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Driving Safety and Comfort Enhancements through Efficient Usage of E-Powertrain Functions

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Abstract

The paper shows how different possibilities of electrified propulsion can bring more benefit into the vehicle regarding driving comfort, driving safety and driving pleasure without additional components. Complex control functionalities of electric motors in the propulsion system and their effects on the vehicle behavior are explained. It is shown, how advanced control functions can influence steering behavior, movements in the vehicle structure and the response behavior of component operation in a positive way. The shown robust technology with the cross-linked functions is versatile with different potentials for diverse drivetrain configurations. The paper demonstrates how to let the physical propulsion system untouched and takes into account the interaction of all components of the entire vehicle. First tests, simulation and validation results are presented.

This increases safety and comfort aspects but also more fun to drive and generate ‘the electric smile’ on the customers face.

Keywords: hybrid, electric, braking, recuperation, oscillation, torque, traction control, safety, comfort, performance

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1 Introduction

In modern vehicles most powertrains are equipped with electric components to reduce fuel consumption and emissions. Other advantages of electric propulsion get lost because of higher costs. The market does not accept higher prices for just the same characteristics. However, there is a demand for added values.

In order to open up this potential, MAGNA STEYR developed additional functions for vehicle improvements without additional expenses for supplementary components. The knowledge of the complexity of the entire vehicle behavior is one of the main issues within the described technology in this article.

The paper is divided into three main parts which explain the relevant functions for driving comfort, safety and pleasure:

- component backlash compensation and oscillation damping on the electric powertrain
- vehicle dynamics functions for braking and steering by using the electric components in the powertrain
- body motion control concepts by using the electrified vehicle architecture.

In the following chapter after that an hybrid vehicle demonstrator for the implementation and tests of these functions is discussed and described in detail. In the last section of the paper, the issues concerning the complete vehicle architecture integration are presented and evaluated.

2 Electric Powertrain Oscillation Damping

While regenerating energy during deceleration maneuvers, both driving comfort and vehicle stability must be preserved. Due to drive shaft elasticities and backlash within the differential gear, unwanted oscillations occur during operation. This behavior results in vehicle jerk and high mechanical stress. Therefore, the powertrain has to be controlled in such a way that oscillations can be sufficiently suppressed best at the root cause.

For that purpose the drive shaft torque has to be known. Due to high costs of torque sensors, techniques estimating the drive shaft torque with sufficient accuracy and reliability are preferred.

2.1 Modeling and Control Concept

A mathematical model of the dynamics of an electrically driven axle was derived which also incorporates the backlash. The wheels are combined such that the powertrain can be modeled as a two-mass system. With help of variable structure theory, see e.g. [1], different state observer concepts were developed calculating the shaft torque although unknown external load forces, like road gradients acting on the vehicle [2], [3]. In general, the motor and load speeds and the motor currents are measured. By knowledge of the stiffness k_s of the shafts the shaft torque T_s can be calculated with help of the estimated shaft torsion angle θ by $T_s = k_s\theta$. The control concept is based on the calculated shaft torsion angle and it tracks a desired reference torque. In addition to that the control eliminates the negative effects of backlash, such as noise and torque overshoots at abrupt load changes.

2.2 Implementation Aspects

The load speed signal is generated by the mean value of the wheel speed sensors. Due to the low resolution, automotive wheel sensors cannot measure the speed accurately at low speed such that they are useless for state estimation.

Therefore the controller and observer concept can focus on the measurement of the motor angular speed signal only [2]. In general the algorithms have to be implemented in the motor inverter where the control routines run in a high frequency task. Therefore, methods of the variable structure theory are advantageous because of their robustness with respect to certain class of uncertainties and their low computational effort.

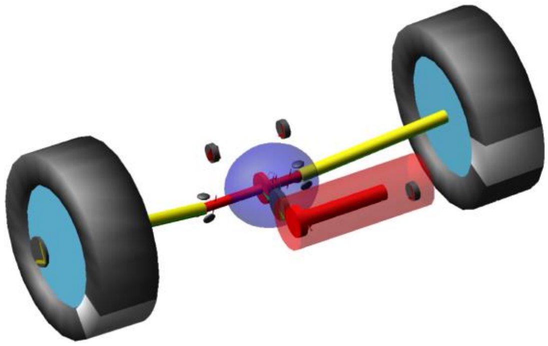

Figure 1: Multi body system (MBS) model of an electrically driven rear axle of a hybrid vehicle.

