Handbook of Driver Assistance Systems
DOI 10.1007/978-3-319-09840-1_32-1

Steering Actuator Systems

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Abstract

The steering converts the turning movement applied to the steering wheel by the driver into a change in the steering angle of the steered wheels. At the same time, its job is to inform the driver, by means of the haptic feedback, of the current driving situation and the road conditions.

Keywords

Angle superimposition; Electrohydraulic power steering; Electromechanical power steering; Hydraulic power steering; Rear-axle steering systems; Steer-by-wire steering system and individual wheel steering; Superimposing angles; Superimposing torques; Torque sensor; Torque superimposition

1 General Requirements Placed on Steering Systems

The steering converts the turning movement applied to the steering wheel by the driver into a change in the steering angle of the steered wheels. At the same time, its job is to inform the driver, by means of the haptic feedback, of the current driving situation and the road conditions. The steering system is therefore a crucial factor helping to ensure comfortable and safe control of the vehicle. Its main features are the following:

– The actuating force of the steering should be as low as possible and adjusted to the driving state. The requirement for low actuating forces in particular when the vehicle is stationary or slowly rolling has led to the situation where nearly all vehicles today are equipped with power steering. At the same time, however, it must be ensured when complying with this requirement that the low actuating forces do not lead to any loss in the haptic feedback from the roadway during fast driving and hence to uncertain and unstable straight-ahead driving.
– The number of steering wheel turns from one steering stop to the other should be as low as possible, while it is however also necessary to support the straight-line stability of the vehicle at higher driving speed by a not-too-direct steering ratio.
– The transmission of the steering wheel angle up to the wheel stop angle must be absolutely precise and backlash-free.
– As soon as the vehicle is moving, the wheels must revert back by themselves to the straight-line position once the steering wheel is released. This applies both for exiting from bends and for very minor steering movements on straight stretches, for example, during motorway driving.
– The feedback and jolts indicating the driving state and the roadway conditions must be strong enough to be noticed by the driver, but cushioned to prevent stress and fatigue for the driver.

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DOI 10.1007/978-3-319-09840-1_32-1

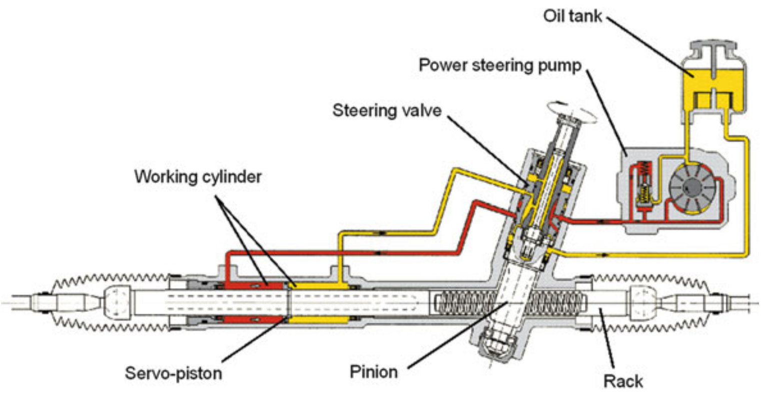

Fig. 1 System concept for hydraulic rack-and-pinion power steering

The statutory requirements relating to steering systems in motor vehicles govern in particular the maximum permissible actuating force and duration in an intact and failure-prone steering system and are described in the European Directive 70/311/EEC.

2 Basic Solutions for Steering Assistance

Due to the requirements relating comfort and safety, power steering systems are now being used in all vehicle classes. Until a few years ago, these were mainly hydraulic systems. Continued development of electrical and electronic systems plus additional requirements, such as that of energy saving, has resulted in more and more electrically assisted steering systems being used, from small cars and compact and midrange vehicles up to those in the luxury class.

2.1 Hydraulic Power Steering (HPS)

A conventional hydraulic power steering system consists of integrated steering valve and hydraulic cylinder within the steering gear, a power steering pump, an oil tank, and tubes and pipes to connect these components (cf. Fig. 1).

The power steering pump powered directly by the combustion engine is designed to provide a sufficient oil pressure and oil quantity at the idling speed of the combustion engine. Since this design would lead to an excess delivery quantity at high speeds, for example, when driving on motorways, a valve is integrated to regulate the oil flow. To prevent overloading, for example, when steering against the end stop, a pressure relief valve is incorporated.

The power steering pump is connected to the steering gear by pipes/tubes. The expansion hoses used are able to absorb the pressure peaks caused by the power steering pump and by roadway impacts. They also ensure control stability of the hydraulic circuit.

While hydraulic car steering systems once used above all the so-called recirculating ball-and-nut steering, the demands for compactness, low weight, and simple design have resulted in the use of rack-and-pinion steering gear in nearly all cars. The turning movement by the driver is converted by a pinion into a pushing movement of the rack. The connection to the wheels is made by means of tie rods and matching joints.

To control and convert the hydraulic auxiliary power, a control valve and a working cylinder are integrated into the steering gear. The control valve controls an oil pressure in the steering cylinders that

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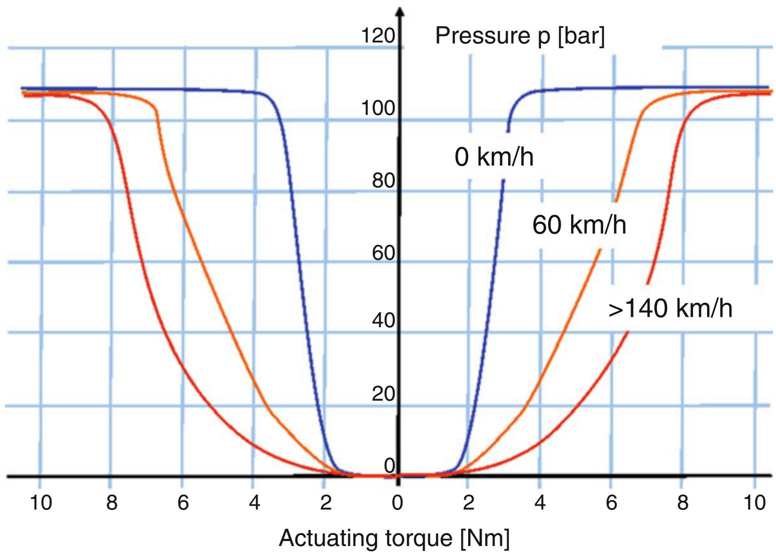

Fig. 2 Servotronic® valve characteristic

corresponds to the turning effort of the driver. The turning of a torsion bar leads to a mechanical control travel in the steering valve which is proportional to the force. Due to this control travel, control edges designed as chamfers and facets are displaced and thus form the opening cross section for the oil flow. The steering valves are designed according to the "open-center" principle, meaning that the oil coming from the pump flows without pressure back to the oil tank when the control valve is not actuated.

The double-action steering cylinder on the rack converts the controlled oil pressure into an appropriate auxiliary force. Thanks to the control valve, the compartments of the steering cylinder are switched in the neutral position in such a way that an unhindered pushing movement of the rack is possible. By introducing a torque at the steering valve, the oil flow of the pump is diverted into the appropriate left-hand or right-hand cylinder compartment, generating the required force. Appropriate design and shaping of the chamfers on the control edges of the valve allows the relationship of the actuating torque at the steering valve and the force curve at the cylinder to be traced. This matching allows the intended individual steering characteristics of the respective vehicle to be achieved.

2.2 Parameterizable Hydraulic Power Steering

Rising demands for comfort and safety in the vehicle have resulted in the development of steering valves with electrically modulatable assistance characteristics. An electrohydraulic converter determines the hydraulic effect and hence the actuating force on the steering wheel. The electrical actuation of the converter is handled by an assigned electrical control unit. The main input signal for the control unit is the vehicle speed. The electric current in the converter is controlled in such a way that the steering assistance decreases as the vehicle speed increases. This results in high steering comfort, thanks to the low actuation forces at low vehicle speeds and high steering precision at high speeds (Fig. 2).

