Demands of the Decentralized Autonomous Intersection Management on the Steer-by-wire System in Passenger Cars

Norbert Neuendorf
Mechatronics Laboratory Paderborn (MLaP)
Prof. Dr.-Ing. J. Lückel
University of Paderborn, Germany
E-mail: Norbert.Neuendorf@MLaP.de

Ulrich Dierkes
Mechatronics Laboratory Paderborn (MLaP)
Prof. Dr.-Ing. J. Lückel
University of Paderborn, Germany
E-mail: Ulrich.Dierkes@MLaP.de

Abstract— **The present article shows the extensions and adaptions necessary for employing the future steer-by-wire system with passenger cars in a potential autonomous intersection management, with special emphasis being placed on the structuring concept as a basis for the design of such a system.**

I. Introduction

The next few years are bound to witness an increasing use of X-by-wire technology in car manufacturing because it offers a variety of advantages to both the car manufacturer and the client due to the omission of mechanical elements in favour of controlled electrical actuators.

To the car manufacturer, the omission of mechanical components means a gain in constructive liberties. Moreover, he has the chance for a software realization of functions that so far have necessitated a complicated mechanical structure or have not been realizable at all.

The advantage for the client lies in the fact that these additional functions can be made available to him.

When a conventional system is exchanged for an X-by-wire system, the first aim is most often to design the X-by-wire system in a way as to make the client see no difference to the conventional one. In the case of the steer-by-wire system the behaviour and impact are to conform with those of a conventional steering.

Further possibilities of the steer-by-wire system will be opened up in the subsequent design steps, among them the variable steering-transmission ratio and steering assistance or the action of driver-assist systems by means of additional steering angles. The choice of appropriate interfaces with the actual system will limit the expense required for an extension.

The present paper shows the way a steer-by-wire system replacing a conventional steering has to be modified so as to be applicable for the decentralized autonomous intersection management.

The paper describes the structure of the steer-by-wire system that has to allow

- replacement of a conventional steering,
- provision of extended functions, such as variable steering ratio and steering assistance, and
- autonomous driving in the context of the decentralized intersection management.

The elected structure substantially determines the expense required for designing the information processing of a mechatronic system.

II. Demands on a Steer-by-wire System as an Extension of a Conventional Power Steering

A. Conventional Power Steering

The power steering systems employed in conventional vehicles are marked by the fact that steering-wheel force is transmitted via the steering gearbox to the steering linkage and there positions the front wheels. In order to limit the steering-wheel torque induced by the driver, a hydraulic cylinder assists the steering motion. Yet, a steering of this kind will always remain a compromise. Thus pulling into a parking space requires much steering assistance and a small steering ratio so as to be smooth and quick. On the other hand, when going at high speed the driver desires few steering assistance and a high steering ratio for the feeling of steering directly. Conventional power steering systems, however, only allow a fixed ratio and assistance.

This is why an adjustable oil feeding (EPHS steerings, adjustable vane pump) or even a purely electric assistance are installed in modern power steering systems. It allows at least a variable design of the power assistance. In order to make also a variable transmission possible, some car manufacturers [1], [2] have developed steering systems with a variable gear ratio that are bound for series production.

Yet, even these novel power steering systems cannot offer the functionalities that car manufacturers actually want. Only with a complete decoupling of steering wheel and steered wheels, i.e., a so-called steer-by-wire system, will these promises be fulfilled. At present, this is forbidden by safety regulations which are in the process of alteration.

B. Structure of an SBW System

A steer-by-wire system consists of the feedback actuator and a steering actuator.

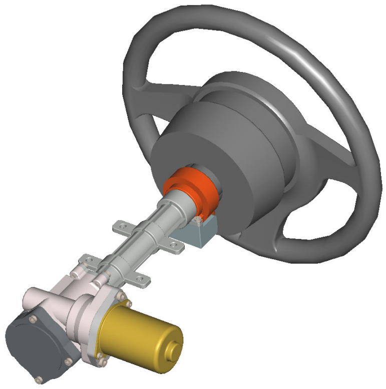

Fig. 1. Realization of a feedback actuator [3]

The feedback actuator is the input unit for the driver. He uses it to set the steering torque and thus the steering angle. It is a system with retroactive effects: a force or a torque is applied onto the steering wheel or the steering stick by means of an actuator (most often an electrical one) so that the driver senses the self-aligning force of the steered wheels.

