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A safe Torque Vectoring function for an electric vehicle

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Short Abstract

A safe Torque Vectoring function is applied to an electric vehicle with a two front motors drivetrain concept. The function has been embedded in a lean and scalable functional architecture adaptable to various drivetrain concepts. The Torque Vectoring function comprises an LPV control algorithm with good performance even in extreme test cases. The controller can be parameterised for case specific performance. The implementation of functional safety requirements is presented for one safety goal.

1 Introduction

The application of an advanced Torque Vectoring System (TorVec, TVS) to a two front motor electric vehicle is presented. The choice of a two motor drivetrain is a reasonable compromise between a four wheel motor approach which is complex and expensive and a conventional single motor drive with no freedom of driving wheels individually. However, the advantages of an individual torque control on the wheels (i.e. torque vectoring) must exceed the disadvantages by the extra costs and the extra effort for the higher complexity (package space, weight, number of parts). This benefit for the driver first must be carefully developed and then clearly communicated as a unique selling point for the car manufacturer to enter the market with electric vehicles.

The results in this article will be presented for the two front motor drivetrain configuration but can be extended to arbitrary multi wheel drives. An alternative to use two motors can be one central motor combined with an active electric differential. This solution also suffers from extra costs and package and compared to the use of two individual motors the dynamic range is limited by the maximum differential ratio of torque transmission.

The advantages of a Torque Vectoring function are multiple. The first benefit arises by the mandatory need to have a differential function for a two motor drive to compensate for different wheel speeds in cornering situations. This principle can be used to support the steering request of the driver by a torque increase of the outer and a torque decrease of the inner wheel. This results in a lower steering force and is equivalent to the effect of a power steering system.

The option of automatic steering can also be used for supporting modern advanced driver assistances systems (ADAS) functions like Lane Keeping Assistance Systems (LKAS). After identifying the lane markings, these systems keep the vehicle in the track by controlling the yaw rate via an electric steering system. For small road curvatures, like on highways, this could also be achieved by the asymmetrical application of torque by a TVS.

Beside comfort applications like the above mentioned the largest benefit of TorVec is the safety aspect. In contrast to stabilising assistance systems like electronic stability control (ESC) or antilock braking systems (ABS) which are effective by braking individual wheels, TorVec is able to support this functionality by applying less positive or negative torque instead of using the hydraulic brakes. This benefit is experienced by the driver in situations where an increasing wheel slip could lead to an unstable condition. Before ESC would be engaged, TorVec is able to smooth out the wheel slip by reducing or increasing the torque accordingly. Examples of these situations are laterally different friction coefficients (e.g. dry asphalt on the left and ice on the right; "µ-split") or oversteer / understeer. Here, TorVec extends the capability of ESC to the very onset of these slip phenomena.

The different regimes of the assistance systems are shown in figure 1. The borders between the validity regions are drawn sharp but will smooth out in the future when one master dynamics controller is capable of stabilising the vehicle in both lateral and longitudinal direction. This controller must be able to drive the hydraulics brakes, the individual electric motors, and the steering system to have maximum flexibility and redundancy.

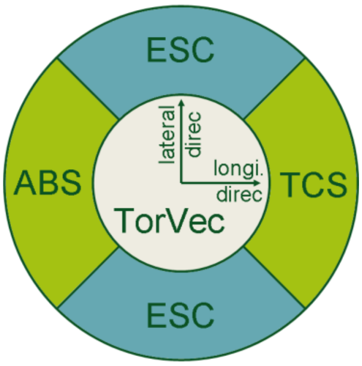

Figure 1: Regime of TorVec as the interfacing function between other stabilising functions. The borders could smooth out in the future by merging the functions to a master dynamics controller. ESC = electric stability control, ABS = antilock braking system, TCS = traction control system.

The TVS has been embedded into a new functional architecture as the link between the execution layer and the command layer [1, 2]. This architecture approach aims at a safe and efficient operation of the EV. The distinct separation of tasks is an important presumption for the scalability and flexibility of the concept. One major goal in the eFuture project was to support the Functional Safety requirements with a clearly arranged topology of the architecture and to ensure that all safety related functions – like TorVec – will have an easy and transparent dependency from other functions which are also easy controllable.

The paper demonstrates a technical deployment of a safe drivetrain architecture for an electrical vehicle. The implementation of the main safety requirements as prerequisites for the integration of dynamical stability functions is shown. The approach of a LPV controller for Torque Vectoring is described and examples for the performance of the assistance function are given.