2.3 Concept Evaluation

For evaluation of the concept an electrically driven rear axle with a layshaft design was chosen. Figure 1 shows the Adams/Car™ multi body system (MBS) model of that vehicle part. The three small flat cylinders beside the (red colored) motor and the differential gear show the mountings at the vehicle body.

The parameterization of the MBS model mainly results from CAD data. The maximum torque of the electric motor is defined with 72 Nm. Since the motor and the differential gear are not centered, the stiffness for the left and right half shaft are different. The vehicle mass is considered in the wheel inertias, as the MBS model consists of the axle only. Table 1 shows the parameters of the Adams/Car™ powertrain model.

Table 1: Parameters of the electrically driven rear axle

Parameter	Value
Stiffness left wheel shaft	80 Nm/°
Stiffness right wheel shaft	60 Nm/°
Vehicle mass	860 kg
Gear ratio	12
Backlash width	8°
Rotor inertia	0.0047 kgm^2
Differential gear inertia	0.011 kgm^2
Wheel inertia	0.9 kgm^2
Wheel inertia (including vehicle mass)	33 kgm^2

The control concept was evaluated in a co-simulation with Matlab®/Simulink® and Adams/Car™. A reference torque signal of 300 Nm within 0.5 s was generated.

Figure 2 shows the torque of the left half shaft in both the controlled and uncontrolled case. Although the reference torque is small, considerable oscillations occur in the uncontrolled case. With activated control the real shaft torque tracks the reference. Figure 2 shows also the vertical force at the rear motor mounting. It can be seen that the control also reduces considerably the force oscillations such that the mechanical parts are less stressed.

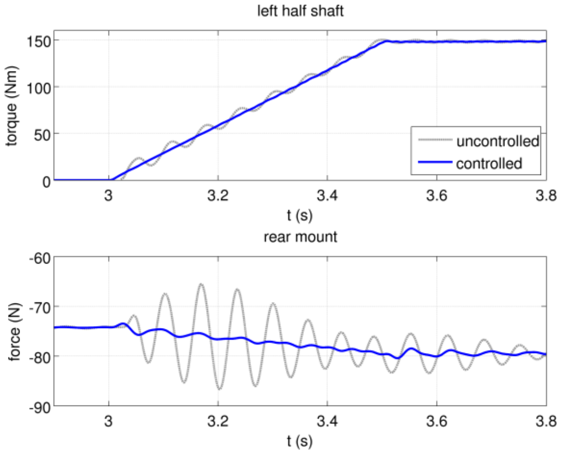

Figure 2: Comparison between uncontrolled and controlled torque of the rear axles left half shaft and the vertical force of the electric motor rear mounting.

This approach is applicable to all load cycle situations in the e-powertrain like driveaway and hybrid mode changes.

3 Vehicle Dynamics

In this section another functionality for the electrified powertrain is described: Longitudinal dynamics and lateral dynamics can be influenced by applying electric traction motors.

Based on the hybrid concept as described in chapter 5, a strategy for vehicle motion control is developed.

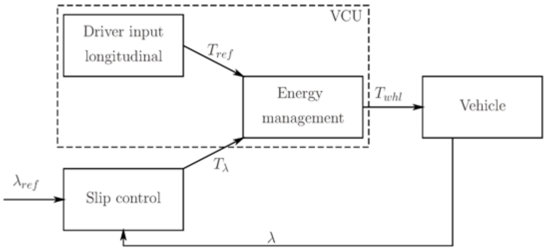

Figure 3: Structure of the longitudinal dynamic control strategy

The vehicle dynamics is affected by means of an electric traction motor installed on the rear axle. An energy management system is required for the operation of the hybrid vehicle (see Figure 3).

Based on different system parameters, as e.g. the state of charge of the battery and the driver drive/brake pedal inputs, a reference torque T_{ref} is calculated. When the driver steps on the brake pedal, a brake torque and a recuperation torque are set up. Both torques are computed by the energy management with the objective to maximize the energy efficiency. This leads to a wheel torque T_{whl}.