2.3 Electrohydraulic Power Steering (EHPS)

An alternative to conventional hydraulic power steering with a vehicle-engine-driven hydraulic pump is a system which uses a steering pump, driven by an electric motor. A major advantage of this system is the energy saving achievable with this operation of the electric motor. The required electrical energy is drawn from the vehicle's electric power system, while the electric motor is operated by an electric control unit (Fig. 3).

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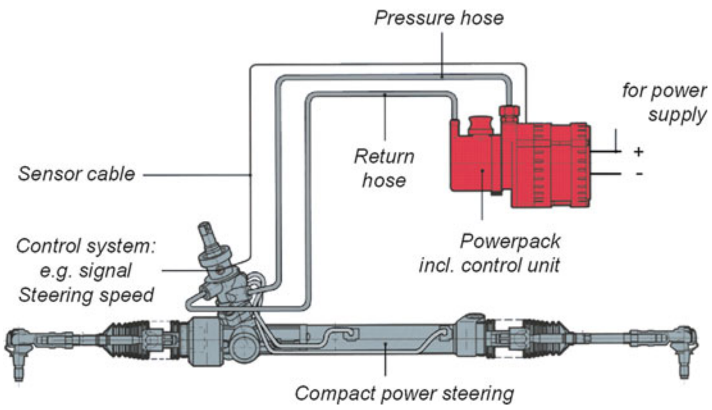

Fig. 3 System concept for electrohydraulic power steering

The hydraulic pump is designed in current systems as a gear pump or roller vane pump. The electric motors used in the standard solutions are designed as brush-type or brushless DC motors. The required steering effort is ascertained by sensors in the steering system and from the vehicle. These are primarily the steering and vehicle speed which is evaluated by the electric control unit, from which the set speed for the electric motor is calculated and regulated using the integrated end power stage.

2.4 Electromechanical Power Steering (EPS)

Electromechanical power steering was developed to increase steering comfort, to further reduce energy consumption, and to simplify installation work in the vehicle. Originally used only in small vehicles, it is becoming increasingly widespread in all vehicles, including the luxury class. The basic operating principle is always the same: A torque sensor records the manual force of the driver, and an electric control unit evaluates these signals and calculates from them, taking into account further information from the vehicle such as vehicle speed, an appropriate set assistance torque for an electric motor. The latter is operated by an appropriate end power stage and passes its output torque to the steering via one or more gear stages. The type and design of the gear stages depend mainly on the requirements of the steering system in terms of installation space and the maximum steering assistance to be achieved.

2.4.1 Column-Type EPS

In case of vehicles with less strict demands placed on steering assistance and maximum steering speed, the servo force is usually introduced to the steering column. The servo unit, consisting of the torque sensor, the electric motor, and the reduction gear, is arranged inside the vehicle interior on the steering column. The electric control unit can here be designed separately as a remote solution or attached to the motor or sensor. The reducing gear is usually designed as a worm gear. In designing this gear stage, care must be taken that a sufficient back-turning efficiency is achieved in this unit in order to assure the necessary haptic feedback of the steering system to the driver or to assure back-turning of the steering system by itself when the steering assistance is switched off. The nonpositive connection to the steered wheels is achieved via the intermediate steering shaft and a mechanical rack-and-pinion steering gear (Fig. 4).

2.4.2 Pinion-Type EPS

A similar solution is pinion-driven electric steering. The servo unit, consisting of torque sensor, electric motor, gear stage, and a possibly integrated or attached electric control unit, is here arranged on the steering gear in the area of the steering pinion.

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Fig. 4 Column-type EPS

Fig. 5 Pinion-type EPS

The assistance power provided by the electric motor via the worm gear is supplied directly to the pinion. The resultant advantages of this solution are a compact design and, in comparison to the steering column solution, a stiffer mechanical connection of the steering assistance to the rack. This leads not only to a possible higher assistance capacity but also to an improvement in steering precision. Disadvantages arise due to the more strict demands relating to environmental conditions, since the servo unit is installed in the engine compartment, exposing it to higher ambient temperatures and splash water (Fig. 5).

2.4.3 Dual Pinion-Type EPS

For a further increase in the assistance capacity and in steering precision, solutions are used which transmit the servo force directly to the rack. With the dual pinion solution, the force of the servomotor acts

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Fig. 6 Dual pinion-type EPS

on a pinion, as in the pinion solution, via a worm gear. This is however arranged on a second and separate toothing on the rack. The spatial separation from the pinion permits higher flexibility during integration inside the vehicle. Thanks to the independence of the servo pinion to the steering pinion, the different objectives of these two pinion stages can be taken into account and so optimized in respect to comfort, capacity, and service life. The torque sensor for recording the steering torque introduced by the driver is, like in the following variants, arranged on the steering-spindle-side input of the steering gear (Fig. 6).

2.4.4 APA-Type EPS

A further possibility for converting the rotary movement of the servomotor into a pushing movement of the rack is to use a ball screw on the rack. This gear type combines very high mechanical efficiency, high loading capacity, and the absence of backlash necessary for precise steering. The transmission of forces with this gear type is from the ball nut via a continuous chain of hardened steel balls to the rack, which is provided with one or more ball screw threads. The ball nut is driven by an electric motor arranged parallel to the rack and connected to the ball nut via a toothed-belt gear stage. This gear stage too operates without backlash and with a very high mechanical efficiency. By appropriate design and selection of the transmission ratios, it is possible with a steering gear of this type, as is also the case with the dual pinion solution, to adjust the performance of the steering to the vehicle in question and to adjust the available motor capacity in the direction of high and maximum rack forces or toward high steering dynamics. Electrical steering gears with this design solution can be used in vehicles up to the luxury class and large SUVs (Fig. 7).

2.4.5 Rack-Type EPS

The rack solution is a further option for transmitting the rotary movement of the electric motor to the rack. The ball nut of the ball screw is here driven directly by the electric motor without any additional gear stage. Therefore, the electric motor must be designed with a hollow shaft through which the rack is passed. A high degree of steering precision and dynamism can be achieved with this compact and direct connection of the motor, recirculating ball gear and rack. The lack of a gear stage when compared with the axis-parallel solution leads to the electric motor needing to have a comparatively high torque at lower

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Fig. 7 APA-type EPS

Fig. 8 Rack-type EPS

speeds. The direct connection of the motor also requires a particularly high quality for the steering and motor control (Fig. 8).

2.5 Electrical Components

The general requirements placed on the electrical and electronic components of the EPS solutions presented are substantially identical. They differ only in the specific requirements relating to environmental conditions and the performance to be achieved.

2.5.1 Torque Sensor

The torque sensor is designed as a proximity-measuring angle sensor which records the angular rotation of a torsion bar and converts it into electric signals. The measurement range of a torque sensor for an electric

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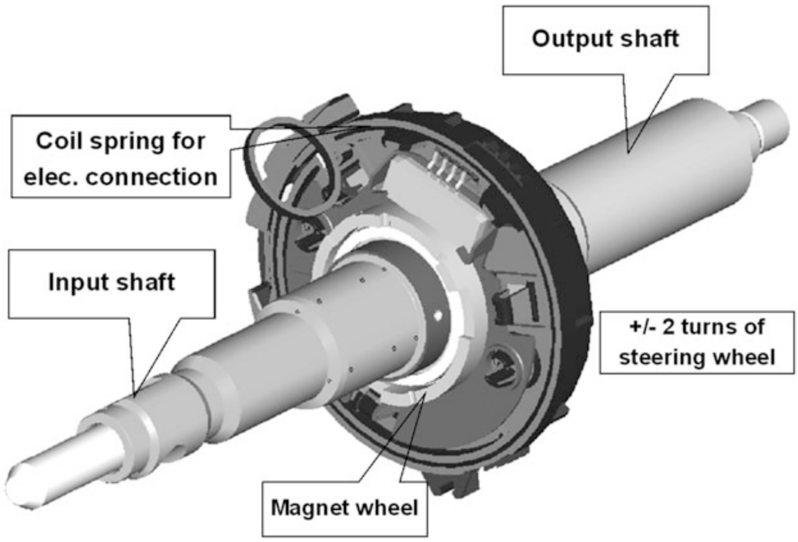

Fig. 9 Torque sensor

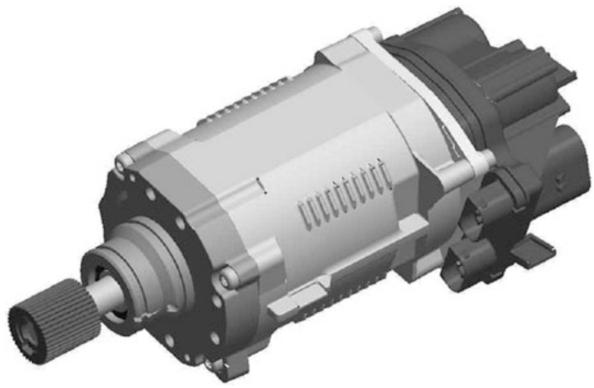

Fig. 10 Electric motor

power steering system is usually in the range from ±8 to ±10 Nm. In case of higher manual torques, a mechanical angle limiter on the torsion bar ensures that the latter is not overloaded. The electric control unit calculates the current torque value from the sensor signals. The high safety requirements expected from electric steering systems demand that all errors occurring in the sensor can be detected and result in a safe state in the steering system (Fig. 9).

