Current and Future Architectures for Integrated Vehicle Dynamics Control

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***Abstract*—Today's vehicles use coordination strategies downstream their subsystems to avoid conflicts. This is possible as far as a very limited number of integrated subsystems is concerned. This paper discusses the potential of this approach and proposes an eventual substitute. A brief review is given to speculate about the architectures' compatibility with respect to control problems. It appears that autonomous vehicles require additional subsystems for safety. Therefore, an upstream approach is no longer appropriate to handle vehicle's subsystems interactions.**

***Index Terms*—Control Architectures, Over-Actuated Systems, Coordination, Control Allocation, Vehicle Dynamics.**

I. Introduction

In the past years, a large interest has been given to autonomous vehicles. Automation promises safer and smarter vehicles. In this context, several researches has been carried out in robotic vision, decision algorithms, big data management, and others. As soon as the vehicle is "aware" of its environment and a trajectory is planned, the chassis system should be actuated in a way to ensure reference[1] tracking with the desired dynamics. To do so, the vehicle has more than one subsystem per control axe [1]. This redundancy aims to ensure safety and improve other performances as handling and manoeuvrability. Therefore, vehicle's subsystems interact and conflicts could occur. To avoid this, automotive engineers use rule-based strategies to coordinate the different subsystems [2]. This requires an expert knowledge on vehicle dynamics to predict the influence of each actuators over an another, and then on the overall vehicle. For example, the work in [3] used Active Differential (AD), Electronic Stability Control (ESC), and Torque Vectoring (TV) to improve the vehicle lateral performances. A simple method based on prioritizing one system over another has been used. A more complex method based on *Artificial Neural Network* had been adopted in [4]. This method consists of simple averaging or via a non-linear interpolation function weights. These functions could be chosen to ensure smooth transitions between coordination modes. A larger review could be found in [5].

However, as broad as an expert knowledge could be, it cannot foresee all the possible situations. Thus, optimization is not explicitly formalized. We cannot prove that the downstream coordination is the best solution. Consequently, a single objective is aimed most of the time [6], while secondary objectives could be achieved as far as the vehicle is over-actuated. Control objectives should then be formalized to enable optimization. This can only be ensured if we act differently on the subsystems references. The coordination should then be upstream the subsystems. Because of the over-actuation, the system of equations to be solved has more unknowns than equations. Moreover, each actuator has its own limits. Command vectors are then constrained. This is called *the control allocation problem* [7]. This problematic has already been encountered in flight-control systems. While ganging has been used in many of these systems, control allocation methods have become necessary regarding advanced aircraft with more numerous actuators [7].

In the automotive sector, optimization methods are considered too complex and too time-consuming to be implemented in a vehicle [6]. However, dramatic increases in computing speed and algorithms efficiency have been elaborated. In this paper, we discuss the capacity of the upstream approach to handle more complex coordination difficulties with respect to the downstream approach. Architecture models based on the upstream approach offer the possibility to incorporate optimization-based control allocation algorithms. Better solutions are provided, secondary objectives are ensured, and performance is then enhanced. Moreover, fault-tolerance is naturally managed and reconfiguration methods are more efficient [8]. These characteristics constitute a major aspect for autonomous vehicles safety.

We start by presenting the downstream approach in Section II. The upstream approach is then presented in Section III. Our work in progress is described in Section IV. Finally, conclusions are drawn and future works are outlined (see Section V).

II. Downstream Coordination Architecture

Here, additional layer is added to manage the subsystems influence on the overall system. Coordination is ensured downstream the subsystems. In [2], this is referred to a "bottom-up approach". In fact, this is about taking two or more well-understood controllers and apply them to the vehicle. As a multi-variable system is concerned, each controller could deteriorate the performance of the other. Automotive engineers

[1] Here, it is the trajectory planned.

use then their expertise to foresee these interactions. This enables the development of rule-based strategies to mitigate the subsystems conflicts. Fig. 1 illustrates this architecture in a more general scenario, when a future vehicle could integrate a 4-Wheel Drive (4WD), Torque Vectoring (TV), Electric Power-Assisted Steering (EPAS), 4-Wheel Steering (4WS), Electronic Stability Program (ESP), and Adaptive Suspension (AS) systems.

