2004-21-0073

Concept and Functionality of the Active Front Steering System

Willy Klier, Gerd Reimann and Wolfgang Reinelt
ZF Lenksysteme GmbH, Schwäbisch Gmünd, Germany

ABSTRACT

Active Front Steering (AFS) provides an electronically controlled superposition of an angle to the steering wheel angle. This additional degree of freedom enables a continuous and driving-situation dependent adaptation of the steering characteristics. Features like steering comfort, effort and steering dynamics are optimized and stabilizing steering interventions can be performed.

After the successful introduction of AFS (or active steering) together with the new BMW 5-series into the international market, ZF Lenksysteme focuses on aspects like system modularization and integration. For that reason the system bounds, its functionality, and the required system interface are defined to provide a compatibility to several overall chassis control concepts. This paper focuses on a modular system concept and its respective advantages and requirements.

1. INTRODUCTION

This steering system developed by ZF Lenksysteme and BMW AG enables driver dependent as well as automatic steering interventions without loss of the mechanical connection between steering wheel and road wheels [1,2,3] (see Figure 1).

This fact together with current definitions for steering systems imply that AFS is not a steer by wire system. The AFS system provides (compare [3,4,5,6]):

- an improved steering comfort (reduced steering effort),
- an enhanced dynamic behavior of the steering system (quick response to driver's input) and
- vehicle stabilization (active safety).

After a short description of the steering system and respective components in Section 2, the modular concept, its functionality and the required system interface will be illustrated in Section 3. Some conclusions and an outlook will be presented in Section 4.

2. COMPONENTS AND FUNCTIONALITY

The electrical and mechanical components as well as the functionality of the AFS system will be briefly described in this section. Figure 2 shows the following AFS components and subsystems:

- Rack and pinion power steering system including (see Figure 2) the main gear (1), a Servotronic valve (2), a steering pump (9), an oil reservoir with filter (10) and the respective hoses (11),
- AFS actuator including the synchronous motor (3) with its respective electrical connections, the superposition gear system (4) and the electromagnetic locking unit (7),

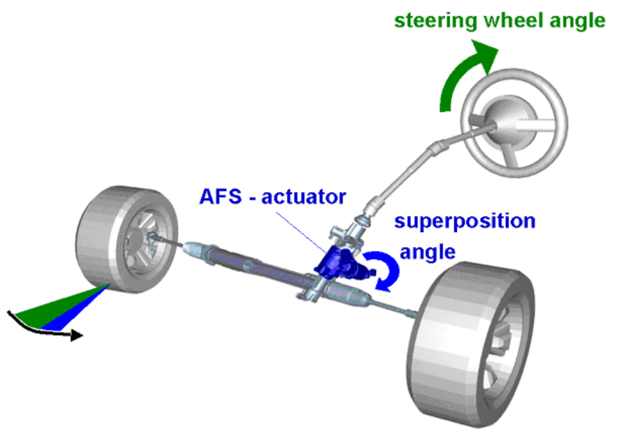

Figure 1: Principle of the angle superposition

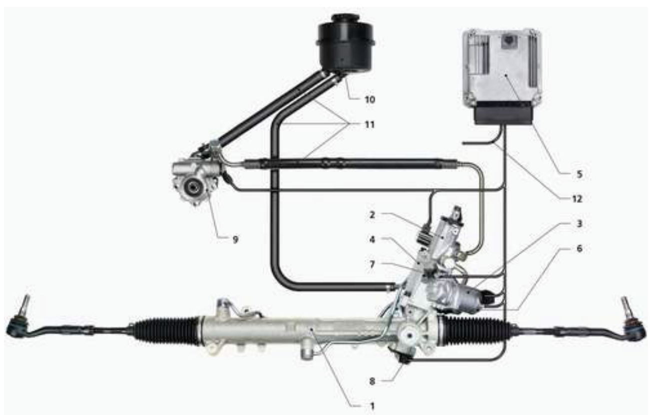

Figure 2 : Schematic representation of the AFS-system components

- AFS electronic control system with the AFS ECU (5), the pinion angle sensor (8), the motor angle sensor (6), the respective electrical connections of the ECU and the required software modules.