2.5.2 Electric Motor

The electric motors used in electric steering systems can be a brush-type DC or a brushless DC motor as well as an induction motor. Thanks to their sturdiness and the higher power output possible, it is the brushless motor variants that are increasingly being used. Steering power for vehicles in the upper midrange and luxury classes in particular calls for the use of highly effective and brushless DC motors. These motor variants require a motor position or motor speed sensor which is evaluated by the electric control unit and used for commutation and control of the motor (Figs. 10 and 11).

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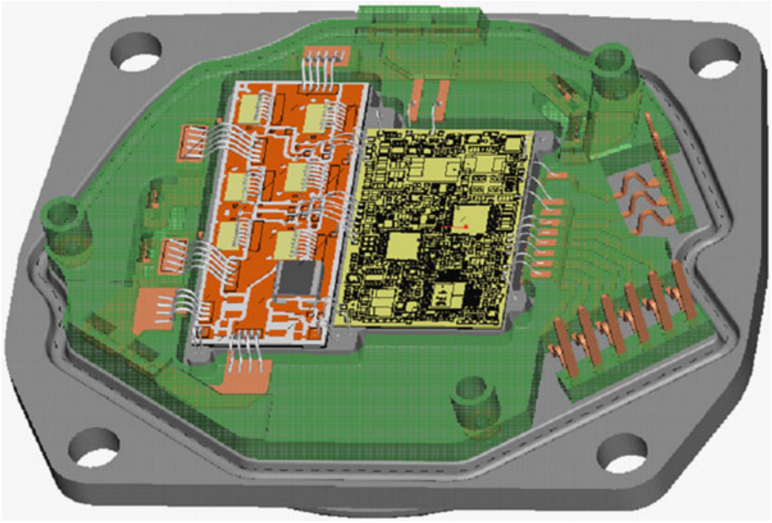

Fig. 11 Control unit

2.5.3 Control Unit

The associated electric control units contain one or more microprocessors which evaluate the sensor signals from the steering components and from the vehicle and then compute the set assistance torque and operate the motor using an appropriate motor control system and the end power stage integrated into the control unit with MOS field effect transistors. Sensors for recording the motor current and the control unit temperature are integrated into the control unit. To increase the steering comfort, further vehicle signals, in particular the vehicle speed and the steering wheel angle, are evaluated by the control unit. Using the information on vehicle speed, a speed-dependent steering assistance can be achieved which permits low actuating forces when the vehicle is stationary or moving slowly, while the steering assistance is continuously scaled back as vehicle speeds increase, improving the haptic feedback from the steering and also the directional stability. With the signals of the steering angle sensor, the return movement of the steering can be set and improved particularly for low and medium vehicle speeds and so adapted to the target vehicle. A multistage safety concept ensures that a reduction of the steering assistance ensues, gradually where possible, in the event of unusual states or errors. In the event of a complete failure of the steering assistance, it is ensured by the electrical and mechanical design that manual steering of the vehicle remains possible. The error memory of the control unit can be output at the diagnostic interface of the control unit, permitting an accurate diagnosis in the event of a fault. Operation of the electric motor by the software in the control unit permits a very sensitive and individualized adjustment of the steering assistance to the target vehicles. By evaluating further sensors from the vehicle or by providing appropriate communication interfaces with the control unit, it is possible with the EPS steering systems to implement efficient and innovative driver assistance functions (Fig. 11).

3 Solutions for Superimposing Torques

If haptic feedback is to be provided to the driver via the steering wheel or by autonomous assistance functions, a steering torque influence that can be activated independently of the driver is required in the steering systems. In the case of hydraulic steering systems, this is not possible without additional actuators, apart from the parameterizable hydraulic steering. Since this system however generally already requires a steering torque to be built up by the driver in order to vary the assistance, this cannot be regarded

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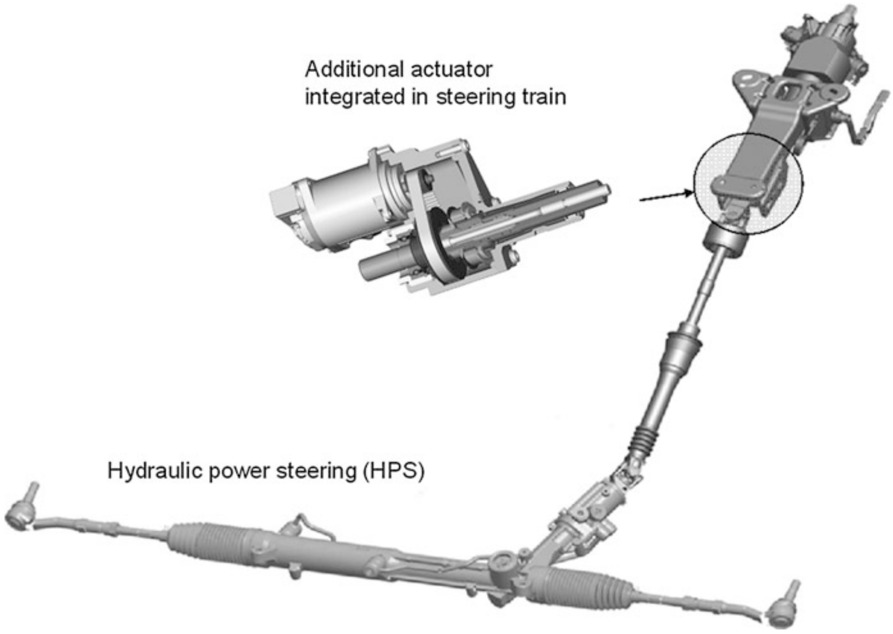

Fig. 12 Additional actuator

as a fully fledged solution for self-contained superimposition of assistance torques. If steering torque assistance is nevertheless to be implemented with a hydraulic steering system, then additional actuators are needed to do so.

3.1 Additional Actuator for Hydraulic Steering Systems

An obvious solution for an additional actuator to implement steering assistance functions with a hydraulic or electrohydraulic basic steering is a steering actuator in which an additional torque, controllable independently of the driver, can be applied to the steering column via a gear stage and an electric motor. The design of an actuator of this type does not differ in principle from steering column EPS (Fig. 12).

Since however only one additional torque, and not the entire steering torque as is the case with EPS, has to be applied by this actuator, the dimensions of the mechanical and electrical components are markedly reduced. If a hydraulic steering system is to be operated with an actuator of this type, an effective torque of 8–10 Nm relative to the steering column is sufficient. Since this also results in lower demands on the loading capacity of the gear stage compared to steering column EPS, alternative and constructive solutions can be applied for the gear stage between the motor and the steering column.

It must however still be ensured that no disruptive torque unsteadiness that might irritate the driver is transmitted into the steering train by the additional actuator.

If this additional actuator is to be used for implementing functions which require a steering torque from the driver, a torque sensor must be installed either in this actuator itself or at another suitable position in the steering train between the driver and the actuator.

