# Advanced real-time multi-domain optimization controller approach for multi-motor electric vehicles using automotive-suitable methods and heterogeneous embedded platforms

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**Summary**

The presented work reflects the key aspects of the research related to the current work on a PhD Thesis. It is located in a context involving multiple domains in the fields of automotive technology, electric motors, control methods, embedded systems, software development and vehicle dynamics. Several hot topics related to next-generation technologies with remarkable research and innovation potential have been identified. These topics, which present notable interdependencies and also certain restrictions, are discussed in the upcoming subsections. The article also provides an outline of relevant points of the control problem of a multi-motor electric vehicle, and the corresponding multi-domain controller approach that has been taken. This includes keywords such as torque-vectoring, heterogeneous embedded platforms, model-based development (MBD) and machine learning algorithms.

## 1 Introduction and technological context

Two fundamental topics which constitute a complex scenario in the automotive context are the rise of electrified multi-motor vehicles and the new generation of heterogeneous embedded platforms. With the introduction of individual motors for different wheels, besides energy optimization, new degrees of freedom are provided for vehicle dynamics enhancements, as electric powertrains offer greater controllability regarding response time and precision when compared to powertrains with combustion engines. The increase of variable count and complexity, together with reduced time constants, will inevitably demand notable computational capacity. This capacity is provided by upcoming automotive-suitable heterogeneous embedded platforms. Furthermore, such platforms and their intrinsic parallelism are very suitable for the application of advanced control techniques [1].

Two additional considerations need to be contemplated in this context. The first are new regulations regarding functional safety for critical systems in automotive applications, such as the ISO-26262. These inevitably will imply certain limitations and additional effort in automotive system development. The second is that, given the cited regulations and the steadily growing complexity of automotive systems, the need for MBD is strengthened [1].

Therefore the underlying concept in this research work is to not exclusively focus on algorithms themselves, but to extend the addressed topics to cover the bigger picture of the automobile. The main objective is to demonstrate the potential, suitability and benefits of applying certain technologies which go beyond the state of the art for automotive applications, especially for safety critical applications like the powertrain. And this will be done targeting a remarkably complex multi-objective multi-domain control and optimization challenge.

## 2 The Multi-Domain Challenge of Multi-Motor Powertrains

The proliferation of vehicles with electric motors has enabled the appearance of different types and topologies of multi-motor vehicles, either purely electric or hybrid. This is the first hot topic related to this work. As already mentioned the presence of different motors notably increases the complexity -and possibilities- from the powertrain control point of view, as the degrees of freedom grow and the controllability of the electric motors enables faster dynamics and better precision [2].

For hybrid vehicles, a relevant control problem is to satisfy the driver's torque demand with high efficiency while handling the operating point of each of the engines (power, efficiency, etc.) in coordination with the energy management strategies. Nevertheless, this work will focus on the implications of a control problem addressing the faster time constants and their implications on a different domain: vehicle dynamics. Therefore it addresses purely electric multi-motor vehicles which offer the opportunity to independently control different axis or even wheels, similarly to certain vehicles which apply mechanical measures. While in both cases the dynamic behavior can be notably influenced, the ability to apply independent torque values to the wheels on each side of a vehicle -which is known as torque vectoring, a further hot topic- and to do so in a precise and fast manner driven by the characteristics of electric motors, opens remarkable opportunities to actively influence the dynamic behavior of the vehicle in curves and other maneuvers. Applying more torque to the curve exterior wheel increases yaw raw and exploits its transient grip [1, 3].

Besides the vehicle's dynamic behavior, considering again energy efficiency, for the case of purely electric multi-motor vehicles the differences among the multiple motors regarding individual electric efficiency and operating points are not so obvious as for the case of hybrid powertrains. Nevertheless it is still an aspect to be considered, especially for the case of four wheel drive setups, where major margin for torque distribution -among axes- can be exploited with minor impact on the dynamics [1, 3].

Another aspect to be considered in both cases are thermal constraints. Having several motors -each of them composed by different subcomponents which handle high power - means that depending on the operating conditions, subcomponents will heat up differently. This can be influenced by changing the torque distribution as well as the low level control strategies of the power electronics, aiming to avoid the overheating of certain components which could eventually force to apply power limitations (derating) or even cause excessive stress to some components [1, 2].

## 3 Proposed Controller Development and Implementation Approach

The engineering work presented in this article basically consists in implementing advanced real-time multi-domain algorithms on heterogeneous embedded platforms for multi-electric-motor powertrain control using MBD methods. Several key points are highlighted in the space available for the following subsections.

### 3.1 Controller conception

The developed controller will apply torque vectoring techniques and include a multi-domain optimization algorithm. The main objectives to optimize are those described in the previous section: dynamic vehicle handling, energy efficiency and thermal constraints. The application of machine-learning is evaluated for virtual sensors -for difficult to measure magnitudes- and for prediction of upcoming values. For instance, the controller could use the vehicle's inertial sensors and the wheel rotation speeds to estimate the grip available on each wheel and avoid traction and stability issues. So it will govern over the motor control functions, but it will be conceived to, if necessary, be preempted by the vehicle's conventional stability control functions [3].