In the case of a too high wheel torque e.g. when driving on low friction road conditions, the resulting wheel slip λ will exceed a threshold λ_{ref}. This causes a loss of traction force and potentially results in an unstable driving situation. To keep the slip λ within reasonable bounds, the vehicle control unit (VCU) is extended by a slip controller, shown in Figure 3. A virtual slip is determined based on the measurement of vehicle speed and wheel speed. If this virtual slip exceeds the threshold λ_{ref}, the slip controller calculates a torque T_λ which counteracts T_{ref}. It is now the task of the energy management to adapt T_{whl} according to T_λ.

The wheel slip controller development is based on the detailed insight into the physical behavior of the entire wheel assembly. For the description of the wheel dynamics, the statements from [4] are used. It is assumed that the rear axle propulsion unit is equipped with an advanced recuperation system applying a wheel slip controller.

In Figure 4, an ABS braking maneuver starting from 70 km/h is depicted. On the front axle (FA) a conventional two-point control strategy is used to adapt the brake pressure. On the rear axle (RA) the braking torque must be limited according to the slip controller instead of only using the hydraulic braking system. The recuperation is continued, where the wheel torque T_{RA} is adjusted according to T_λ. Due to the slip control the desired set point λ_{ref} can be achieved perfectly.

As the wheel motion can be influenced by the traction motor torque, a positive influence on the vehicle motion is possible as well.

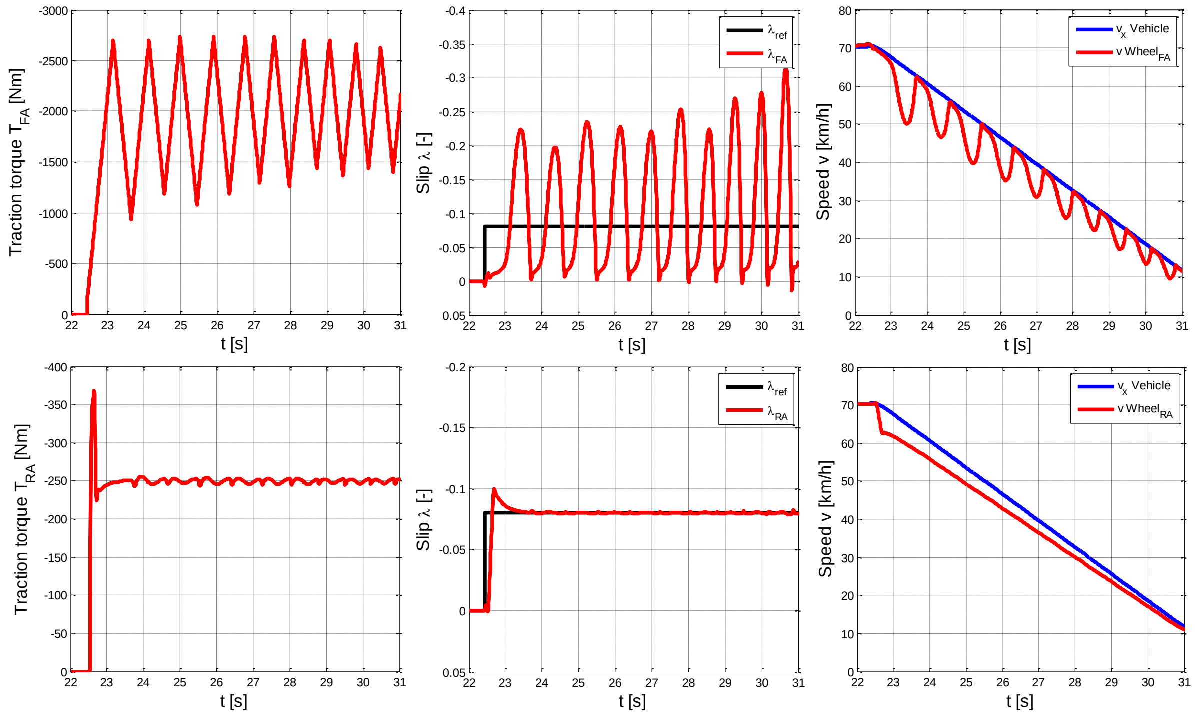

Figure 4: ABS braking maneuver starting from 70 km/h. Comparison of the hydraulic braking system on the front axle (FA, above) and advanced recuperation with wheel slip control on the rear axle (RA, below)

It is now the aim to perform vehicle yaw motion control (vehicle dynamics controller, VDC) with the help of an electric motor. To achieve this, the VCU is further extended by a lateral dynamics controller and a component monitoring system (see Figure 5).