Since this is purely an additional system for an already installed power steering system, the safety considerations here are focused on this additional actuator and on the control units connected to it. If the degradation stages in the event of detected faults in the assistance functions are disregarded, the actuator must, whenever an error is detected in the motor or in the sensors connected to it, be put in a state that largely reduces disruptive additional torques and rules out dangerous ones. This means that the motor must be either mechanically disconnected from the steering train using a coupling or the motor must be

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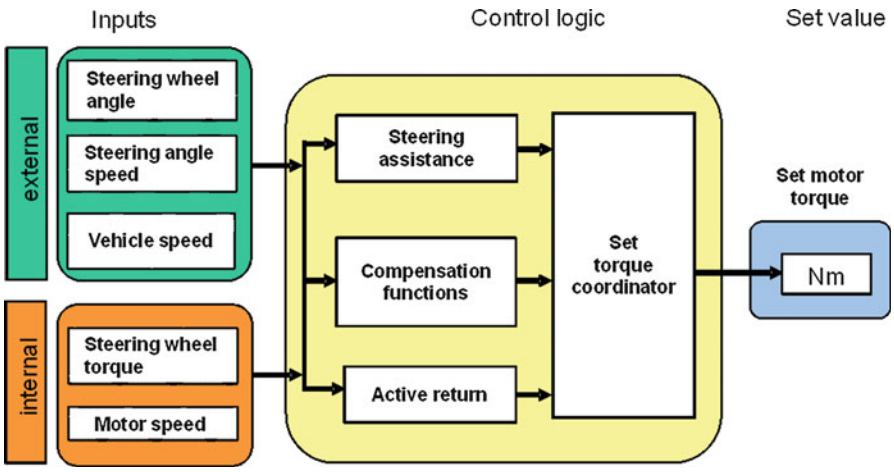

Fig. 13 Control structure of EPS

switched off in such a way that it can on no account build up disruptive braking torques that prevent safe driving of the vehicle.

3.2 Electric Steering Systems

Electric power steering offers ideal conditions as an actuator for steering-based assistance functions, since the electric motor is operated using the software of the control unit. The torque sensor implemented for recording the driver steering torque in the EPS can also be used for the assistance functions to be provided. The electric motor, already firmly connected to the steering train via an appropriate gear stage, can be used not only for providing the servo power but also and at the same time to apply the assistance torque required by the higher-level systems. Since the magnitude of the assistance torque is several times less than the servo torque, it is not necessary as a rule to design the electric motor of the EPS and to increase its power output in order to provide the additional torque (Fig. 13).

3.2.1 Torque Superimposition

Even in the case of electric power steering without a connected assistance system, the motor torque is made up of different components and determined as the set torque for the motor control algorithm (direct assistance torque setting or triggering by predefined functions, e.g., vibration). The most important individual components here are the steering assistance varying with vehicle speed and active return of the steering to the straight-line setting of the steering, plus active damping and friction compensation functions. These differing individual set torques for the electric motor are collated by a torque coordinator and added up to a total set torque, if necessary allowing for priorities of the individual functions. The additional torque required by the external assistance system is thus provided via a further input into the torque coordinator and hence considered as an equally valid or appropriately prioritizable individual set torque by the electric power steering.

In view of the possibly limited options for data transmission on the bus system between the assistance control unit and the electric power steering, it is additionally possible, for direct determination and transmission of the assistance torque, to simulate predefined superimposition functions in the software of the steering control unit and to trigger them by a single control instruction via the data bus. This can be useful in the case of functions which trigger an oscillating additional torque, for example. In this way it is possible to trigger a lane-departure warning using only one control instruction containing information on the amplitude and frequency to be set for steering wheel vibration (Fig. 14).

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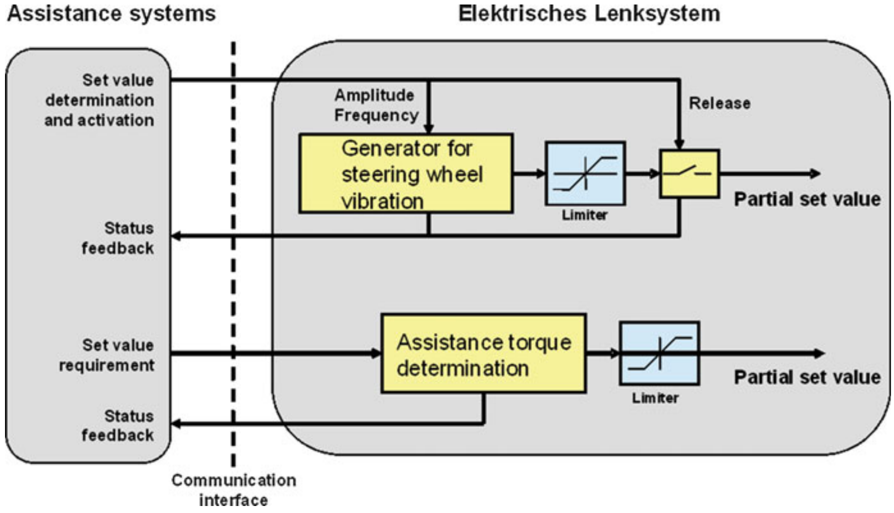

Fig. 14 Predefined superimposition functions transferred to steering control unit

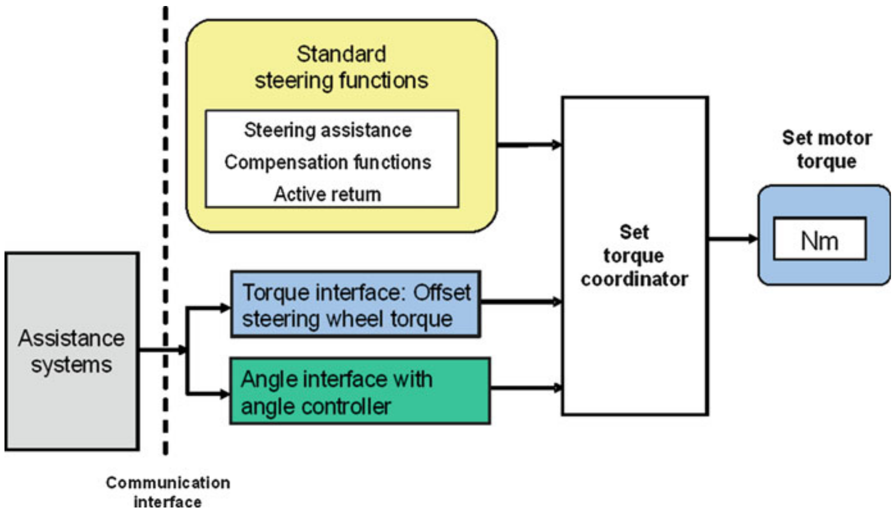

Fig. 15 Superimposition of assistance and standard steering functions

3.2.2 Angle Superimposition

For assistance functions, for example, automatic maneuvering into a parking space, an angle determined by the higher-level control unit is required. However, since the control concept of electric power steering is primarily a matter of torque control, autonomous adherence to a set lane requires a control algorithm that calculates a variable for the electric motor, in the form of a torque requirement, from the set and the actual steering angles of the steering, and stipulates this variable. This angle controller is best integrated into the software of the steering, since the CAN bus mainly used in the vehicle for data transmission at present does not permit time-synchronous transmission. The running time fluctuations inevitable for that reason make it impossible to provide the necessary quality of angle control (Fig. 15).