### 3.2 Embedded Platform

As complexity, control variables and sophistication of control algorithms increase, the computational effort associated to the control functions also grows. Furthermore, driven by downsizing and efficiency, new electric motors tend towards higher rotational speeds and increased pole-pair count. This makes their current control cycles get shorter, putting a higher burden on the power electronics control, typically a microcontroller. Furthermore, if, aiming to reduce the electronic control unit (ECU) count in a vehicle, control functions are centralized, integrating the algorithms for several motors into a single ECU, the computational demand is further increased [4].

Recently released and upcoming embedded platforms will provide not only vast computing performance -at least one order of magnitude above current automotive microcontrollers- but will also cost points and integrity mechanisms that make them suitable for automotive applications. This is another hot topic. The clearest example is Xilinx's Zynq product range. These heterogeneous platforms combine multi-core devices with FPGA hardware in a single device with high internal bandwidth. Furthermore, the recent Zynq Ultrascale+ devices offer lockstep cores -besides other integrity and safety features- in addition to quad-core processor and a GPU unit [5].

### 3.3 Development methodology and setup

The development activities in this work rely on a MBD process. It includes a high-fidelity multibody vehicle model, hardware-in-the-loop setups (including virtual hardware), automated testing, code-generation and automatic hardware synthesis (Fig. 1). These methodologies are a further hot topic. They not only enable an agile and efficient development workflow with good requirement traceability, but also provide sufficient abstraction to handle the complexity of the implementation aspects.

The target vehicle is the demonstrator of the Eunice project: a motor-in-wheel (MiW) vehicle with two motors, each on one wheel of the front axis [1, 6].

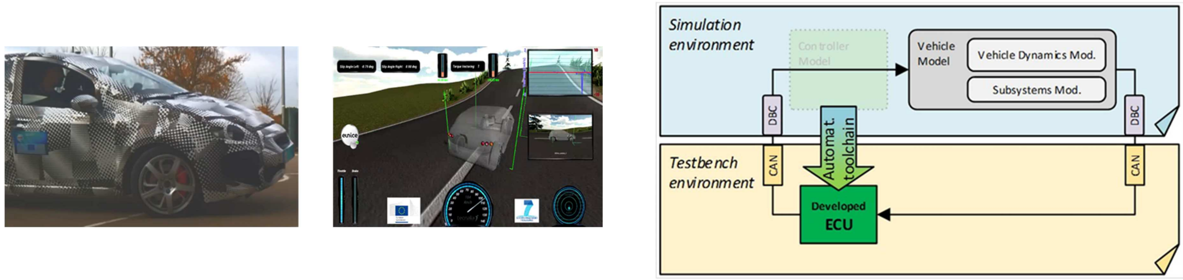


Fig. 1: Eunice MiW vehicle; Tecnalia Dynacar simulator; MBD methodology [1, 6]

A last hot topic, also related to MBD, cannot be covered in the scope of this article: safety considerations. While some of the innovative solutions proposed in this work would typically arise certain concerns, the control functions, architecture, platforms and methodology followed greatly support to obtain a reliable and safe design [1].

## 4 Preliminary Results, Conclusions and Future Work

This article has highlighted a series of hot topics which are closely related. Multi-motor vehicles open new control opportunities but also involve higher complexity and computational costs which can be satisfied with modern heterogeneous embedded platforms. The complexity of both the previous should be covered by applying MBD methods, which furthermore are important to tackle new functional safety regulations.

The preliminary results of the present work have been remarkably satisfactory until the date. The MiW demonstrator has shown a clearly noticeable handling improvement when applying torque-vectoring control. The multibody vehicle dynamics simulator has proven a high fidelity and is therefore a valuable resource for efficiently developing and training complex algorithms. The machine learning algorithms are showing their capacity to estimate challenging non-linear magnitudes. Finally, the heterogeneous embedded platforms are demonstrating their notable potential for real-time execution of machine-learning algorithms.

A foreseen impact is providing a path for innovative technical solutions, with a relevant contribution by demonstrating the real-world applicability of the discussed technologies. Efficiency and reliability of multi-motor vehicles will be enhanced while providing enhanced cornering speeds and stability. Furthermore, the methodology and implementation approaches can be applied to diverse powertrain topologies and offer valuable effort and cost savings. It should also serve as a step towards ECU consolidation: merging the control of several subsystems into a single ECU.

Future work will cover several of the topics which could not be yet extensively discussed in this article nor in previous publications. This will mainly an exhaustive analysis involving machine learning for the vehicle dynamics of a four wheel drive car and a more careful  discussion on functional safety and integrity topics.

## 5 Acknowledgments

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