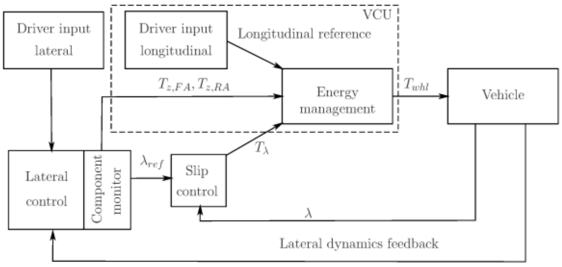

Figure 5: Structure of the extended VCU for vehicle dynamic control

The dynamics control development requires a mathematical description of the vehicle motion. Usually the so-called single track model is used [5]. A yaw torque T_z is calculated based on the lateral dynamics feedback (side slip angle β, yaw rate $\dot{\psi}$) of the vehicle. To establish the yaw torque T_z the potential of the tires to generate the yaw torque must be determined. This is done in the component monitor, where a tire model [6] and a so-called torque coordinator is utilized. Depending on its calculations, the resulting correction torques $T_{z,FA}$ and $T_{z,RA}$ are used to influence the vehicle yaw motion by an intelligent propulsion torque shift. The development of all controllers involved in this strategy was motivated by the variable structure systems theory [7], [9].

Multi body simulations have been carried out to verify the proposed VDC strategy. As shown in Figure 6, a comparison between a vehicle with VDC (blue) and a vehicle without VDC (red) was carried out. At a constant vehicle speed of 40 km/h (road condition: $\mu = 0.2$) a steering wheel step of 90° was applied to both vehicles. It can be seen that the proposed VDC strategy leads to an agile vehicle. In addition, Figure 6 shows, that the vehicle stability can be enhanced. This way the desired vehicle characteristic can be achieved without neglecting the aspect of energy efficiency.

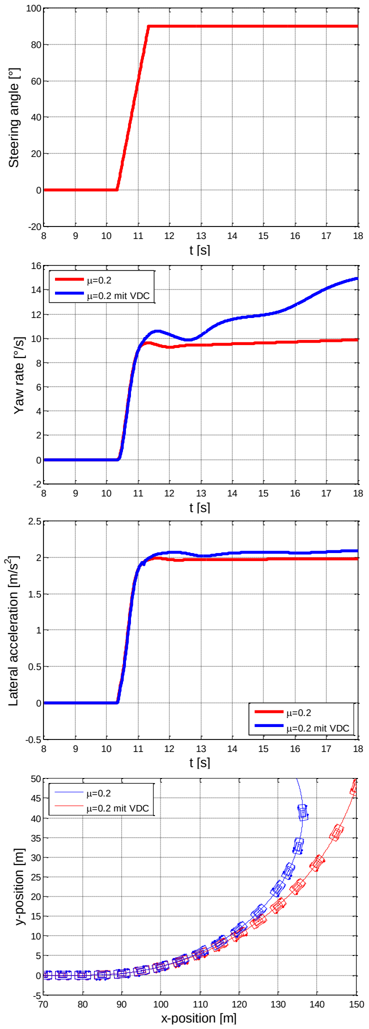

Figure 6: Steering step test maneuver on low friction surface

4 Body Motion Control Concepts

In addition to the concepts for controlling vehicle dynamics by electrical powertrain components presented previously, this section is intended to explain the cross-coupling between driving torques and body motion. Furthermore, the possibility of influencing the vehicles body motion by making use of this effect, should be emphasized.