When an appropriate angle requirement is made to the steering, the actual assistance torque functions are then deactivated and the angle control circuit handles the determination of the set value for the electric motor. For automatic maneuvering into a parking space in particular, it is possible to detect, by evaluation

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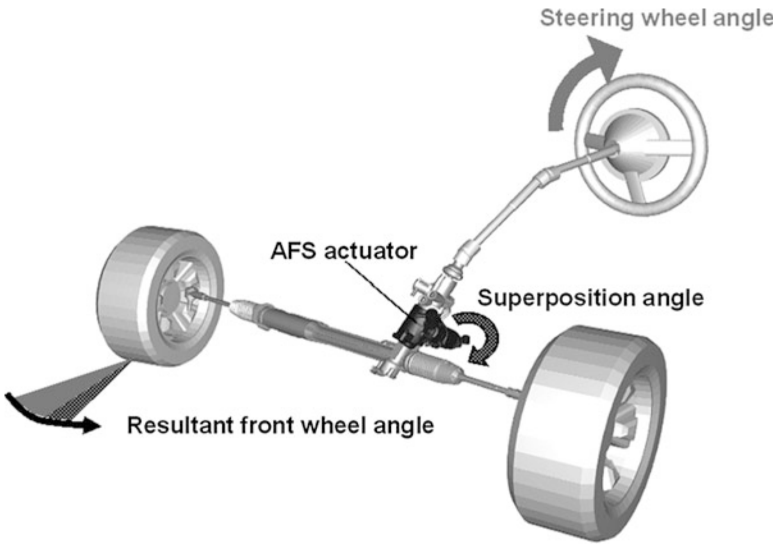

Fig. 16 Principle of superimposed steering (VDI/GMA Fachtagung 2004)

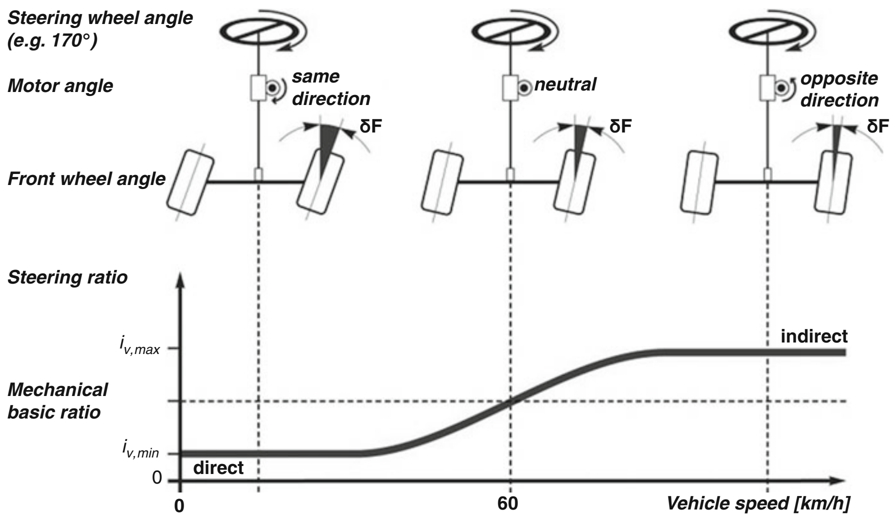

Fig. 17 Principle of variable steering ratio (VDI/GMA Fachtagung 2004)

of the torque sensor of the steering, whether the driver intervenes in the steering process and intends to abort the function.

4 Solutions for Superimposing Angles

4.1 Introduction

Conventional steering systems always work with a fixed transmission ratio, for example, 1:18. This is a compromise to ensure that on the one hand minor steering corrections on the motorway do not greatly impact stability and on the other hand that the driver does not have to turn the steering wheel so much in city traffic or when parking. Superimposed steering or active steering by contrast varies the transmission ratio actively and dynamically, from around 1:10 when stationary and up to about 1:20 at high speeds.

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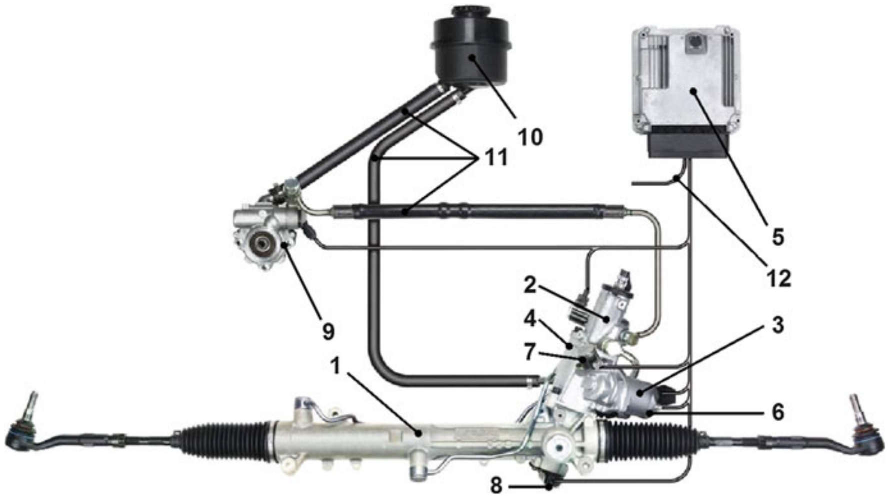

Fig. 18 Components and subsystems of the superimposed steering integrated in steering gear (VDI/GMA Fachtagung 2004)

Superimposed steering permits both a steering intervention depending on the driver (dynamic) and an active steering intervention at the front axle, without having to disconnect the mechanical coupling between the steering wheel and the front axle (Fig. 17) (VDI/GMA Fachtagung 2004). The additional degree of freedom permits continuous and situation-dependent adaptation of the steering properties. Comfort, steering effort, and steering dynamics are as a result actively adjusted and optimized. Moreover, steering interventions to improve vehicle stabilization are also possible. These are superior to those in existing systems, since the response behavior is faster by an order of magnitude, so that interventions taking place are hardly perceptible. The system limits, the function scope, and the necessary system interface should be defined such that the system is independent of other chassis control systems (Fig. 16).

4.2 Functionality

The active steering system has a complex functionality consisting of kinematic and safety functions (Reinelt et al. 2004; Eckrich et al. 2002).

Based on the signals of the vehicle sensors (steering wheel angle, speed, etc.), the assistance and stabilization functions (e.g., variable steering ratio and yaw rate control) compute a required superimposition angle. This acts as the desired value for the controlled actuator, which emulates as precisely as possible the time response of the required superimposition angle. A safety system monitors and checks correct functionality of the entire system. The measures range from a differentiated switch-off of part functions to a complete shutdown of the actuator.

Steering assistance functions are preliminary control actions of the steering system with the aim of adapting the static and dynamic steering properties to the driving situation depending on the driver's steering activity. This adaptation is restricted mainly by the actuator dynamics and the steering feel (feedback to the driver).

Figure 2 shows the variable steering ratio as the kinematic steering assistance function. This function $i_V(v_X(t)) = \delta_S(t)/\delta_F(t)$ is used to change the ratio between the steering wheel angle $\delta_S(t)$ and the mean front wheel angle $\delta_F(t)$ depending on suitable vehicle and steering quantities, such as vehicle speed $v_X(t)$ and deflection. The dependence on speeds permits, thanks to a more direct ratio, a reduction in the steering effort in the lower- and medium-speed ranges. Precise lane keeping and safety in the upper speed range are achieved by an indirect ratio. Furthermore, the dependence on deflection optimizes accuracy in the medium range, reduces the steering effort for large steering angles, and permits a modification of the steering behavior in the case of constant steering kinematics (Fig. 17).

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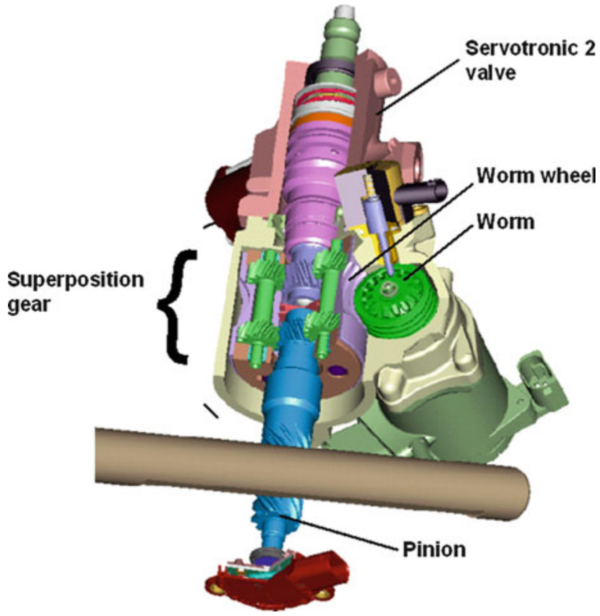

Fig. 19 Section through the superimposed actuator

4.3 Actuator Variants

The actuator with superimposed gear can be integrated in the steering column or alternatively in the steering gear. Integration in the steering gear is advantageous in terms of the haptic effect, since the friction up to the steering valve is not affected and acoustic propagation in the form of airborne sound in the engine compartment is less noticeable. The steering column solutions are all designed fixed to the vehicle. The dynamic requirements are comparable in each case.