COMPONENTS

The electric motor (see Figure 3) generates the required electrical torque for the desired motion of the AFS actuator. This synchronous motor has a wound stator, a permanent magnet rotor assembly and a sensor to determine the rotor position. The motor torque is controlled by a field oriented control. This control strategy transform the stator currents into the torque- and rotor-flux-producing components. These current components can be controlled separately and do not depend on the rotor angle. The motor angle sensor is based on a magneto-resistive principle and includes a signal amplification and a temperature compensation. This sensor signal is used for control and monitoring purposes.

In analogy to the motor angle sensor, the pinion angle sensor is also based on a magneto-resistive principle and includes a signal amplification and a temperature compensation. This sensor also includes a CAN-interface which enables other control systems like ESP to directly use the raw signal. The pinion angle is used as an input to the steering assistance functions and for monitoring purposes.

The metal stud of the electromagnetic locking unit (ELU) is pressed towards the worm-locking gear by a spring. This mechanism is unlocked by a specific current supplied by the ECU. The ELU locks the worm (Figure 3) if the system is shut down and in case of a safety relevant malfunction (compare [7,8,9]). In this case the driver is able to further steer with a constant steering ratio (i.e. the mechanical ratio).

The electronic control unit developed for the AFS system establishes the connection between the electrical system of the vehicle, the vehicle CAN – bus, the AFS sensors and the electric motor.

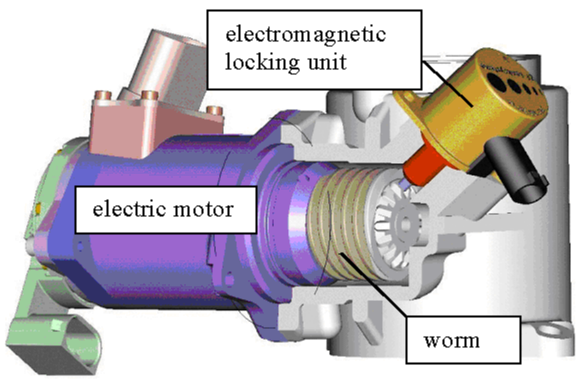

Figure 3 : Electric Motor and Electromagnetic Locking Unit

The core components of the ECU are two microprocessors. They perform the computations required for control, monitoring and safety purposes. Via the integrated power output stages, the electric motor, the ELU, the ECO–pump and the Servotronic subsystem are controlled. The microprocessors also perform redundant computations and monitoring.

The basis of the AFS system is the well-tried and reliable rack and pinion power steering system of ZF Lenksysteme.

The core subsystem of AFS is the mechatronic actuator which is placed between the steering valve and the steering gear (see Figure 4). The actuator includes the planetary gear set with two mechanical inputs and a single mechanical output. The servo-valve connects the input shaft of the planetary gear with the steering column and the steering wheel. The second input shaft is driven by the electric motor and is connected to the planetary gear by the worm and worm wheel. The pinion angle sensor is mounted on the output shaft, which is the mechanical input for the steering gear. The relation between the input of the steering gear (pinion) and the road wheel angle is a nonlinear kinematic relation.

FUNCTIONALITY

The functionality of AFS is defined by the so-called hardware oriented (low level) and the user oriented (high level) functions. These functions can also be classified into application and safety functions (see Figure 5).