The work is supported by the European Commission in the project eFuture [3] (grant no. 258133). The aim is to demonstrate innovative functions embedded in a flexible and lean architecture to support safe and efficient electric driving.

2 Functional architecture

The complexity of automotive architectures grew constantly through the last decades. The demand for safer cars, driver assistances, and car multimedia led to new components and functions requiring an increased number of interfaces, cables and control units with the corresponding software. This evolution, in turn, results in a confusing system of interconnected devices and functions which hampers the introduction of new features.

New vehicle generations offer the opportunity to think new ways for relieving this situation by modular approaches to account for different markets and vehicle types, and to ease the integration of future technology. The electro mobility age with its new use cases and new vehicle requirements enables the development of innovative architectures with reduced complexity and higher sustainability.

By defining a modular and flexible architecture for a full electric vehicle (FEV), the project eFuture translates this challenge into a demonstration car to examine the feasibility, the limits and the benefits of a "revolution" in E/E architecture. The top level picture of the approach basically consists of four layers and is shown in figure 2.

The perception layer collects all information of the vehicle's environment via exteroceptive sensors and the sensor fusion extracts the relevant information for the guiding ADAS function on the command layer. The driver with his senses is part of the perception layer but could also be attributed to the command layer as he performs the transition of perception to driving commands.

The human machine interface (HMI) is split into the two directions "driver to vehicle" and "vehicle to driver" which is advantageous for the modular implementation of new driver actuators (control buttons, pedals, etc.) and new driver feedback devices (displays, acoustic senders) and enables an easy adjustment of the driver's look-and-feel.

Both the HMI (driver-to-vehicle in this case) and the guiding ADAS (ACC, LKAS, EBS, etc.) are calculating motion requests consisting of the longitudinal acceleration and the steering angle. The requests are forwarded to a central control function, the Decision Unit 1 (DU1) which mitigates between the potentially conflicting motion requests [1, 2]. The DU1 also receives information on the energy status of the vehicle via the Energy Management function on the energy layer. According to the recommendation of the Energy Management, the DU1 can choose a limitation for acceleration and/or velocity avoiding an excessive current which could damage the high voltage battery.

The DU1 selects the best motion vector in terms of efficiency and safety and forwards this to the execution layer, responsible for choosing the best way to realise the motion vector by the actuators present in the vehicle (brakes, motors, active steering). The implementation of a Torque Vectoring function enables the dynamical split of torque required for the requested acceleration to the drive wheels. Together with the conventional stabilising ADAS (ESC, ABS, TCS), TorVec ensures safe and comfort driving in all situations. This will be addressed in section 3.

An important part of the execution layer for the perception of the dynamical vehicle status is the Vehicle Observer (VehObs). This function examines information of the various vehicle sensors (wheel speed sensors, yaw rate sensor, steering wheel sensor and acceleration sensor), improves their signal quality by the use of Extended Kalman filtering, and calculates immeasurable quantities out of the primary signals [4]. The VehObs is the source of information on dynamical vehicle stability and its limits for all functions in this architecture.

The concept of the decision unit has also been applied to the execution layer by implementing a central control function, the Decision Unit 2 (DU2), which decides, based on the inputs of the energy management (recuperation en-/disabled, current limitation) and the VehObs (dynamical limits), which actuator shall perform the requested action to achieve the requested trajectory. Here, the steering can be done by TorVec or Power Steering, and deceleration can be performed by recuperation or hydraulic braking.

The philosophy of the novel functional architecture is to decouple the core functions from the hardware (HW) and to create interfacing functions to the HW which can easily be adapted to different HW concepts (e.g. drivetrain architectures, ADAS equipment, degree of autonomous driving). This concept also avoids bypassing of functions by applying a hierarchic composition with the decision units being the final instance.

In chapter 4 the use of this modularity for the implementation of important safety requirements from the functional safety concept will be outlined. High ASIL ratings can be restricted to the core functions which only carry simple calculations and thus, can easily be secured by redundancies.