Variant 1 positions the electric motor transversely to the superimposed gear (cf. Fig. 18). The greatest advantage is the use of a self-locking worm gear to prevent the undesired back-turning in the passive state. For the integrated solution inside the steering gear (in the engine compartment), sufficient installation space must be available and taken into account during the early concept phase of vehicle development. Installation of this variant in the upper part of the steering column is also possible here. Meeting the package conditions and crash requirements for modern vehicles would however appear to be difficult with this actuator version.

Variant 2 involves the coaxial arrangement of the superimposed gear and electric motor (cf. Fig. 22). The use of a hollow-shaft motor in conjunction with a strain wave gear is required here. This combination is very compact and also advantageous with regard to package and crash behavior when installed in the steering column. The haptic effects are insignificant, since the strain wave gears used work almost free of backlash.

Installation of this actuator is also suitable as a fixed-to-steering shaft variant. The upper steering shaft is here firmly connected to the actuator housing and rotates it too (cf. Fig. 26).

The technical criteria determining the development of a superimposed gear are:

– Achievable dynamics
– Pleasant steering feel
– Meeting the radial installation space requirement
– Meeting the axial installation space requirement
– Low noise behavior
– Controlled back-turning behavior

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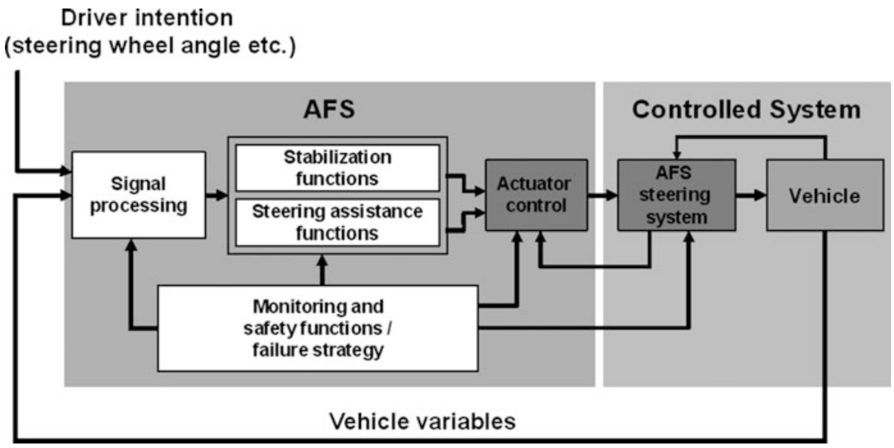

Fig. 20 General signal flow (VDI/GMA Fachtagung 2004)

– Suitability for absence of backlash
– Low weight

4.4 Example of Use in BMW E60: Actuator on Steering Gear

The practical implementation of the superimposed variant 1, integrated in the steering gear, is made up of the following parts (Fig. 18):

Rack-and-pinion power steering consisting of a steering gear (1), a Servotronic valve (2), an electronically controlled steering pump (9), an oil tank (10), and appropriate hoses (11).
Actuator consisting of a brushless DC motor with appropriate cables (3), a superimposed gear (4), and an electromagnetic lock with appropriate cables (7).
Control system consisting of a control unit (5), a pinion angle sensor (8), a motor angle sensor (6), appropriate software modules, and cables between the control unit and the sensors and actuators.
Brushless DC motor generates the required electrical torque for a required movement of the actuator. The electrical torque is under field-oriented (FO) control.
Motor angle sensor is based on a magnetoresistive principle and includes a signal booster and temperature compensation in the sensor module.
Pinion angle sensor is based, similarly to the motor angle sensor, also on a magnetoresistive principle and contains a signal booster and temperature compensation. With a CAN interface, the sensor signal can be used by other chassis systems, e.g., ESP.
Electromagnetic lock blocks the worm during system shutdowns: A spring presses the metallic pin of the lock against the locking teeth of the worm (see Fig. 19). This mechanism is opened (unlocked) by a specific current control action from the control unit.

4.4.1 Actuator with Lock and Pinion Angle Sensor

The core of the system is the mechatronic actuator between the steering valve and the steering gear (Fig. 19). This includes the superimposed gear (planetary gear) with two input shafts and one output shaft. One input shaft is connected to the steering wheel via the steering valve and the steering column. The second input is driven by an electric motor via a worm gear as a gear reduction stage. The pinion angle is applied as a weighted sum at the output shaft, which acts on the input of the steering gear, i.e., on the pinion of the rack-and-pinion steering. The steering kinematics determined by the steering gear and the geometry of the steering linkage are effective between the input of the steering gear and the front wheel.

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DOI 10.1007/978-3-319-09840-1_32-1

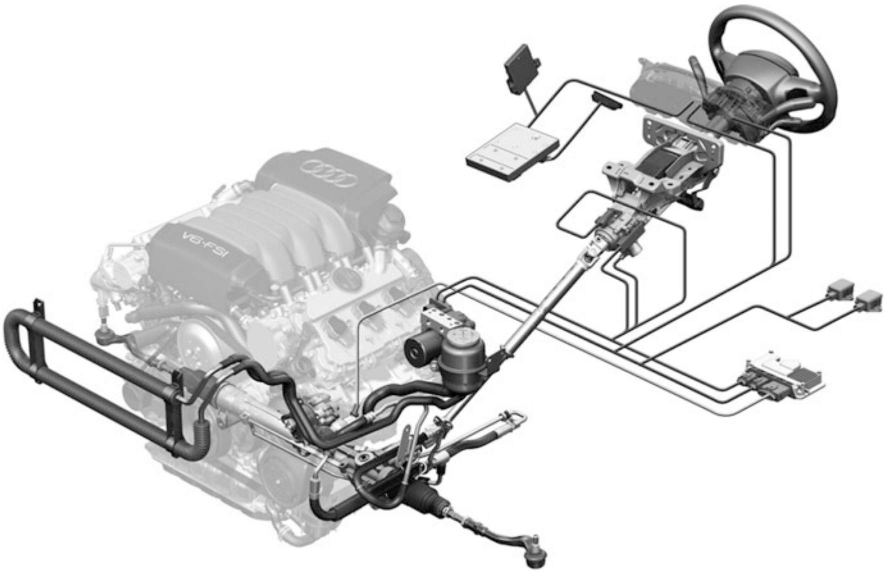

Fig. 21 Components and subsystems of the superimposed steering integrated in the steering column (Schöpfel et al. 2007)

4.4.2 Control Unit (ECU)

The control unit represents the connection between the vehicle electrical system, the sensors, and the actuators (Brenner 2003). The core components of the control unit are two microcontrollers. These controllers perform all the necessary computations for actuator control and for the utility and safety functions. The electric motor, the electromagnetic lock, the controlled pump, and the Servotronic are operated via the integrated output stages. In addition, the microcontrollers perform redundant computations, thus representing part of the safety concept.

4.4.3 Signal Flow

Figure 20 (VDI/GMA Fachtagung 2004) shows the signal flow: The signals of the steering wheel angle and the vehicle variables (e.g., yaw rate) are processed in the control unit, and the set values of the steering assistance and stabilization functions are computed. This is followed by the coordination of the steering requirements, actuator control, and operation of the electric motor. The actual value of the motor angle is reported back to the controller. All modules are monitored using the safety functions and failure strategy.

4.5 Example of Use in Audi A4: Actuator in the Steering Column

The components are comparable to those in the previous example (see Sect. 4.4). The actuator is in this example integrated behind the steering console in the upper steering column. The compact design of the coaxial arrangement of motor and gear permits positioning above the footwell (Fig. 21).

4.5.1 Actuator with Lock

The high-reduction wave gear is combined with an electronically commutated DC motor and a locking unit that locks the electric motor in the current-free state. The motor must be designed with a hollow shaft. The steering-wheel-side shaft is positively connected to the flexible gear cup (flex spline) (Schöpfel et al. 2007). The rotary movement of the steering wheel is transmitted to the output shaft on the steering train side by the outer toothing of the flexible cup via the hollow wheel (circular spline). This force flow also corresponds to the direct mechanical link between the steering wheel and the steering gear in the locked state of the motor (Fig. 22).