4.1 Vehicle suspensions

The force coupling between drive torque and vertical forces of vehicle suspensions is commonly known as anti-dive or anti-lift geometry. Together with the location of the torque device (hub- or body-fixed) and certain vehicle parameters, the suspension geometry preserves high body pitch when a vehicle is braking or accelerating, see e.g. [8].

In recent electric hub motor R&D publications, this effect is utilized to control the vehicle body motions like pitching and – when there are four individual hub motors – even roll, see e.g. [9], [10].

In this approach a control of body motion is considered and includes beside all available e-powertrain components also the braking device. It is supposed that the brake-device is quick enough for control, which is an realistic assumption due to the demand of blending recuperative and frictional torque in dynamic situations, see e.g. [11]. Through the suggested cooperative control of all available components the functionality can be applied to a great variety of vehicle configurations.

4.2 Vehicle configurations

The effect strongly depends on the vehicles powertrain topology, degree of electrification and the geometric relations of the suspension. Vehicles with electrified powertrains are developed in various configurations: The variety spreads from hybrid vehicles in different power-classes to purely electrically driven vehicles with electric hub-motors. In the following, possibilities and limitations of common configurations are discussed. A dynamic motion control (i.e. reducing overshoot, static values of e.g. pitch angle remain unchanged) is assumed.

4.2.1 Pure electric four-wheel drive with hub motors (eAWD)

The wheel individual torque application and the high support angles of the anti-dive/anti-lift geometry, when mounted on the wheel-hub, enable the full range of body motion control (pitch/lift and roll control) when braking, accelerating or cornering.

4.2.2 Electric auxiliary drive with hub-motors on the rear axle (eRWD)

The above mentioned advantages are valid for the rear axle only in this application. Without cooperative control of the brake device pitch control is only possible, if the acceleration is maintained. Adding a sufficiently fast braking device the full range of body motion is enabled too.

4.2.3 Electric auxiliary drive with central-motors on the rear axle (eRAD)

With cooperative control of the brake device pitch control is possible, roll control cannot be achieved.
The following table summarizes the discussion, regardless to the limitations of power, battery content etc. .

Table 2: Common topologies enabling vehicle motion control in different domains

	Lift/Pitch	Roll	Yaw/Drive
eAWD	+	+	+
eRWD	+ / ○	+ / ○	○ / +
eRAD	+ / ○	–	○ / +

4.3 Control concept

The dynamic behavior of the vehicle modes are specified by means of a eigenfrequency and damping ratio for each mode. The steady state behavior is defined in that way, that the specified brake or drive force distribution of the actuators is reached after some time. This means that there is no steady state deviation in the wheel-torques compared to a passive vehicle. This is a key issue for the control design, since the body motion control is an add on to other duties of the actuators (i.e. recuperation) and should therefore be seen as a second goal.

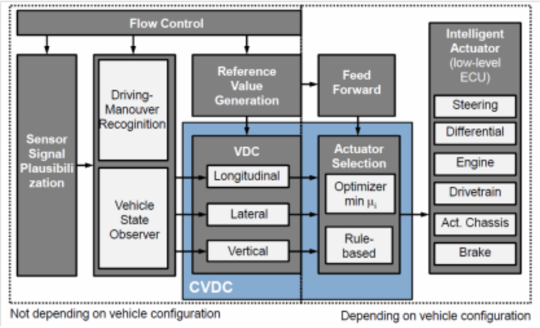

Figure 7: Framework of the MAGNA STEYR Vehicle Dynamics Controller (VDC)

The framework for the control concept, depicted in Figure 7 is the MAGNA STEYR Vehicle Dynamics Controller (VDC), see [7], where the controller is designed in two steps. In the first step a control law is designed for each vehicle motion with actuating signals representing virtual forces. In the second step these virtual forces are allocated to the real, vehicle-depended, actuator configurations. This approach creates a modular and easy to use framework that can be applied to different vehicles and applications.

4.4 Simulation

In a simulation study the described concepts are build up with the proposed controller compared to each other. The baseline vehicle is a middleclass limousine, that presets the suspension angles and springs. A straight-line braking maneuver with 0.4g is simulated with the different controller concepts.
In Figure 8 acceleration and body pitch are depicted, while the wheel forces are shown in Figure 9. To give detailed insight into the behavior it is assumed that only the electronic components of the vehicles are applied.