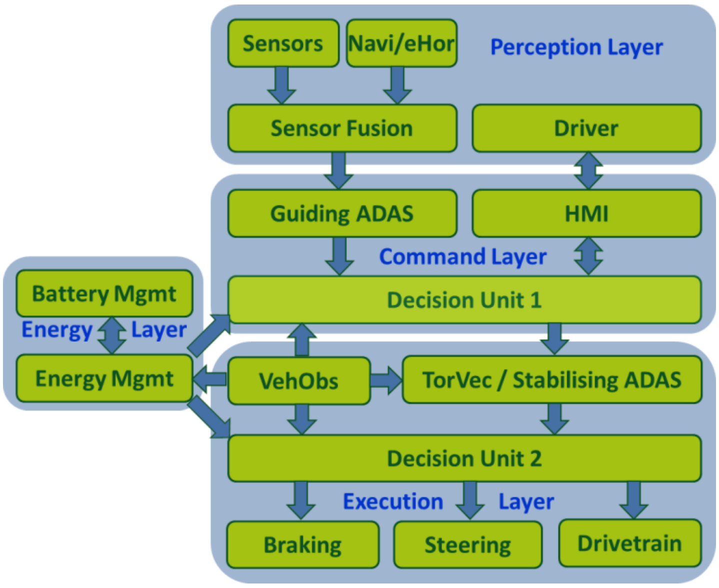

Figure 2: Top level schematics of the functional architecture used in the eFuture project

3 Control strategy and performance of Torque Vectoring

To use a Torque Vectoring System (TVS) a special vehicle configuration must be given. In the project eFuture the vehicle is equipped with two independent electric motors which drive the front wheels of a compact car – as shown in figure 3.

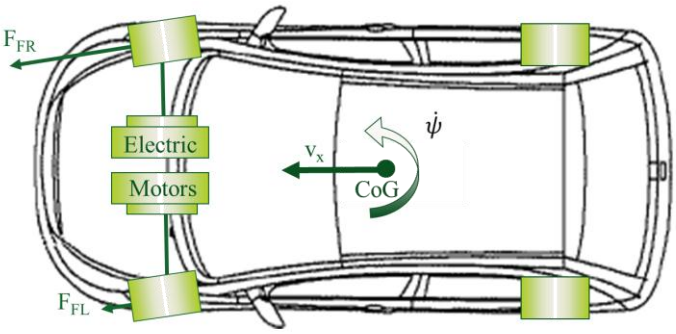

Figure 3: eFuture propulsion system

With the two electric motors, the lateral dynamics of the vehicle can be influenced and the control of the two motors is called torque vectoring. TVS is considered as a performance enhancement function which also improves the vehicle stability and thus, the safety of the vehicle. In normal, every-day driving conditions, the vehicle movement can be described with the nonlinear single track model [5]

$$\dot{v_x} = \frac{\sum F_x}{m} + \dot{\psi} v_y$$

$$\dot{v_y} = \left(\frac{-a_1 C_{\alpha f} + a_2 C_{\alpha r}}{m v_x} - v_x\right)\dot{\psi} - \frac{C_{\alpha f} + C_{\alpha r}}{m v_x} v_y + \frac{C_{\alpha f}}{m}\delta$$

$$\ddot{\psi} = -\frac{a_1^2 C_{\alpha f} + a_2^2 C_{\alpha r}}{I_z v_x}\dot{\psi} + \frac{a_2 C_{\alpha r} - a_1 C_{\alpha f}}{I_z v_x} v_y + \frac{a_1 C_{\alpha f}}{I_z}\delta + \frac{1}{I_z} M_z$$

Here the vehicle states are the longitudinal velocity v_x, the lateral velocity v_y and the yaw rate $\dot{\psi}$. The system inputs are the total longitudinal force $\sum F_x$, the front wheel steering angle δ and the yaw moment M_z. Geometrical properties of the vehicle are included as distance a_1 which is the length between the front axle and the centre of gravity (CoG) and the variable a_2 which is the distance between the rear axle and the CoG. The vehicle mass is given as m and the vertical moment of inertia is given as I_z. The parameters $C_{\alpha f}$ and $C_{\alpha r}$ represent the cornering stiffness of the front and rear axle, respectively.

In critical driving situations including icy road, vehicle spinning or wheel spin / blocking, the real vehicle behaviour is different from the nonlinear single track model. With unknown and unpredictable vehicle behaviour, most drivers are overstrained and cannot safely operate the vehicle. Torque Vectoring tries to keep the real driving behaviour as close as possible to the normal driving behaviour reflected by the above equations. Therefore the two electric motors at the front wheels are used to generate a total longitudinal force $\sum F_x$, which accelerates and brakes the vehicle. Additionally, the motors are used to generate the yaw moment M_z which controls the lateral movement of the vehicle.