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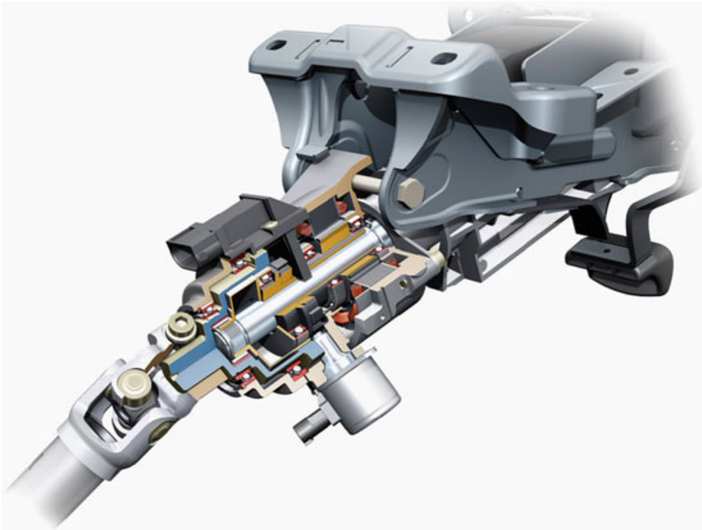

Fig. 22 Sectional view (Schöpfel et al. 2007) and sketch of actuator inside steering column

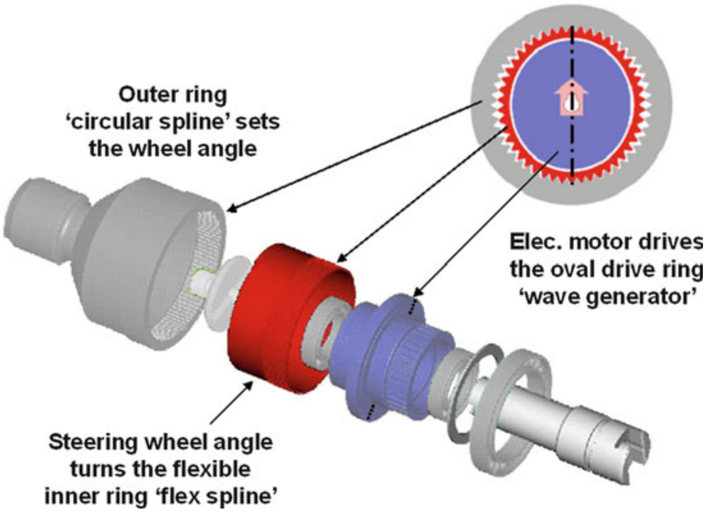

Fig. 23 Superimposition principle, wave gear

4.5.2 Angle Superposition

Angle superposition is achieved by the hollow shaft of the electric motor, formed on the gear-side end as an elliptical internal rotor (wave generator). The generator warps, using a flexible thin-ring ball bearing, the thin-walled flexible cup connected to the steering input shaft. The outer toothing on the flexible cup is, at the high axis of the elliptical rotor, engaged with the hollow gear of the output shaft. Due to the differences in the number of teeth between the flexible cup and the hollow wheel (steering gear side), the result during rotation of the elliptical rotor is superposition (Fig. 23).

4.5.3 Control Unit and Safety Concept

The electronic control unit also meets all the requirements as stated in the example for use 1. The difference is in the 1-processor concept with a smart watchdog (Schöpfel et al. 2007). To meet the safety requirements, all functions must be present in a redundant way (designed independently duplicated).

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DOI 10.1007/978-3-319-09840-1_32-1

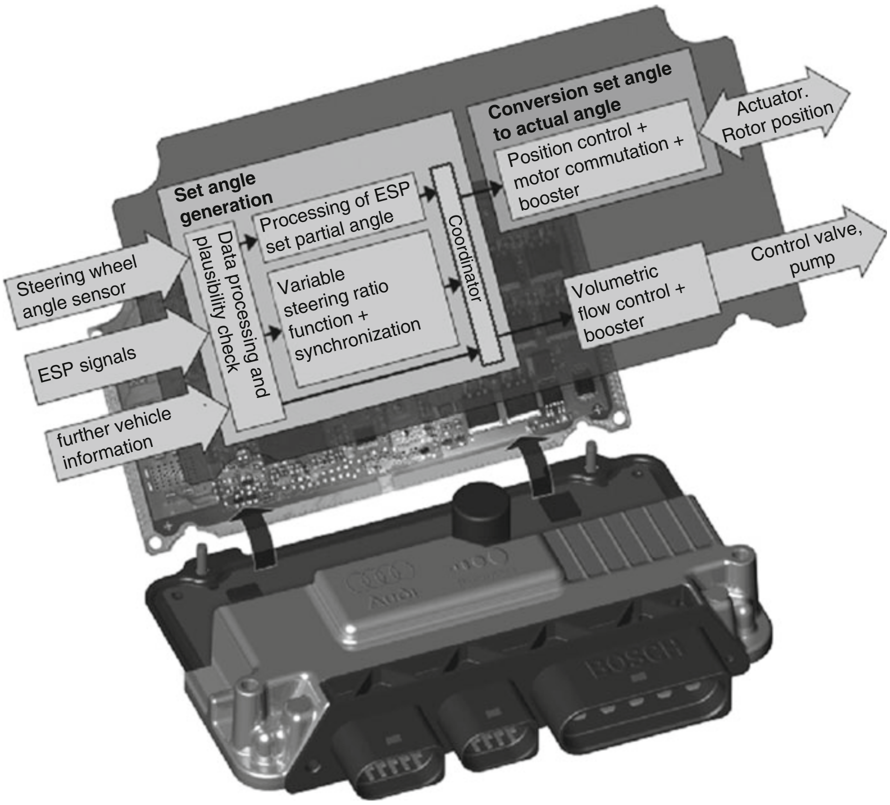

Fig. 24 Control unit with SW architecture (Schöpfel et al. 2007)

At the start are signal processing and a signal plausibility check. In addition, this module computes the vehicle speed. The variable steering ratio function inputs these signals and computes the steering angle correction. As a further task, it synchronizes harmoniously a nonmatching wheel position relative to the steering wheel. This kind of asynchronicity can occur, if in the inactive state, for example, when the combustion engine is switched off, major steering wheel movements have taken place. The sum of these partial angle values is added up together with the processed ESP set partial angle in the coordinator to obtain a total set angle (Fig. 24).

The position control and the motor commutation have the task of passing on the set angle to the output stage driver with the required control quality. The installation position of the superimposed gear between the steering valve and the steering wheel leads to a direct haptic feedback to the driver. This essential condition places heavy demands on the permissible torque ripple of the electric motor.

The control unit must also electronically detect failures and prevent their effects. The derived requirements placed on the control unit are (Schöpfel et al. 2007):

- Avoidance of reversible and irreversible faulty setting requirements that may be caused by the control unit, the electric motor, or the motor position sensor
- Monitoring of externally computed stabilizing interventions and initiation of suitable measures so that the maximum permissible number of faulty setting requirements is not exceeded
- Ensuring that in the event of error, the maximum tolerable jump in the ratio is not exceeded
- Prevention of an uncontrolled steering situation

Figure 25 shows the three-level safety concept of the control unit (Schöpfel et al. 2007). In the first level, all software modules are integrated which are necessary from the functional viewpoint, including

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DOI 10.1007/978-3-319-09840-1_32-1

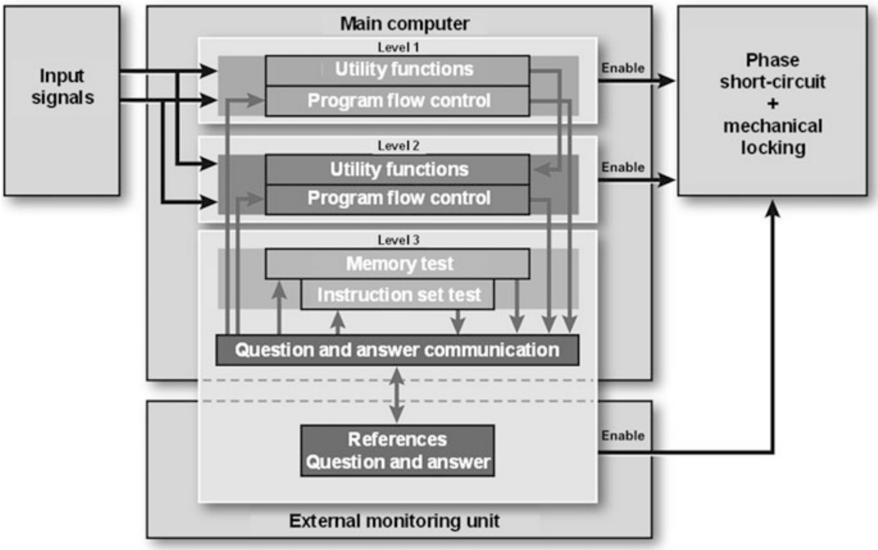

Fig. 25 Three-level safety concept of control unit (Schöpfel et al. 2007)

signal plausibility check and failure strategy. All critical paths that can lead to a failure are computed in redundant manner in the second level. This ensures that systematic error causes (e.g., programming errors) cannot lead to a failure. The third level ensures the program sequence and correct performance of the instruction set.