The steering actuator controls the forces and angles at the steered wheels according to the driver's wishes.

The feedback and steering actuators are interconnected only via informational couplings. A mechanical link no longer exists. Possible safety measures warranting a redundant or fail-safe system are not considered in this context.

A steer-by-wire system of this kind offers the following advantages as compared with a conventional power steering:

- variable steering transmission
- variable steering assistance
- passive safety (no one-piece steering column)
- constructive liberties (no one-piece steering column)
- active safety due to additional ESP input
- automated vehicle guidance, such as autonomous convoy driving or automated pulling into a parking space or intersection management (see below)

C. Feedback Actuator

The feedback actuator is a steering wheel connected to an electric motor. The steering torque induced by the driver and the steering angle are measured. The electric motor serves to generate the feedback torques that the driver will sense. Fig. 1 displays a possible realization of a feedback actuator:

In ordinary steering operation, steering torques of about 5 to a maximum 8 Nm occur. However, the motor has also to simulate a mechanical limit. Therefore it has to be oversized accordingly (up to about 25 Nm).

D. Steering Actuator

The steering actuator generates the steering angle of the steered wheels. In the present case it is a hydraulic cylinder. The cylinder is supplied with oil via two throttle valves. The hydraulic interconnections are those of the open-center operation of a conventional power steering [4].

For vehicles with small dead weight, an electric actuator would be useful as well.

E. Interaction

Both the feedback actuator and the steering actuator are complete subsystems in themselves (MFM, see below). An additional controller that exchanges the reference and measuring signals of the two systems combines the latter to make up a steer-by-wire system. Here additional functionalities can be implemented, e.g., steering inputs for ESP or autonomous driving. The following chapter will describe the structure of this superordinated controller.

III. Structuring of the Steer-by-wire System

A. Structuring of Mechatronic Systems

Modularization and hierarchical structuring in the design of mechatronic systems help to reach various goals. On the one hand, structuring serves to establish order required to master the complexity of the products in the design process [5]. On the other hand, the modular structure is a prerequisite for a stepwise realization (keyword: hardware-in-the-loop simulation [6], [7]) at a later stage of mechatronic design (realization of prototypes).

At the MLaP, four structuring elements resp. levels were defined altogether. Three of them have already been proved effective in many practical applications [8]. When working on the intersection management, however, we extended the system by a fourth structuring element in order to meet the demands resulting from a large amount of information processing. This element is the Mechatronic Function Group (MFG).

The four structuring elements/levels are based on the four basic elements of mechanics, actuator system, information processing, and sensor system [9]. The structuring elements are the following:

MFM (Mechatronic Function Modules): An MFM consists of all basic elements, i.e., it is equipped with both a kinematic-mechanical supporting structure with actuators and sensors as well as local information processing/control. This ensures the desired motion behaviour. An energetical (mechanical, hydraulic, electrical) interconnection of several MFMs yields MFMs of higher order. An example of an MFM is a brake with local braking-force controllers.

AMS (Autonomous Mechatronic Systems): The AMS level is the highest mechanical level of a mechatronic system. Therefore this structural unit is complete and autonomous. An entire passenger car is an AMS.

CMS (Cross-linked Mechatronic Systems): CMSs are a result of the purely informational coupling of several AMSs. An example of this is a convoy.

Structuring by means of the three above-mentioned elements/levels is defined by the mechanical structure of a mechatronic system: a mechanical coupling of several MFMs yields MFMs of a higher order; the highest mechanical level is the AMS, and above it there are the CMS levels.

Another element serves to structure the information-processing unit of a mechatronic system and is called:

MFG (Mechatronic Function Groups): If an information-processing block does not possess a link to an actuator but gives orders exclusively to MFMs (or MFGs) on a lower level, it is then called MFG so as to emphasize its position apart.