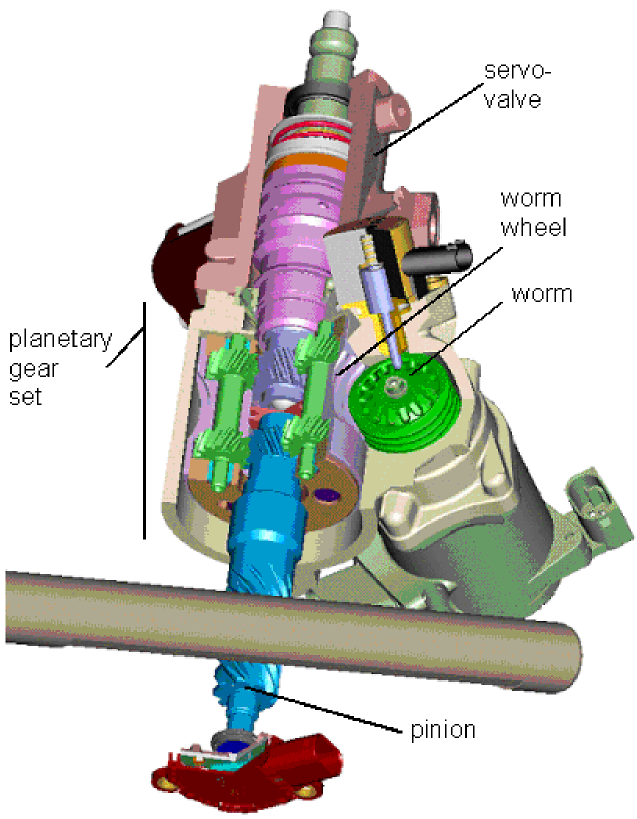

Figure 4 : AFS actuator

Application functions are those functions, that are required for the normal operation of the system. All other functions are part of the safety system. High level application functions can be classified into kinematic and kinetic functions (see Figure 6).

Figure 7 shows the signal flow of the AFS system in the vehicle-driver overall closed loop. With the vehicle signals as input, the stabilization (e.g. yaw rate control) and the assistance functions (e.g. variable steering ratio) compute a desired superposition angle. This angle serves as command input signal to the controlled actuator. A safety system monitors the function and the components of the steering system (compare [7] and [8]). Every failure or error, that may lead to a safety relevant situation, is identified and suitable actions are initiated in order to keep the system in a well defined state.

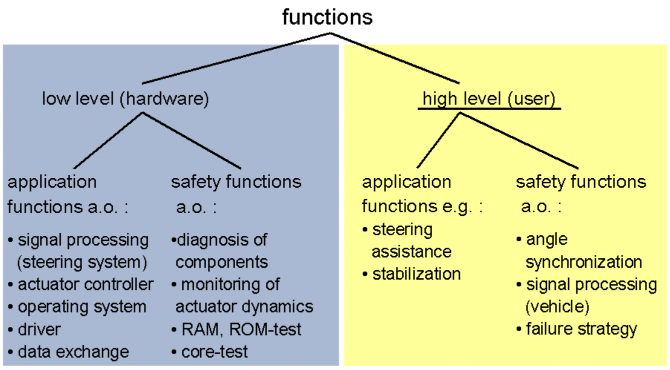

Figure 5 : Structure of the AFS Functionality

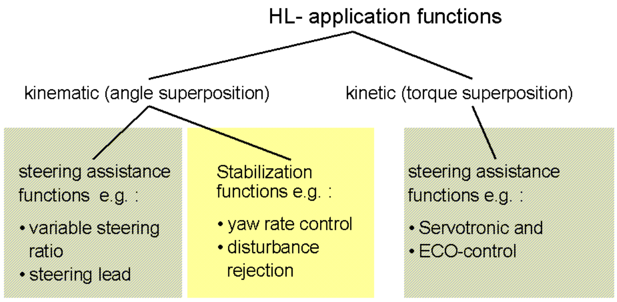

Figure 6 : Structure of high level functions

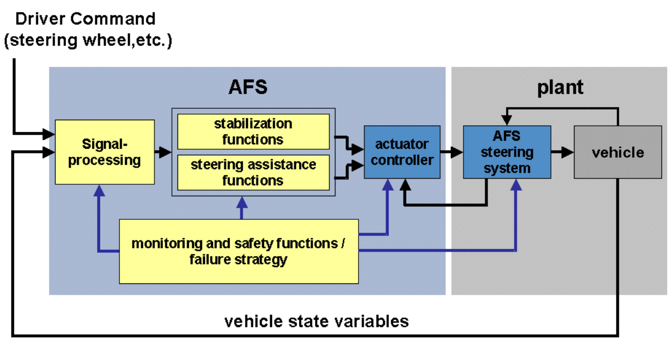

Figure 7 : Block diagram including the overall signal flow in the AFS system

These actions reach from partial deactivations of single functions to shutting off the AFS system (fail silent behavior).

In the next subsections, some high level functions of the AFS system will be described.

KINEMATIC STEERING ASSISTANCE FUNCTIONS

Kinematic steering assistance functions are feedforward controllers which adapt the static and dynamic steering characteristics to the current driving/vehicle situation as functions of the steering activity. This functionality is restricted by the actuator dynamics and the steering feel. These functions are part of the steering system (see Section 3). They are developed and implemented by ZF Lenksysteme.

