicles to be homologated, car manufacturers can adapt their control architectures in an agile way. This type of architecture should be therefore standardized, and the necessary benchmarks should be provided in order to accelerate the development of future vehicles.

Before stepping into more elaborated architectures, experiments should be carried for different systems configurations. Our ongoing experiments concern the first configuration exposed in this paper. Prototypes implementing the systems required to perform the two other conflict are in preparation. Once all the experiments has been successfully completed, we will start thinking about a three-dimensional control thanks to adaptive suspensions.

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