The control of the vehicle dynamics can be realised with different controller types [6, 7]. For the application in eFuture a linear parameter-varying (LPV) control design is chosen as Torque Vectoring controller. In LPV control linear time invariant (LTI) design concepts are applied to a certain class of non-linear systems [8]. The non-linear single track vehicle model fits perfectly the requirements of LPV control because the non-linearity of the system can be included into the controller design. With LPV control, it is possible to design a controller which guarantees stability over the complete operation range while maintaining the vehicle performance [9] – which can only be guaranteed for PID controllers with an unfavourable controller performance.

Besides the LPV controller, a torque and slip limiter (TSL) is included in the software which deals with the physical limitations of the actuators. TSL is composed of two elements.

1. An anti-windup configuration which deals with the physical limitations of the electric drivetrain. The power limitation introduced with the battery and the torque limitations related to the electric motor decrease the performance of the controller as soon as the physical limitations are reached. The anti-windup scheme [10] reduces the effects of the limitations and suppresses excessive overshoots and vehicle instability due to actor limitations.
2. The anti-windup scheme is enhanced to TSL because it also limits the tyre slip. Excessive slip values which represent spinning or blocking of the wheels have negative effects on the vehicle performance and safety. To suppress these events, TSL monitors the wheel slip and keeps it in the defined boundaries. In the actual configuration TSL does not perform any action until the tyre slip leaves the interval [-0.1 ; +0.1]. If the tyre slip exceeds these limits the driving torque is reduced towards zero to suppress spinning or blocking of the wheel.

The final control architecture is given in figure 4 with a desired value generator which uses the steering angle and acceleration request of the driver to calculate a velocity request and a yaw rate request. A similar scheme is used by [11] and shows satisfying results. The LPV controller controls the longitudinal velocity and the yaw rate with the two electric motors. The TSL is idle if moderate requests are performed. If the limits of the electric drivetrain or tyre slip are reached the TSL gets activated and reduces the torque requests of the controller in order to stabilize the control-loop and thus, the vehicle.

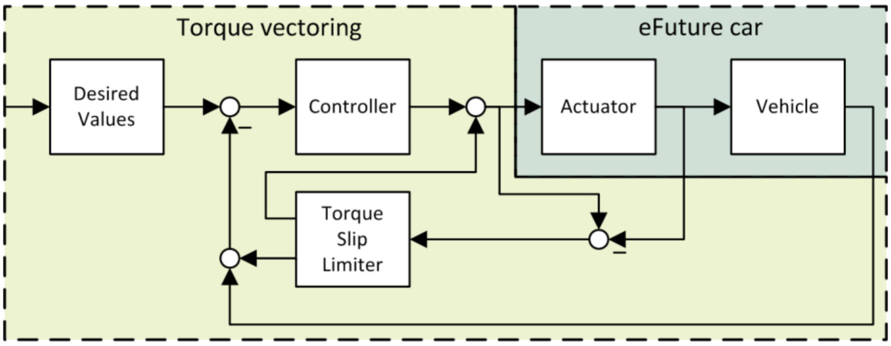

Figure 4: Torque Vectoring control architecture

In eFuture the vehicle movement is simulated with a 14 degree of freedom model, including a linear suspension model and a Pacejka tyre model [12]. This model is used to simulate the vehicle behaviour and to tune the TorVec control parameters. In order to validate the controller the following test cases are simulated:

- Straight line acceleration
- Straight line braking (ISO 21994)
- Constant radius turning (ISO 4138)
- Brake in bend (ISO 7975)

- Acceleration in a bend
- Step steer (ISO 7401)
- Lift off oversteer (ISO 9816)
- Sine with dwell (NHTSA [13], for ESC effectiveness)

In order to validate the lateral performance the National Highway Traffic Safety Administration (NHTSA) advises to use a sine-with-dwell manoeuvre [13]. This test should be used to evaluate the lateral performance of a vehicle and especially the functionality of an ESC system because an average vehicle gets unstable in this test. Here the same test is applied to test the lateral performance of Torque Vectoring. In the sine-with-dwell manoeuvre, the steering wheel is turned in a sinusoidal movement with a maximum angle of 120° at the steering wheel. At the second maximum the steering wheel is kept constant for 0.5 seconds. This manoeuvre is an open-loop manoeuvre which means that no real driver is necessary which makes the test repeatable. However, for a real vehicle test, this scenario might be too complicated because no suitable test track or steering robot is available. In this case a double lane change provides a similar test condition and should be used with a real driver and a real vehicle.