An example of an MFG is ESP in cars: it exclusively uses actuators (in the present case: the brakes) of lower hierarchical levels.

Moreover, the elements "environment" and "driver" are taken into account and exemplified in the following. Then the symbols displayed in Fig. 2 are employed with these elements:

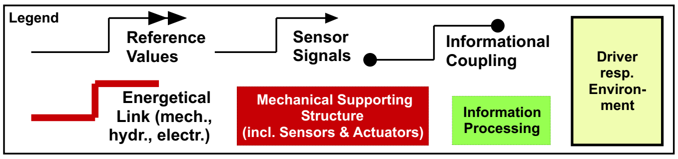

Fig. 2. Legend of the structuring elements employed

B. *Structuring of the SBW System*

1) Structure and Control of the Feedback Actuator: The feedback actuator comprises two hierarchical levels. The lower level is the MFM Electric Motor. It controls the motor current in such a way that this control serves to set a reference motor torque for the motor. This control is provided by the manufacturer of the motor.

The motor torque applied by the current control is not necessarily the torque sensed by the driver at the steering wheel. The two torques coincide in the static state. For the driver, the steering is a very ticklish interface. The driver senses the moment of inertia during fast steering operations and feels them to be a bad steering experience. Therefore the control (MFG Torque Control) of the force-feedback unit has to compensate for such influences as well. The MFG Evaluation provides additional functionalities that are necessary for its being used as a feedback actuator for the power steering in question here. By means of it, data such as steering angle or steering torque, among others, are exchanged with higher-level MFGs.

2) Structure and Control of the Steering Actuator: The steering actuator is a hydraulic steering-angle actuator consisting of 3 subordinated MFMs: an MFM to control the pressures of the left-hand and right-hand cylinder chambers, respectively, and a variable oil supply that provides the necessary oil flow for the pressure-control loops. The MFM Oil Supply is either a so-called power-pack of an electro-hydraulic power steering (EHPS) or a variable oil supply with V-belt drive. To each of the two cylinder chambers, a hydraulic valve is assigned which is actuated by the corresponding controller. The superordinated MFG Coordination Pressure Controller transmits the respective reference pressure to the pressure-control loops. The steering-angle controller completes the MFM Steering-angle Actuator.

3) Overall Structure of the SBW System with Superordinated MFG: The two MFMs Feedback Actuator and Steering Actuator are completely independent systems, ready for any use, e.g., the steering actuator can also be employed with an automatically co-steering rear axle. Only the two MFGs Variable Steering Assistance and Variable Steering Transmission combine these two MFMs to make up a steer-by-wire system. The task of the MFG Variable Steering Transmission is to determine the servo support in dependence of the respective situation. Thus, the driver will be supported as much as possible when pulling into a parking space but as little as possible during a fast ride, so as to feel like steering directly. A similar task falls to the MFG Variable Steering Assistance. Car stabilization systems like ESP or autonomous car cruise-control systems use this level for inputs into the steering system [10].

IV. Demands of the Intersection Management on the Steer-by-wire System

Because the mechanical coupling between driver and steering is dropped, the steering can be operated independently of the driver. This is a prerequisite for the steering in autonomous vehicles like those required for an intersection management.

The decentralized autonomous intersection management is divided into different spatial zones resp. temporal phases [11]. In the first phase, the so-called contact phase, control of the vehicle is withdrawn from the driver, and he is asked to indicate the desired direction. In this phase, the vehicles are brought to a defined constant velocity and initial data on position, velocity, desired direction etc. are exchanged among them. Then, in the so-called strategy phase, discrete optimization algorithms are taken as a basis for determining the right-of-way and consequently to assign each vehicle a velocity profile by means of which they can cross the intersection safe and collision-free. In the next phase, the optimization phase, the velocity profiles of the vehicles (and in part also the trajectory profiles in the intersection) are further optimized by a continuous Multi-objective Parameter Optimiser (MOPO, [12]). For this purpose several objectives are considered that can be divided into three classes: performance, comfort, and safety. The discrete and continuous optimizations in the strategy and optimization phases run decentrally and are distributed to the respective vehicles. In the operation phase, the vehicles leave their constant velocity to follow the computed velocity profiles. In the exit from the intersection the driver regains control of his vehicle.