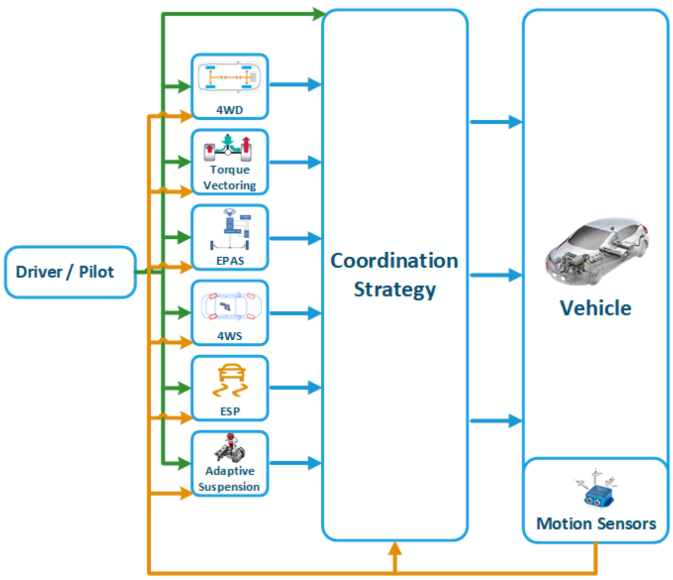

Fig. 1. Structure of the downstream coordination approach [5].

Four coordinator types have been distinguished in [9]: *Pure Subsumption* (Fig. 2 - (A)), *Largest Modulus Activation* (Fig. 2 - (B)), *Artificial Neural Network* (Fig. 2 - (C)), and *Fuzzy Logic Control* (Fig. 2 - (D)).

Regarding the pure subsumption approach, the highest level non-zero command takes precedence over of the other sub-commands [3]. In the largest modulus activation, several high level commands are considered, and the one with the highest modulus takes precedence over the rest [9]. The Artificial Neural Network consists of simple averaging or via a non-linear interpolation function weights [4]. The Fuzzy Logic uses "easily understood" rule-based coordination functions, where the highest level predominates and smooth transitions are ensured [10].

Each of these coordinators requires several studies in advance to predict the eventual conflicts. Different scenarios should be imagined to find the best solution. Rule-based strategies are then developed to mitigate the conflicts issued from the scenarios imagined. For single-objective control problems, one could develop a global overview of the possible problems that could occur. Regarding multiple-objective control problems, rules are less obvious to develop. An optimization problem with multiple cost functions and constraints should be formalized. Interactions at the vehicle level should be taken account of. A global multi-variable controller is then developed. Command requests are then distributed in an optimum manner to the different standalone controllers. In other words, the coordination should be made upstream the subsystems.

III. Upstream Coordination Architecture

Here, the coordination layer is located upstream the standalone subsystems. The command requests are distributed in a way to avoid conflicts before their occurrence. Relations between control commands and performance outputs are mathematically described to find an optimal solution or a sub-optimal one. In [2], this is referred to as a "top-down" approach, as a general supervisor is synthesized to distribute the commands to the different subsystems. Fig. 3 illustrates this concept.

Three structures have been distinguished in [5]: *centralized control*, *supervisory control*, and *multi-layer architecture*. Next, each structure is described.

A. Centralized Control

A central global controller is synthesized to control the overall vehicle. As multiple objective are concerned, the controller must be multi-variable. Its outputs are then transmitted to the different subsystems as illustrated in Fig. 4.

However, if one want to add an additional subsystem, the whole control synthesis should be done once again. This architecture is not flexible. As long as autonomous vehicle control architecture is not frozen, flexibility is necessary. A distributed method is then more attractive.

B. Supervisory Control

In order to ensure flexibility, controllers are separated and a supervisory layer is added (see Fig. 5).

This has additional advantages:

- **Fault-tolerance**: it ensures a minimum of operations safety even if the high-level controller fails,
- **Extensibility**: it can be evolved to a multi-layer hierarchical structure to add more functionalities,
- **Modularity**: it allows manufacturers and suppliers develop independently complementary control algorithms.

As an example, in [11], the authors used three main layers with two levels of abstraction: *Decision Layer*, *Control Layer*, and *Physical Layer*.

C. The Multi-layer architecture

As a result of extensibility, the supervisory control can be generalized to a multi-layer architecture. Each function of the control process is separated. As multi-variable systems are concerned, functions with the same nature are grouped into different layers:

- Layer 1 : Generation of vehicle motion reference,
- Layer 2 : Decision on the control mode,
- Layer 3 : Calculation of the generalized forces and moments through the high-level controllers,
- Layer 4 : Distribution of the commands to the available actuators through control allocation logic,
- Layer 5 : Control of stand-alone subsystems,
- Layer 6 : Execution of the various operations through smart actuators.