In this paper, simulation results for the sine-with-dwell test case are presented. Figure 5 shows the corresponding driver commands. The vehicle starts with 80 km/h, the road surface is in good condition and no cross-wind exists. At the beginning the virtual driver does not step onto any pedal, which means that the maximum recuperation torque for the specified velocity is requested. After 0.5 seconds the driver starts with the steering manoeuvre and steps to the accelerator pedal in order to request zero acceleration ('sailing' condition).

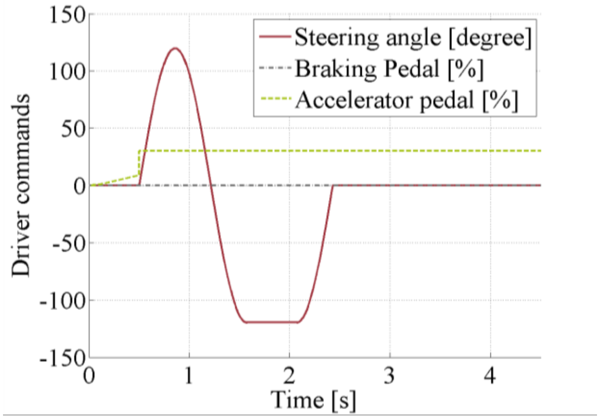

Figure 5: Driver commands for the sine-with-dwell test case (initial velocity = 80 km/h, friction coefficient 0.9)

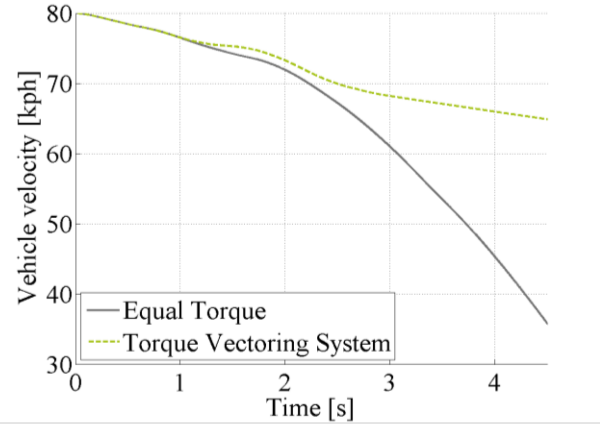

Figure 6: Vehicle velocity plot for the sine-with-dwell test case of figure 5

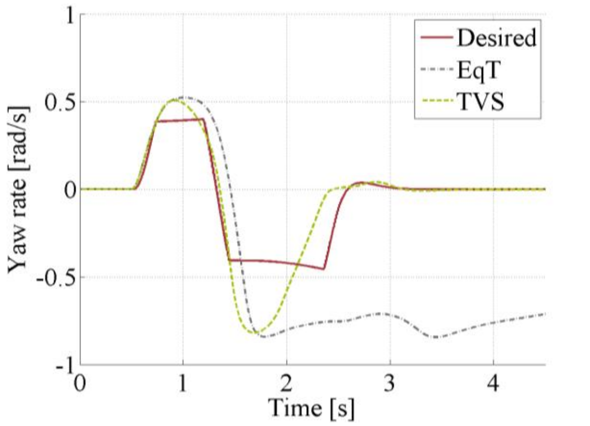

Figure 7: Vehicle yaw rate plot for the sine-with-dwell test case of figure 5.

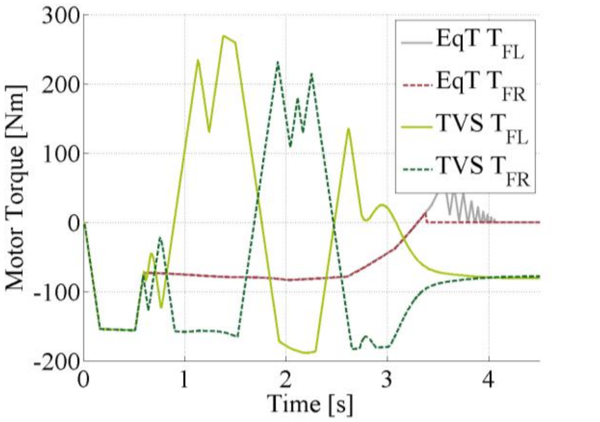

Figure 8: Electric motor torque plot for the sine-with-dwell test case of figure 5.