Currently, the *variable steering ratio* (VSR) provides the most noticeable benefit for the driver. This kinematic function adapts the steering ratio i_V (1), between the steering wheel angle and an average road wheel angle, to the driving situation as a function of e.g. the vehicle velocity (see Figure 8). Under normal road conditions at low and medium speeds, the steering becomes more direct, requiring less steering effort (see Figure 9) of the driver which increases the agility of the vehicle in city traffic or when parking. At high speeds the steering becomes less direct, offering improved directional stability. Additional to the velocity dependency, the variable steering ratio developed by ZF Lenksysteme includes a dependency of the pinion angle i.e. rack displacement. This feature provides a reduced steering effort for large steering angles and a more precise steering for small steering angles.

The principle of this function is based on the definition of the steering ratio

$$i_V := \frac{\delta_S}{\delta_{Fm}} \quad . \qquad (1)$$

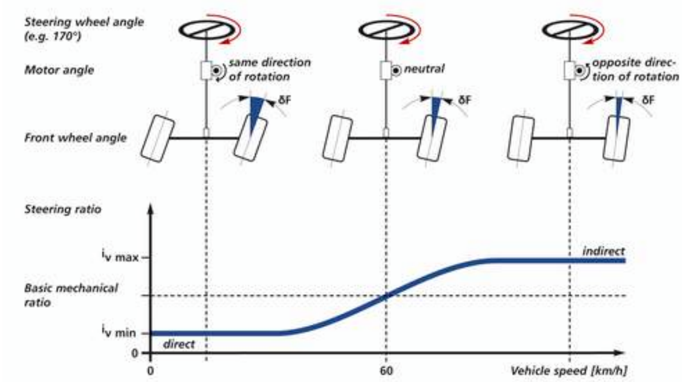

Figure 8 : Example of the variable steering ratio as function of vehicle velocity

Inserting the nonlinear kinematic relation $\left(\delta_{Fm} = f_{sk}\left(\delta_G\right)\right)$ between pinion angle δ_G, average road wheel angle δ_{Fm} and the linear kinematic relation $\left(\delta_G = k_M \cdot \delta_M + k_S \cdot \delta_S\right)$ between pinion angle, steering wheel angle δ_S and motor angle δ_M into (1) yields the relation

$$i_V = \frac{\delta_S}{f_{sk}\left(k_M \cdot \delta_M + k_S \cdot \delta_S\right)} \ . \qquad (2)$$

The core algorithm of the VSR function computes a motor angle δ_{Md}^{VSR} that fulfils (2) for a predefined desired steering ratio i_V and a measured steering wheel angle δ_S.

Another steering assistance function that is evident for the driver in usual driving conditions is the so-called *steering lead function* (SLD). This kinematic function adapts the steer response to the driving/vehicle situation as a function of suitable vehicle and steering measured signals. The ZF Lenksysteme approach includes a differentiating prefilter for the steering wheel angle (see Figure 10). The weighted steering wheel angular velocity $T_{SLD} \cdot \dot{\delta}_S$ defines then the desired motor angle (output of the SLD function) for the controlled AFS actuator.

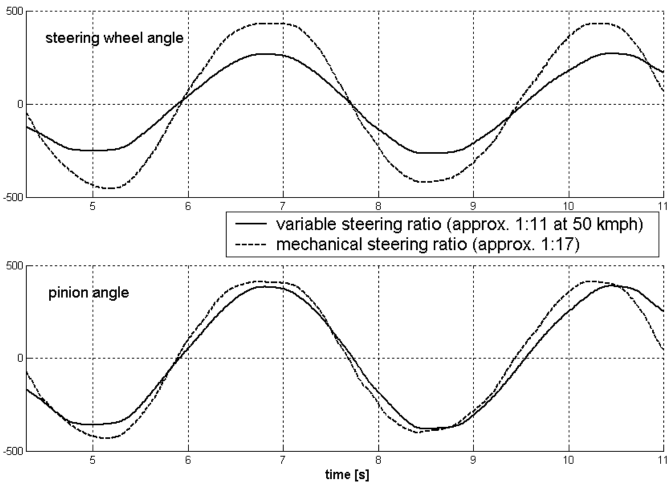

Figure 9 : Slalom ride (cones distance: 16m and vehicle velocity approx. 50 kph) with AFS/VSR and with a conventional mechanical ratio