In the individual phases, the steer-by-wire system has the following tasks:

In the strategy, optimization and operation phases, the only task of the actuator is to follow the defined trajectories. The feedback actuator can be used to give the driver information on the intersection-management processes. Thus, the interdependence between the angles of feedback actuator and steering ceases to exist. The reference values for the steering angle are taken from the trajectory controller.

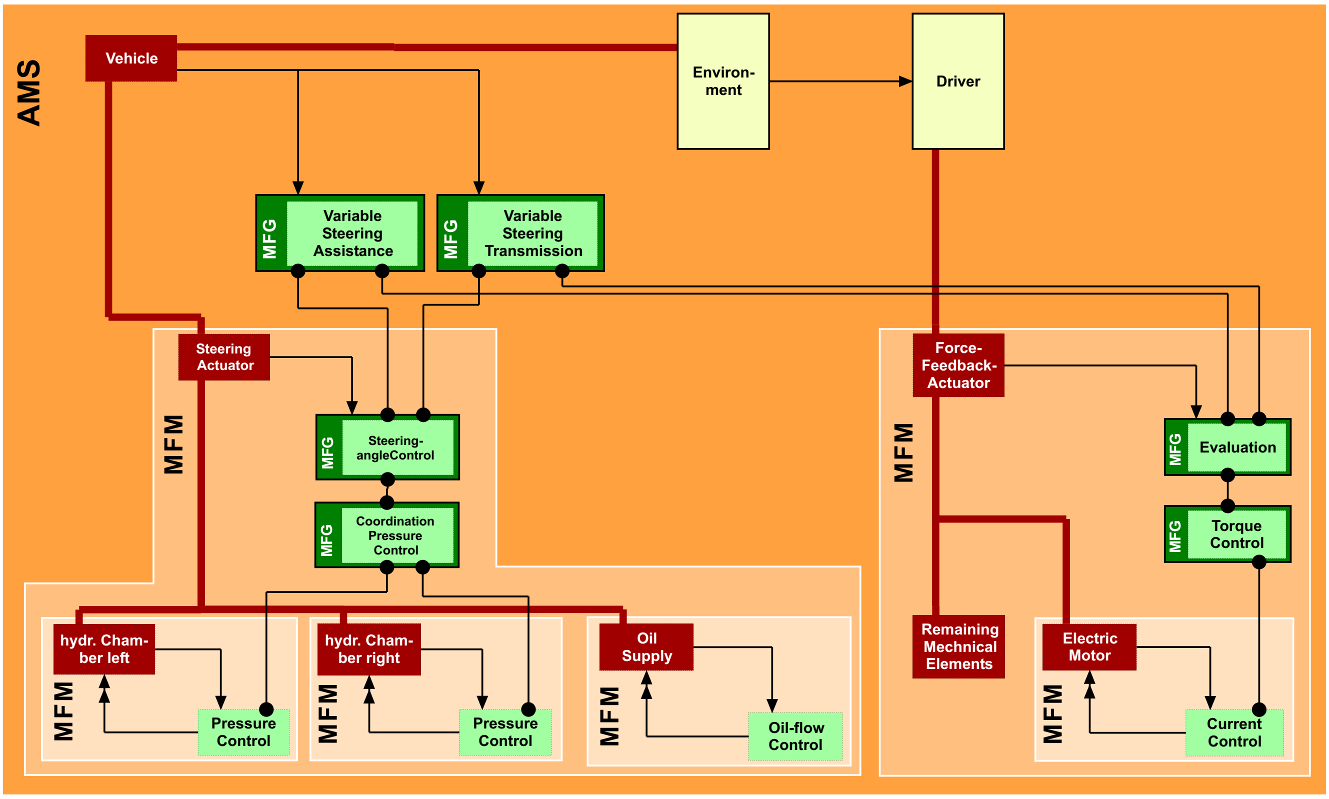

Fig. 3. Structure of the steering

In the contact phase and the intersection exit, the intersection management and the driver "vie" for control of the steering actuator. Access to the steering actuator has to be coordinated by another Mechatronic Function Group (MFG). This MFG will also coordinate the information transmitted to the driver via the feedback actuator.