In the simulation two vehicles with the same properties are compared. The first vehicle (EqT) uses equal torques at both motors while the second vehicle uses the proposed Torque Vectoring System (TVS). Figure 6 shows the velocity of the two vehicles. At the end of the test, the EqT vehicle drives much slower than the vehicle with torque distribution. A low velocity is acceptable from a safety point of view but in terms of vehicle performance and efficiency it is favourable to keep the velocity and avoid unnecessary acceleration. This is accomplished by the TVS vehicle.

Figure 7 shows the major difference between the vehicles. The desired yaw rate (red solid curve) is calculated considering the steering angle and the velocity. The equal torque vehicle (blue dashed curve) has two overshoots and a slow response. Furthermore, the EqT vehicle is in an unstable condition and spins after this test, so it would fail the sine-with-dwell test. The TVS vehicle on the other hand responds faster to the yaw requests and is in a stable driving condition after the steering manoeuvre.

However, an undesired overshoot is still visible in figure 7 for the TVS performance. This overshoot can be explained with the limitations of the electric motor torques. Figure 8 shows the motor torques at the front left and front right wheel. Two major differences between left and right torque of the TVS vehicle can be observed. The first one (0.7 to 1.7 seconds) corresponds to the positive overshoot of the TVS vehicle yaw rate in fig. 7. The second major motor torque difference (1.7 to 2.6 s) is related to the second, negative yaw rate overshoot in fig.7. In both cases, the controller tries to compensate the overshoot and generates a yaw moment against the vehicle turning. However, the intrinsic slew rate limitation (1000 Nm/s) of the electric motor system suppresses a faster reaction to account for the changed vehicle movement. The overshoot is reduced but the motors need some time to reach the desired torque values.

The sine-with-dwell test shows that the Torque Vectoring controller improves the vehicle safety and keeps the vehicle stable in a very critical driving situation. So the major aspect of Torque Vectoring is fulfilled. However, this test shows that the slew rate limitation of the electric motors has a negative impact on the performance of the yaw rate controller and should be kept as small as possible – the faster the motors the better the control performance. Overshoots in the yaw rate response are visible but controllable even in this extreme driving test case.

The results will be validated by driving tests in the next few months and a comparison to the simulation results can be then be drawn.

4 Functional safety

The application of a multi motor drivetrain is connected with a high risk of accidents if an error occurs in the hardware or in one controlling function. Even for a vehicle without a TorVec system the failures by degradation of the HW (motors, inverters) have to be accounted for in the safety architecture. If the vehicle is equipped with an electronic differential or a TorVec function the risk of failures will even be increased by software functions distributing the torque unequally to the wheels. For both cases, possible hazard scenarios are unintended reverse, zero or persistent torque (one sided or two sided).

The safety analysis of the vehicle’s drivetrain architecture led to the identification of four top hazards related to the drivetrain functions:

1. Unintended high acceleration
2. Unintended high deceleration
3. Unintended vehicle movement
4. Too high or unintended yaw rate

As the TorVec function is deemed to be contributing mainly to the fourth hazard, the corresponding safety requirements are deduced in this paper.

For determination of the Automotive Safety Integrity Level (ASIL) according to ISO 26262 the possible impacts of such a hazard are evaluated in a certain driving situation. This evaluation is done in three dimensions:

1. The exposure (E) representing the likelihood for experiencing the driving situation evaluated.
2. The controllability (C) assessing the capability of the driver or others to get him/themselves out of danger.
3. The severity (S) which is a measure for the degree of damage to the driver or other road users that is caused by the hazard in this particular driving situation.