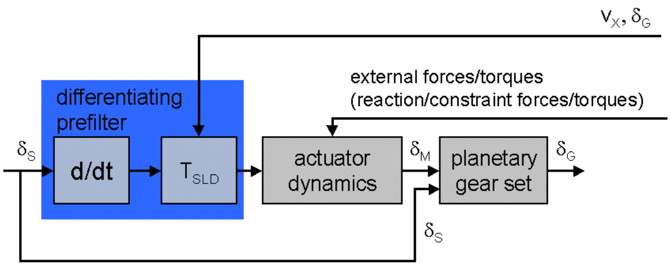

Figure 10 : Overall block diagram of the steering lead function

This algorithm represents an insertion of a zero[1] in the transfer function between steering wheel angle and average front wheel angle. This additional zero is placed so that the delay due to the dynamic of the steering system is reduced, partially compensated or if desired increased. Figure 11 shows the results of a double lane change manouver on asphalt at a vehicle speed of approx. 85 [km/h]. The increased steering dynamic reduces the required steering interventions in order to perform the driving task.

KINETIC STEERING ASSISTANCE FUNCTIONS

Kinetic steering assistance functions also include feedforward controllers. Besides the primary task of providing the usual steering torque assistance like in conventional steering systems, these functions the additional task is providing a reduction/compensation of the reaction torque caused by the AFS actuator motion. These functions are restricted by the steering feel and the dynamics of the steering system. They are part of the steering system (see Section 3) and are developed and implemented by ZF Lenksysteme.

The first kinetic function is the *servotronic control function* (SVT). The function algorithms include the computation of the desired current for the electro-hydraulic converter of the Sercotronic 2 component. The torque assistance is adapted to the driving/vehicle situation as a function of the vehicle velocity and the pinion angle velocity (actuator activity) (see Figure 12). The first dependency is the well-known vehicle-velocity dependent assistance torque, that provides the highest assistance torques for low velocities (i.e. steer comfort) and low assistance torques at high velocities in order to improve the lateral stability of the vehicle.

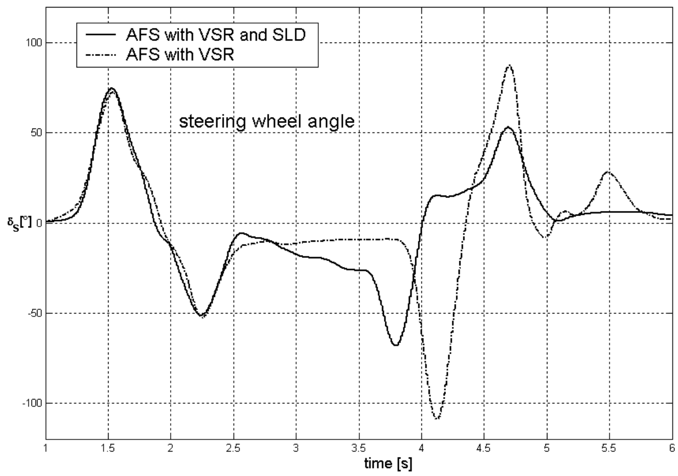

Figure 11 : Double lane change with and without the SLD function

[1] in terms of control engineering

The second dependency is AFS specific and sets a reduction/compensation of the reaction torque.

Due to the possible high rack-displacement velocities, a higher[2] flow rate is required in order to take fully advantage of the AFS functionality. On the other hand thermal strains and a high fuel consumption have to be avoided. For that reason an electronic controlled orifice pump that modifies the flow rate in the hydraulic system has been included into the steering system. Another important kinetic function includes the *control of the electronic controlled orifice pump* (ECO). The main task of this function is to compute a desired current for the ECO-pump as a function of the vehicle velocity and the pinion angle velocity (actuator activity). These dependencies have been chosen in analogy to dependencies for the Servotronic control.

KINEMATIC STABILIZATION FUNCTIONS

The stabilization functions represent another kind of consumer value increment. These functions include closed loop control algorithms that generate automatic[3] steering interventions to stabilize the vehicle (see Figure 13).