4.4.1 eAWD

At the start of the braking maneuver, the rear axle brakes stronger than in steady state, simultaneously the brake forces on the front axle are reduced by the same amount. This behavior can be described as dynamic brake force distribution, that leads a damping of the pitch movement while maintaining a constant deceleration.

4.4.2 eRWD

The pitch movement is damped sufficiently, compared to the uncontrolled vehicle. This is achieved by increasing the brake force on the rear axle, which leads a higher acceleration at the beginning of the braking maneuver.

4.4.3 eRAD

Compared to eAWD and eRWD a higher steady state pitch angle can be recognized. This is a system immanent characteristic. It also can be observed for the uncontrolled car with this configuration. The pitch damping is achieved by lowering the brake force on the rear axle, which leads a smaller deceleration at the beginning of the braking maneuver.

The different behavior of eRWD and eRAD can be explained through the geometrical constraints of the suspension. When applying the brakes too, which is recommended above, the eRWD and eRAD achieve a similar result as the eAWD configuration.

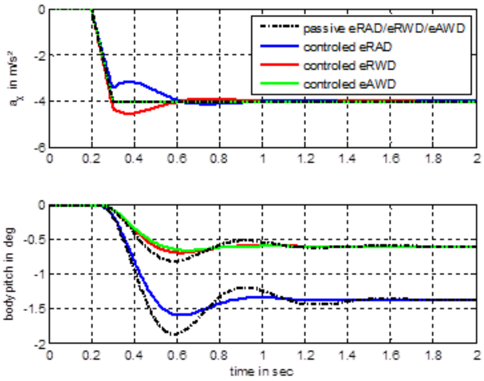

Figure 8: Deceleration and body pitch at straight line braking from 100 kph with 0.4 g

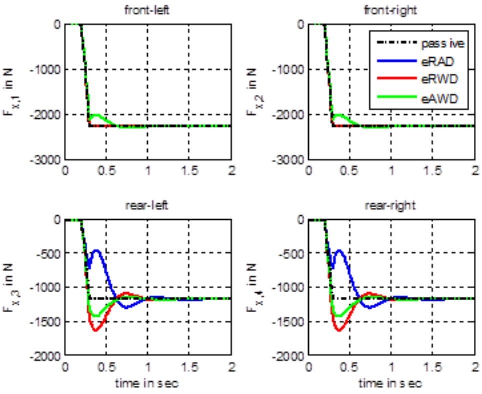

Figure 9: Wheel forces at straight line braking from 100 kph with 0.4 g

It is shown how the force coupling effect of common suspensions is utilized to positively influence the vehicles' body motion. Many different vehicle configurations are available on the market. Only a modular controller concept, like the MAGNA STEYR VDC, is able to cope with this variety and even extend functionalities by linking different actuator groups, like traction and brake devices.

5 Project Validation Environment

The presented functions are partly validated with simulation tools. For the basic reality validation of the developed additional functions an existing full hybrid vehicle is used which was build up in another R&D project. This demonstrator vehicle consists of two electric motors in the propulsion system: one belt driven high voltage starter-alternator combined with the internal combustion engine in the front and one central electric motor with a fixed gear set at the rear axle (see Figure 10).

This topology has advantages for the testing of all developed functions cross-linked in one vehicle.

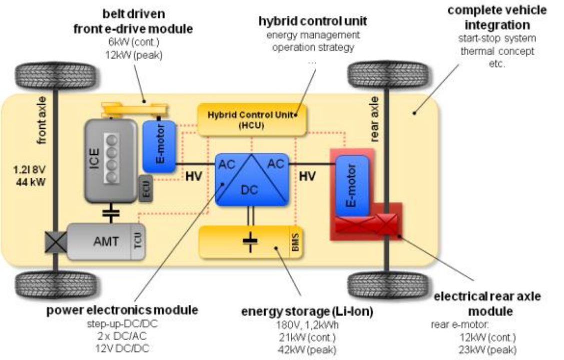

Figure 10: Architecture of the hybrid demonstrator vehicle **compact**city**hybrid**^{e4WD}

With this vehicle configuration all hybrid drive train modes are possible: parallel and serial hybrid, pure electric driving, boost, recuperation, load shifting and all-wheel-drive, see [13], [14].