From all this results a new extended structure which will be detailed in the following.

V. The Structure of the Steer-by-wire System in the Intersection Management

Fig. 4 displays the structure adapted to the requirements:

The central element in the realization of the reference values of the superordinated CMS "Intersection Management" regarding lateral vehicle dynamics is the MFG "Trajectory Control". As has been shown, this controller will only make sense if there is a simultaneous decision if and to what degree the trajectory control or the driver will set the task for the MFM "Steering Actuator". This task falls to the MFG "Coordination". To do so, the coordination obtains information from the intersection management, sensor signals from the vehicle and from the subordinated MFGs. On the basis of these information the reference values set by the driver and the intersection management, in variable proportion, are transmitted to the steering via the MFGs involved.

In the intersection, the simplest case involves transmission of the reference values set by the intersection management to the steering via the trajectory control while the variable steering transmission is switched off by the coordination. Outside the intersection, the reference values set by the driver are transmitted to the steering via the variable steering transmission while the coordination switches off the trajectory control.

The zone where the transition from manual to autonomous driving is realized is more interesting and challenging. Therefore this case is analyzed in the section "Results".

Just as the steering obtains orders from different sources, also the force-feedback unit is subject to situation-dependent conditions. During a ride within the intersection the force-feedback unit is used to transmit information from the intersection management to the driver via coordination and variable steering assistance. Outside the intersection the latter is again used according to its original purpose.

The example proves that increasing system complexity resulting from additional functions in the shape of MFGs necessitate not only the design of additional coordinating elements but also an adaption and suitable extension of existing functions (in the shape of MFGs). An early, sensible structuring, i.e., modularisation and hierarchisation, will keep even the design of complex systems manageable. In our example, the MFMs "Steering Actuator" and "Force-Feedback Actuator" remain unaffected by the extension in view of the intersection management; only steering assistance and -transmission have to be extended.