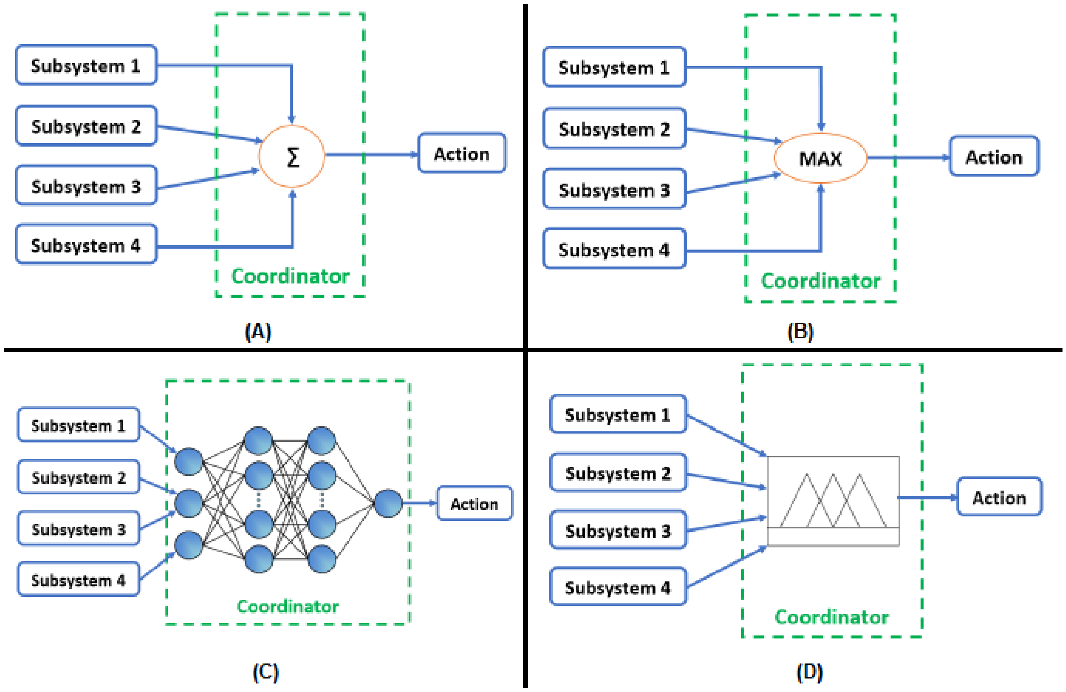

Fig. 2. Coordinator types of the downstream coordination approach [5].

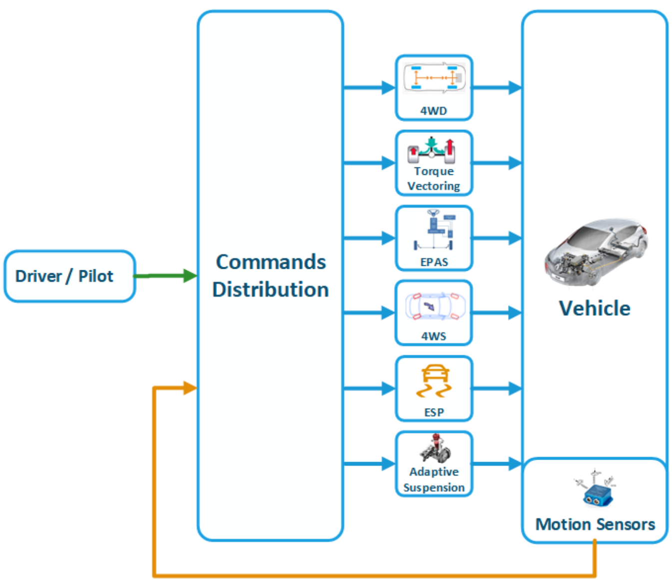

Fig. 3. Structure of the upstream coordination approach [5].

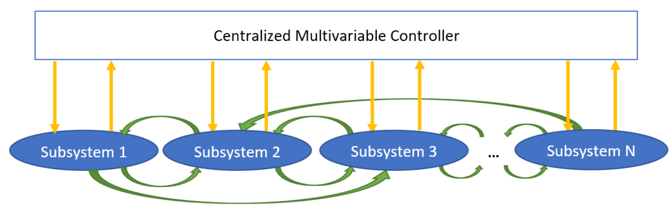

Fig. 4. Centralized control structure [5].