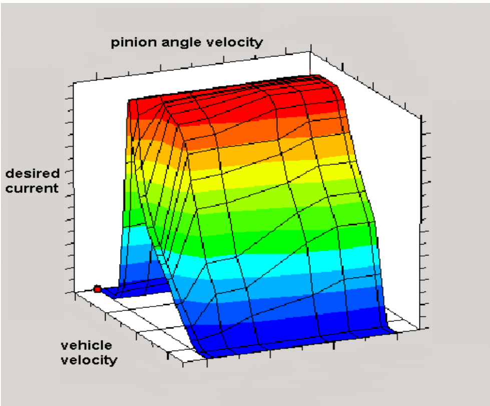

Figure 12 : Example of the dependencies of the desired current for the servotronic control

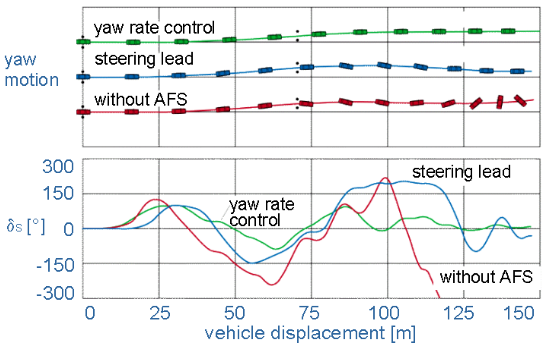

Figure 13 : Lane change / ABS-braking with different steering functions ($\mu \approx 0.2$)

[2] higher than the required flow rate for similar vehicles with conventional steering systems

[3] Automatic in a sense of an explicit independency from the steering wheel angle defined by the driver

They are not part of the steering system (see Section 3), they are developed and implemented by the car manufacturer. Some examples of this kind of functions are (see [4,6]):

- yaw rate control,
- yaw torque control and
- disturbance rejection function.

SAFETY AND MONITORING FUNCTIONS

The above described functions imply high requirements for the safety integrity of the system [8,9]. For this reason ZF Lenksysteme has developed a suitable safety concept for the steering system that includes several safety and monitoring functions on high and low level (see [7]).

3. MODULAR CONCEPT

In the first phase of the market introduction of AFS, ZF Lenksysteme developed the rack and pinion steering components, the mechatronic actuator as well as the electronic control unit which includes the low level software (see Figure 14). BMW developed the safety concept, the application and associated safety high level functions and also took the system responsibility [4,9] (see Figure 14). In the second phase of the AFS development ZF Lenksysteme focuses on a modular concept that simplify the combination and integration of the AFS system with other chassis control systems and in different vehicle platforms [10]. The modular concept implies a clear distribution of responsibilities and the associated functionality and safety distribution (see Figure 15). Hereby, the steering system has to be autonomous and keep the complete steer functionality even in case of failure or absence of several vehicle dynamic control systems (including the kinematic stability functions). The simplest approach to achieve this autonomy is a separation of vehicle and steering functionality and safety in a hardware level.

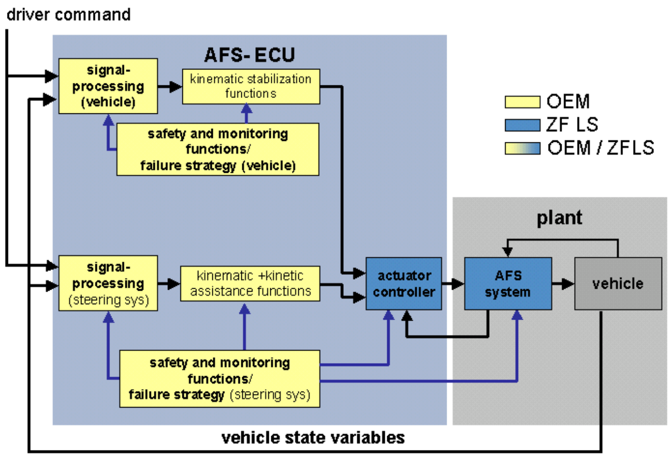

Figure 14 : Overall block diagram of the first system concept

This implies running the kinematic stabilization function on a separated ECU, e.g. the ESP control unit taking into account that several required vehicle motion signals are available and even parts of the required algorithms are already implemented.

An essential requirement for the modular concept is a new system interface that allows an external intervention for stabilization purposes. Such a system interface has been developed together with involved car manufacturers and component suppliers based on well-known principles like the Cartronic approach. This provides a compatibility with current and future system concepts and development organization structures (e.g. integration of the system by a third party). Moreover, the modular concept with the mentioned interface allows a parallel development of the stabilization and steering assistance functions and reduces the required testing activities for the integrated steering system.