Fig. 4 reveals the independent character of the elements

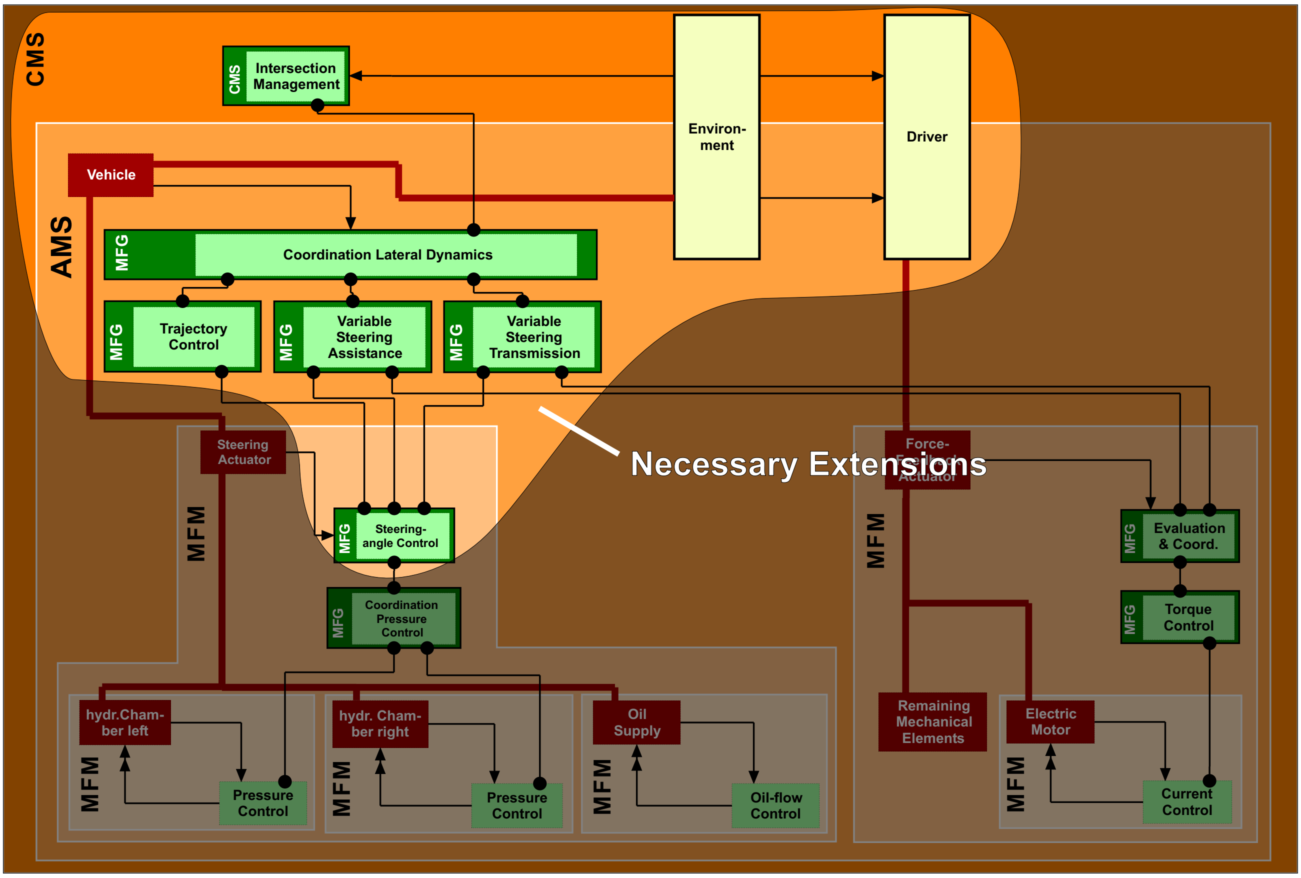

Fig. 4. Extended structure of the CMS

"driver" and "environment". These two cannot be assigned to a single level. Instead, all vehicles move within the same environment as does a single AMS. This is why "environment" is to be found both on the AMS- and on the VMS levels. What is more, the driver of a vehicle acts not only in response to local variables, such as yaw rate or accelerations stemming from the vehicle (AMS), but also according to the traffic situation, i.e., interacting with other road users (CMS).

VI. Results

A main part of the presented work was the development of manifold simulation models such as complex vehicle models with a hydraulic steer-by-wire system and vehicle dynamics controllers, models of the environment (definition of tracks, collision detection, etc.) and driver models. The combined overall model is the basis of the model based optimizations of the autonomous intersection management [13] and the presented results. Modelling and simulation is done in CAMeL-View, a tool devoloped by iXtronics [14] and the MLaP (Fig. 5).

Results showing the transition from manual to autonomous driving are presented in this section. The transition takes place in a zone where a double lane change is executed with constant velocity (Fig. 6).

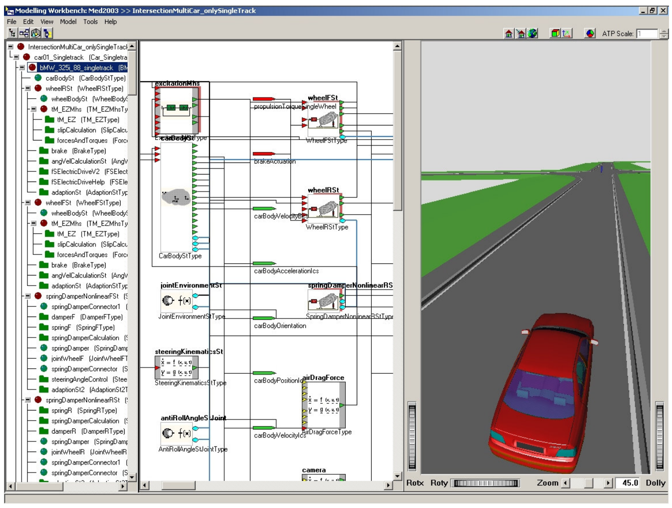

Fig. 5. Simulation model in CAMeL-View

The transition function was realized as a spline in order to have a continuous transition from driver to trajectory controller. Fig. 7 shows the resulting relative contributions by driver and trajectory controller.