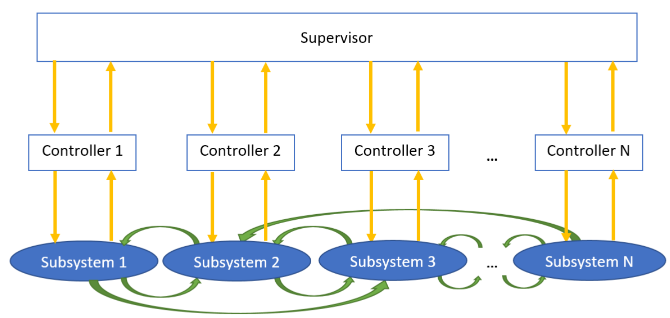

Fig. 5. Supervisory control structure [5].

D. Discussion

Upstream architecture could be used for single-objective control problems [12]. But as long as optimization methods are considered too complex, their implementation should be justified, which is not the case for single-objective control problems.

In the past years, control allocation techniques became more preponderant to face over-actuation problems [1],[13]. For example the authors of [13] used an Integrated Chassis Control (ICC) strategy to improve cornering performance in high speed by combining the ESC, the 4-Wheel Drive (4WD) and the Active Roll Control (ARC) systems. The control architecture is composed of thee parts: a supervisory controller that determines the target vehicle motions, the upper-level controller that calculates the target forces and moment and the lower-level controller that optimally distributes the actuator inputs. However, as pointed out by [6], all the results are made by simulation only. There is a clear lack of experimental results and benchmark requirements that allow comparison between the different methods.

IV. Current Researches

Our purpose is to prove that the upstream coordination architecture will become necessary to handle interactions of the vehicle's subsystems. This could motivate the different stakeholders to start thinking on the standardization of an integrated vehicle dynamics control architecture that suits best autonomous vehicles. Therefore, both architectures should be developed to enable their comparison. This requires different modelling approaches and different control synthesis techniques. Nevertheless, we can allow ourselves to provide a qualitative comparison to explain our motivations.

A. Qualitative Comparison

Three characteristics are chosen that interest most a car manufacturer: *complexity*, *cost*, and *potential*.

1) Complexity: This is the main drawback of the upstream architecture. While the downstream approach uses understood rule-based strategies to manage subsystems interactions, the upstream approach rely on first a MIMO[2] controlled based on a non-linear vehicle model, and then on optimization techniques that should find a solution in real-time operations. But again, the more numerous and complex interactions become, the more the upstream approach is pertinent.

2) Cost: This also does not favour the upstream approach. This latter requires additional high-level controller(s) and may even need additional sensors or estimators [14]. In contrast, the downstream approach requires only a coordination strategy between the standalone subsystems and the vehicle. This is why car manufacturers use this approach until these days.

3) Potential: In the downstream approach, automotive engineers use their expertise to design real-life scenarios. These scenarios help to study the eventual interactions that could occur between the subsystems. Rule-based strategies are then developed to manage these interactions. As engineers cannot foresee all the possible situations, errors could be generated in some cases. The more interactions become numerous and complex, the more errors are probable to occur. In this way, the upstream approach would become necessary. This approach depicts mathematically the different interactions and quantifies the dynamic couplings. Only this way one can hope to find an optimal solution, or at least a sub-optimal one.

B. Motivation

As we have mentioned, the main drawbacks of the upstream approach that have hindered its development are complexity and cost. However, today's Electronic Control Units (ECUs) have became faster, less cumbersome, and cheaper. Moreover, control allocation methods have been reviewed in [7], and tested in a Hardware-In-the-Loop (HIL) procedure in [14]. These methods appear to be more suitable for over-actuated systems. A simple Linear Programming (LP) or Quadratic Programming (QP) could be executed in a few milliseconds with a limited number of iterations.

These new opportunities could finally get rid of the main drawbacks of the upstream approach. More objectives could be handled and more performances could be achieved. Autonomous vehicles could then be controlled in a larger dynamic range. In this context, we aim to develop both architectures to enable their effective comparison and hope to convince car manufacturers to switch to the upstream approach.

Next, a starting working example is described. This example represents a starting point of our plan.

C. A Working Example

We choose to start with only two subsystems. These subsystems should respect the following criteria:

- They should interact often to evaluate the potential of coordination approaches,
- They should be able to influence more than one control axe to be able to study a multi-objective problem,
- They should be mature enough to be able to test them in a real vehicle.

For these reasons, we choose the 4-Wheel Steering (4WS) and the brake-based Vehicle Dynamics Control (VDC)[3] systems. Several vehicles are equipped by these subsystems in the same time[4]. While the 4WS system uses the rear steering to generate a steering angle, the VDC uses the differential braking[5] to generate a yaw moment. Both systems influence the vehicle's yaw rate. Only VDC influence the longitudinal acceleration. As both systems are interacting, we can expect from the 4WS to influence indirectly the longitudinal acceleration.