Within the next project phase all functions will jointly validated in a mass produced electrified vehicle. For that the competence of the functional software integration with the knowledge of the complete vehicle behavior is crucial. The necessary subjects are described in the following chapter.

6 Functional Software Integration

The Hybrid Control Unit (HCU) software of this vehicle allows to successfully test and integrate backlash oscillation and damping compensation described in section 2, electric vehicle dynamic stabilization of section 3 as well as the suspension body motion explained in section 4.

All the main components of the hybrid driveline and actuator system have been modeled by using a graphical technique, named Power-Oriented Graphs (POG). (see [15])

The model based design development approach used in MAGNA STEYR in combination with an innovative software architecture (see [14]) allows to obtain a flexible modularity, as well as functions that are reusable and easy to recalibrate

The following advantages are generated:

- A modular, hierarchical and expandable structure
- It consists of modules with well-defined tasks and proper interfaces

- Coordinators manage requests, priorities and resources between elements on each level in the hierarchy
- The functionality is the result of the communication between the modules

The structure in Figure 11 provides an overview of the complex system functionality of the integration process.

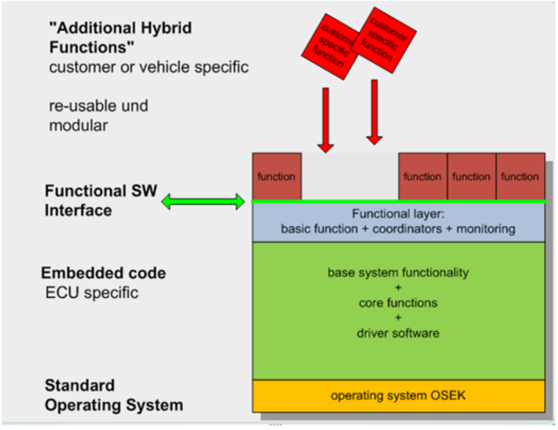

Figure 11: Vehicle software architecture for the integration of additional hybrid functions

The integration of the different additional functions in the hybrid control software was not always an easy feat. The main problem was the limited response time of the control software. In particular when a fast reaction of the vehicle is needed (i.e. at vehicle dynamic maneuvers), it is necessary to operate on component level (i.e. e-motor control software). Other issues are due to an improper interface between the different modules, but this can be kept in consideration in advance with a proper software architecture (i.e. proposed by MAGNA STEYR in [14]). Furthermore, the security level of the implemented solution can be seen as a critical issue that increase the challenge of the integration complexity.

Not just the software integration issues are relevant, also other hardware challenges are coming when sensor or actuator is not present in the vehicle and must be mounted to an appropriate input/output at the new function.

All these topics of the complex problem of functions integration are solved with the knowledge and the competence of MAGNA STEYR in cooperation with the OEM. These tasks are nowadays a bit easier to solve due to the AUTomotive Open System Architecture (AUTOSAR). In this partnership most of the OEMs, suppliers, tool producers and also MAGNA STEYR are working together. This includes the standardization of basic system functions, scalability to different vehicle and platform variants, transferability throughout the network, integration from multiple suppliers, maintainability throughout the entire product life-cycle and software updates as well as upgrades over the vehicle lifetime. In this open and standardized automotive software architecture it is possible to integrate software functions on a distributed network of ECUs in order to maximize efficiency and resources.

7 Conclusion

Different cross-linked functions for additional benefits by influencing steering behavior, movements in the vehicle structure and the response behavior of component operation by using the electrified propulsion system require deep insight and understanding of the complex structures. MAGNA STEYR integrates these functions cross-linked into the complete vehicle. This results in a higher benefit than the single functions can do. Thus, driving comfort, driving safety and driving pleasure are improved without the need of additional hardware components.

All functionalities are developed in a modular way. They are applicable with on manifold drivetrain configurations. This means additional benefit for the customer without extra hardware costs.

Acknowledgments

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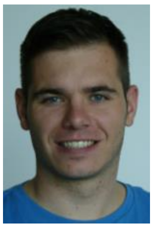

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