The absolute contributions by driver and trajectory con-

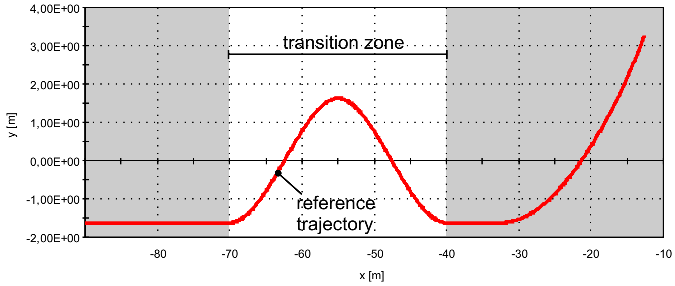

Fig. 6. Reference trajectory and transition zone

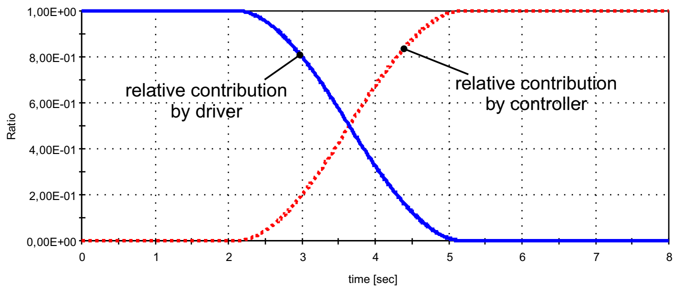

Fig. 7. Relative contributions

troller are the product of relative contributions and current demands by driver and trajectory controller (Fig. 8). The difference between the dynamics of driver and trajectory controller is obvious.

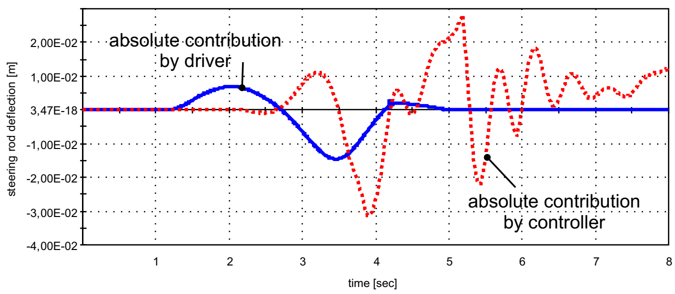

Fig. 8. Absolute contributions

The result of the steering motions, the lateral deviation between vehicle position and reference trajectory, is displayed in Fig. 9. While the driver is not able to follow the reference track very well the increasing contribution by the trajectory controller improves the result significantly.

VII. Summary and Outlook

The present article has proved that an appropriate structuring in the design of mechatronic systems can bring about interfaces of these systems which may reduce the expense required for a subsequent functional extension. The steer-by-wire system is structured in a way as to offer not only a basis for extensions like variable steering transmission and assistance but also a chance for an operation even in more complex systems, such as the decentralized, autonomous intersection management.

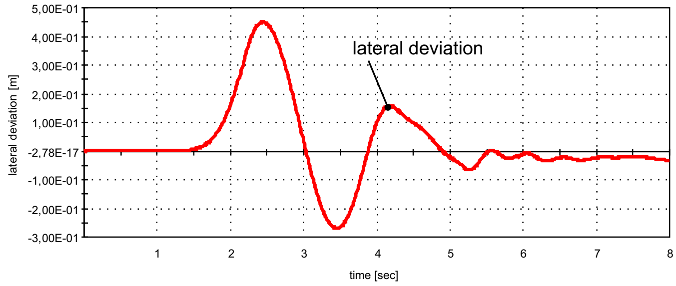

Fig. 9. Lateral deviation

While an intersection management lies in the remote future, the steer-by-wire system is nearing marketability. We are bound to watch it take on other functions little by little, functions that will make driving a vehicle more comfortable and safer than it is today.

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