As each architecture uses different control methods, the problem remaining is which control method to choose in each architecture to enable reliable comparison of both approaches. For simplicity, we can start with basic methods of each structure. Pure subsumption in a downstream approach can be compared to a centralized control structure in an upstream approach.

In the downstream approach, a reduced vehicle model could be considered to synthesize standalone controllers. A pure subsumption strategy is then added to handle interactions. In contrast, as long as a centralized is concerned, a more complete vehicle model should be considered. Therefore, a MIMO controller have to be synthesized taking account of the eventual interactions. Fig. 6 summarizes our ongoing work.

D. Challenges

1) Reliable Comparison: As we have mentioned, it is hard to be fair to each of the architectures when choosing a control technique. Several techniques exist in both approaches. While some techniques could be used in both approaches, others can only be applied in a specific architecture. We are

[2]Multiple Inputs Multiple Outputs

[3]It is just another appellation of the ESP used by Renault.

[4]Renault Talisman for example.

[5]Brake at each wheel independently.

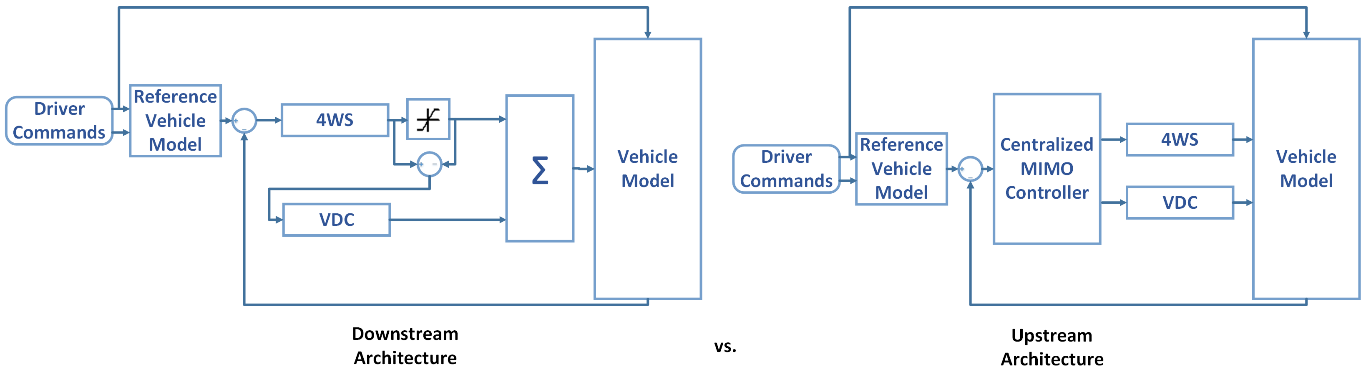

Fig. 6. Ongoing work: comparison of downstream and upstream architectures.

currently testing the techniques described in Fig. 6. One can also test Fuzzy logic in both approaches as this technique has been applied with the different architectures ([10] for the downstream architecture and [15] for the upstream one). And finally, we can also choose some specific and strong techniques that could only be used in one architecture or another to justify the architecture, e.g. Control Allocation for the upstream architecture.

2) Real-Time Implementation: Several architectures were only validated through simulations [6]. As coordination strategies are located in an inner loop, computations must be fast (around 100 Hz according to [7]). This puts a real challenge to automotive engineers and limits their choices. In this context, Linear Programming could be the key. In [7] for example, several control allocation techniques were transformed from a quadratic formulation to a linear one. Optimization is still ensured through few hypothesis, and computation is mush more faster.

3) Multi-Sense: As different subsystems with different dynamics are integrated, different motion feelings could be generated. Command requests should be distributed in a way to favour one behaviour over another. Driving modes can be taken account of in the mean of weighted functions. However, drivers do not have the same definition of comfort or excitement. Weighted functions have to be adaptable. One could think about evolutionary algorithms to enable a vehicle to adapt to its driver.

V. Conclusion and Future Works

In this paper, two major architectures for integrated vehicle dynamics control have been distinguished. Control techniques of each of these architectures have been differentiated. To enable their reliable comparison, a working example has been proposed and its related challenges exposed. This is an ongoing work that we hope will help us to get more evidence to convince the different stakeholders to favour one architecture over another.

To do this, we will start by proposing different vehicle models. One to interpret driver commands (reference vehicle model), one for downstream coordination synthesis, and another one for a centralized MIMO controller synthesis. A new tire model will also be proposed. This model should take account of the dynamic couplings and friction limits to develop realistic coordination strategies. Then using the different techniques presented in this paper, we expect to offer a consistent architecture model for autonomous vehicles.

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