SYSTEM INTERFACE

In order to simplify the description of the interface for the modular AFS system, it will be defined in three phases (see Figure 16)

- assistance,
- assistance and stabilization and
- assistance, stabilization, manual configuration and diagnosis.

The pure assistance interface exclusively includes input signals (**I$_1$**):

- signed road wheel speeds: input signals of safety and steering assistance functions,
- status of the road wheel speeds: requirement for utilization of the road wheel speeds,
- steering wheel angle: input signal of a single safety function and several kinematic assistance functions,

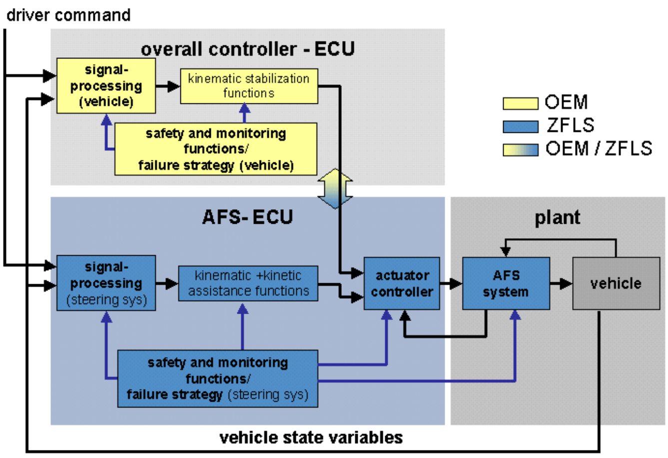

Figure 15 : Overall block diagram of the modular system concept

- ESP and ABS intervention flags: binary signal for each road wheel including a brake intervention flag used in safety functions,
- engine revolutions: input signal of the system dynamic monitoring function,
- current gear: this signal is required only if the sign of the road wheel velocities is not available,

The interface required for assistance and stabilization interventions includes besides **I1** additional input signals (**I2**):

- desired superposition angle for vehicle dynamic stabilization: input signal which includes a relative superposition angle, represented as an average road wheel angle or pinion angle. This angle is relative to the current absolute assistance superposition angle,
- execute flag of the stabilization intervention: condition for performing the stabilization intervention. This signal also includes the associated safety information about the intervention command.

This interface also includes an output (**O2**) required by the overall vehicle dynamics controller and defined by the following signals:

- current average front wheel angle: this signal is computed from the measured pinion angle and the known nonlinear steering kinematics,
- requested steering angle: this angle is computed from the measured steering wheel angle and the current desired steering ratio, represented as an average road wheel angle or pinion angle,
- desired superposition assistance angle: output from the kinematic steering assistance functions, represented as an average road wheel angle or pinion angle,
- dynamic capacity: estimated maximal additional angular speed that can be demanded by an external vehicle controller,
- system status: this signal includes information about the current system mode (e.g. initialization, on, etc.),

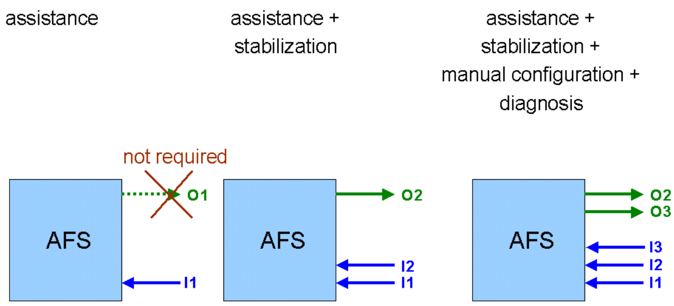

Figure 16 : Interface for the modular AFS concept

- raw pinion angle: raw signal of the pinion angle sensor. The receiver of this signal has to perform own plausibility checks.

Finally the complete system interface includes the inputs **I1** and **I2** as well as **I3** with the signals:

- VSR flag: signal for switching the mode of the VSR (e.g. sport, comfort),
- SVT/ECO flag: signal for switching the mode of the kinetic steering assistance functions (e.g. sport, comfort).