Here we consider a drive on a country road with the typical speed of ~90 km/h. This is a very common scenario occurring very frequently for the average driver. Therefore the highest rating E = 4 is assigned. In this scenario an unintended yaw rate can lead to vehicle skidding and/or going off the lane. Most of the drivers will not be able to master such a situation by keeping track with counter steering. Hence the highest rating for the controllability C = 3 is chosen. By spontaneously applying an erroneous yaw rate it is very likely that the vehicle will leave the road or hit other cars of the opposing traffic. Considering the high speed of around 90 km/h life-threatening or fatal injuries have to be considered as very likely. This leads to the highest rating for the severity S = 3. Following the rating scheme given in ISO 26262, these ratings lead to an ASIL D overall rating for this hazard. This is the highest rating as per ISO 26262. The resulting safety goal derived from this top hazard is: "Avoid too high or unintended yaw rate!" (SG4). The safe state for this safety goal has been defined to "no torque application" because then the driver can keep control of the vehicle by steering and braking. For failures with a lower severity or a better controllability the system will turn in a degraded mode where both motors will receive equal torque requests (deactivation of TorVec). In the degraded mode, the vehicle has a limited driving capability but the driver can continue his trip.

The safety concept for the safety goal 4 has been derived using the results of a fault tree analysis. Safety requirements have been defined accordingly and attributed to the single vehicle functions. Here, the lean and modular architecture was beneficial for the decomposition of the requirements to the functions since the software blocks are small and well defined and the signal routes are simple, straight and non-branched.

The function chain contributing to the safety goal 4 ("Avoid too high or unintended yaw rate!") is shown in figure 9. The ADAS functions do not contribute here as they cover only longitudinal functions. The architecture allows for a clean separation between the different functional blocks. This makes it possible to derive the safety concepts for these blocks rather independently. The safety concept for the vehicle status acquisition in the Vehicle Observer relies on the model-based plausibility check of the observed values from the sensors (steering angle, wheel speeds, yaw rate), thus leading to lower safety requirements for the sensors. The TorVec function comprises several safety checks including

- Compare actual yaw rate with driver request and counteract in case of discrepancies (for SG4).
- Compare left and right torque request with overall acceleration request and limit torque request in case of discrepancies.
- Forward torque request if and only if the requests from the Decision Unit 1 are valid.

Finally, in the decision unit 2 (DU2) the proper application of the requested torques by the inverters / motors is monitored and the safe state is enforced if critical failures occur.

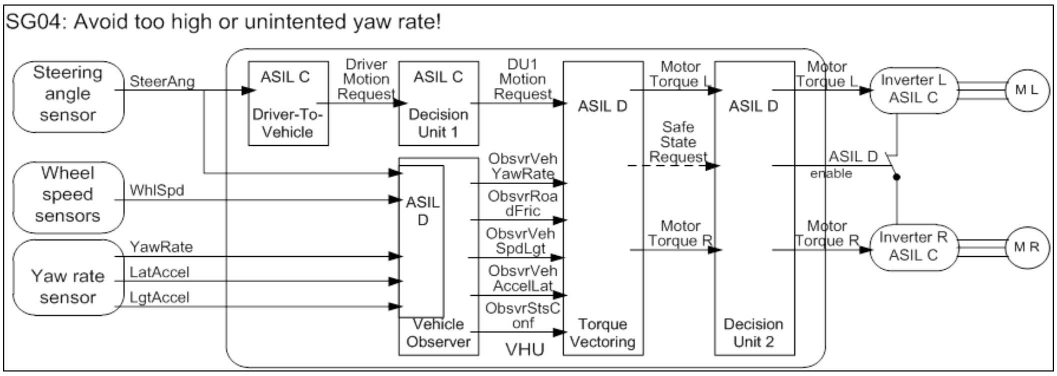

Figure 9: Functions contributing to the requirements of safety goal 4.

All safety requirements have been included in the functions code and proven for effectiveness in various tests. The same implementation strategy holds for the other safety goals, thus leading to a safe system following the ISO 26262 requirements.

5 Conclusion

The implementation and performance of a Torque Vectoring function to and in a two front motor electric drivetrain concept has been demonstrated. The TorVec function is part of a lean and scalable functional architecture applicable to any kind of vehicle architecture by clear separation of core functions and hardware interfaces and also allowing for an elegant consideration of functional safety. The safety requirements for avoiding an unintended yaw rate have been explained for the functional chain including

TorVec. The TorVec algorithm follows an LPV control approach with encouraging results of good vehicle stability for a sine-with-dwell test case. For fast controller performance the dynamics of the inverter-motor system must be optimised. The validation and parameter adjustment will be performed in forthcoming vehicle tests and will be presented in the conference talk.

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