The complete interface also includes besides the outputs **O1** and **O2**, the output **O3** with the signals:

- current superposition angle: this signal provides a redundant information that can be used by the overall vehicle dynamics controller for diagnosis/monitoring purposes,
- failure code: this signal includes information about all failures/errors that are relevant for diagnostics.

4. CONCLUSION

The market introduction of the Active Front Steering system represents an important step towards an entire chassis control in a series vehicle. The high equipment rate of AFS in the new BMW 5-series shows the enormous interest of the customers in the system due to the evident and continuous benefit experienced.

Consequently, ZF Lenksysteme had to focus on a modular system concept that allows an independent development of assistance and stabilization (vehicle control) functions.

Moreover, the enclosure and autonomy of the steering system improves the availability and allows reuse of functions and components for several vehicle platforms. The defined system interface minimizes the application and testing time and costs. The protection of the OEM and supplier know-how is also supported by the modular concept, allowing an overall system integration by a third party.

ACKNOWLEDGMENTS

We would like to thank our colleagues Reinhard Grossheim, Wolfgang Schuster, Ralf Redemann and Christian Lundquist for their excellent work developing the assistance and safety functions as well as the failure strategy for the modular concept of ZF Lenksysteme. We also would like to thank Peter Brenner and Gerd Mueller for making possible the software development of the high level functions.

REFERENCES

1. Klier, W., Reinelt, W., Active Front Steering (Part 1) – Mathematical Modeling and Parameter Estimation, SAE technical paper 2004-01-1102, SAE World Congress, Steering & Suspension Technology Symposium. Detroit, USA, March 2004.
2. Klier, W., Reimann, G., Reinelt, W., Active Front Steering – Systemvernetzung und Funktionsumfang, Steuerung und Regelung von Fahrzeugen und Motoren – AUTOREG 2004, March 2004, pp. 569 – 583, 2004.
3. Reinelt, W., Klier, W., Lundquist, Ch., Reimann, G., Schuster, W., Großheim, R., Active Front Steering for Passenger Cars – System Modelling and Functions, IFAC Symposium – Advances in Automotive Control. Italy, April 2004, pp. 697 – 702, 2004.
4. Knoop, M., Leimbach, K.-D. und Verhagen, A., Fahrwerksysteme im Reglerverbund, Tagung Fahrwerktechnik, Haus der Technik, Essen, 1999.
5. Köhn, P., Baumgarten, G., Richter, T., Schuster, M. und Fleck, R., Die Aktivlenkung - Das neue Fahrdynamische Lenksystem von BMW, Tagungsband Aachener Kolloquium Fahrzeug- und Motorentechnik 2002, pp. 1093 – 1109, 2002.
6. Fleck, R., Aktiv-Lenkung – Ein wichtiger erster Schritt zum Steer-by-Wire, Tagung PKW-Lenksysteme – Vorbereitung auf die Technik von morgen, Haus der Technik e.V., Essen, 2003.
7. Reinelt, W., Klier, W., Reimann, G., Active Front Steering (Part 2) – Safety and Functionality, SAE technical paper 2004-01-1101, SAE World Congress, Steering & Suspension Technology Symposium. Detroit, USA, March 2004.
8. Reinelt, W., Klier, W., Reimann, G., Systemsicherheit des Active Front Steering, Steuerung und Regelung von Fahrzeugen und Motoren – AUTOREG 2004, March 2004, pp. 49 – 58, 2004.
9. Eckrich, M., Pischinger, M., Krenn, M., Bartz, R. und Munnix, P., Aktivlenkung – Anforderungen an Sicherheitstechnik und Entwicklungsprozess, Tagungsband Aachener Kolloquium Fahrzeug- und Motorentechnik 2002, pp. 1169 – 1183, 2002
10. Kirchner, A., Schwitters, F., Vernetzte und modulare Auslegung von Fahrerassistenzfunktionen, VDI – Tagung Elektronik im Kraftfahrzeug 25. Und 26. September, Baden-Baden, 2004.

CONTACT

Dr. Willy Klier, ZF Lenksysteme GmbH, Dept. ZEMF Active Front Steering – (Team Leader) Safety and Algorithms, Richard-Bullingerstr. 77, 73527 Schwäbisch Gmünd, Germany, Tel.: +49/7171312589, Email: Willy.Klier@ZF-Lenksysteme.com