To ensure high availability, a gradual degradation of system functionality is required (Schöpfel et al. 2007) depending on the error which has occurred:

– Setting a constant steering ratio when there is a lack of driving speed information
– Blocking of external stabilizing interventions when low performance is expected, for example, due to fluctuations in the vehicle's electrical system
– System deactivation when steering angle reaches zero if an error is suspected, in order to prevent a misaligned steering wheel
– Complete and immediate system deactivation

Furthermore, availability after a deactivation can be restored by an initialization phase, without the need for time at a garage. In addition to preventing failures, the control unit must continue to supply safety-relevant signals for the other vehicle control systems.

5 Steer-by-Wire Steering System and Individual Wheel Steering

All standard steering systems developed to date for cars are based on a dependable mechanical coupling between the steering wheel and the wheels. The driver thus has, in all operating conditions of the vehicle, a direct mechanical link to the steerable wheels, enabling him to follow directly his intended driving route.

The continuing developments in the steering sector made in recent decades by the steering manufacturers and the vehicle industry relate largely to assistance of the steering power or to steering angle superposition. For example, hydraulic or electromechanical power steering systems offer perfectly adjusted steering power for all possible driving states, but remain based on a mechanical transmission mechanism. In the event of errors in particular, i.e., when power systems change to the so-called fail-safe

DOI 10.1007/978-3-319-09840-1_32-1

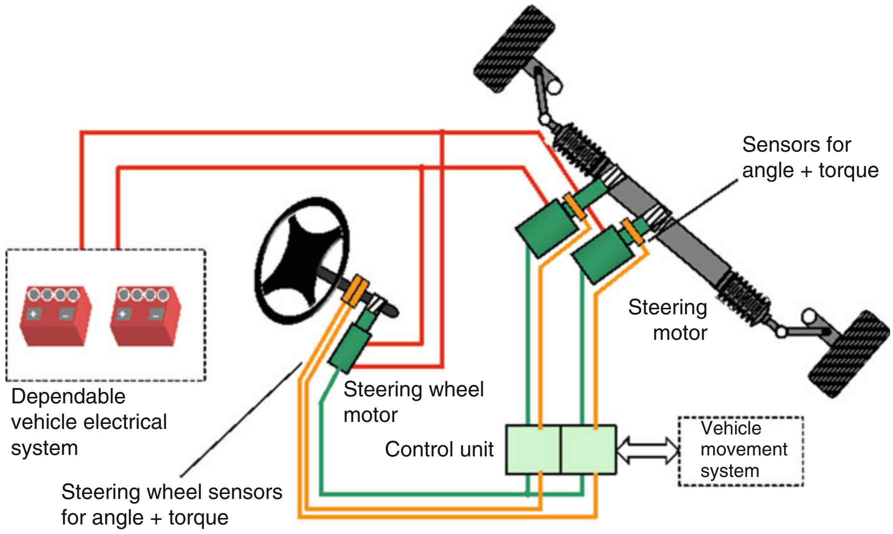

Fig. 26 System structure of steer-by-wire steering system

or fail-silent modes, mechanical components take over the task of transmitting the steering command of the driver to the wheels. This aspect remains important even in steering systems with angle superposition (active steering).

Steer-by-wire steering systems represent a new approach. This is characterized by a purely electronic transmission of the driver's steering intention or of a complete decoupling of the driver's mechanical steering movement and the steering of the wheels. This obviates the need for conventional mechanical transmission devices. The driver generates at the steering wheel only information about his intended steering movement. This information is fed to an electronic control unit. This control module evaluates the information and converts it into appropriate steering commands. This operates the steering gear which performs the intended steering movement (Fig. 26).

– With the aid of hydraulic, electrical, electronic, and sensor systems, many new comfort and safety functions were developed in the past, to make driving a vehicle much more comfortable and safer.
– Despite all these components, the safety concept of current steering systems is still based on a continuous chain of proven mechanical components.
– Steer-by-wire systems clearly differ in their safety concept from conventional steering systems. In the event of an error, shutdown of the system into the fail-silent mode is not sufficient. Instead a fail-operational mode is needed, using a redundant replacement system with the full range of functions.
– For the market launch of the steer-by-wire system in cars, a classic mechanical or hydraulic fall-back level is probably needed as the safety concept for the first phase of confidence building.

5.1 System Concept and Components

A steer-by-wire concept is made up mainly of two assemblies: a steering wheel actuator and a wheel actuator.

5.1.1 Steering Wheel Actuator

The **steering wheel actuator** in the area of the upper steering column comprises a conventional steering wheel with sensors to record the steering wheel angle and the steering torque and a steering wheel motor to pass the appropriate steering feel on to the driver.

DOI 10.1007/978-3-319-09840-1_32-1

In addition, familiar control elements reduce accident risks, thanks to long years of practice with them, in the event that steering corrections by means of reflex movements are required in critical driving states.

5.1.2 Wheel Actuator

The **wheel actuator** consists mainly of an electromechanical rack-and-pinion steering. For safety reasons, the rack is driven by two redundantly designed electric motors. The high-performance electric motors are usually designed as brushless permanent-solenoid-excited DC motors (BLDC). Sensors are also installed in the wheel actuator for recording the wheel angle.

5.1.3 Electronic Control Unit

An **electronic control unit** processes all information provided by the two assemblies and the data available from other vehicle systems. For safety reasons, a redundant system structure is used consistently. In some cases, this requires up to three sensors independent of one another for a single safety-relevant signal. Only then is a dependable fail-operational mode of the system ensured in the event of an error. Depending on the functional and safety structure, up to eight 32-bit microprocessors are needed in the control unit, which mutually monitor each other for plausibility of the computed set values or rather for failures.

5.2 Technology, Advantages, and Opportunities

On the one hand, the technical latitude for designing steering functions for their comfort, safety, and driver assistance aspects offers excellent opportunities for steer-by-wire concepts. Depending on the available sensor signals and on the integrated network with other vehicle systems, it is possible to make driving the vehicle as safe and easy as possible for the driver in all conceivable operating conditions.

As the previously mentioned experience with electromechanical steering and active steering has shown, it must be ensured that newly developed functions and design principles are regarded as supportive and helpful by all drivers. Stabilization functions in particular which are based on automatic driver-independent steering interventions should not be perceived by the driver as a loss of responsibility for the respective driving situation.

A further important point in steer-by-wire systems relates to the haptic information to be imparted in real time when handling the steering and which must describe the tire/roadway frictional connection as precisely as possible. This information is highly valued by the driver, since he can use it to assess the right driving speed and the available acceleration and deceleration capacities of the vehicle. It is usually also the only information source which supplies him quickly enough with knowledge of abruptly changing roadway friction coefficients, so that he can reflexively get a dangerous situation back under control based on practiced behavior patterns.

This so-called feedback information that imparts a familiar steering feel to the driver must be generated artificially by the steering wheel motor in the steering wheel module in the case of steer-by-wire. Depending on the available sensor data, the electronic control unit computes a setting value for the steering wheel motor which thus simulates a steering resistance at the steering wheel. This should ideally reproduce the tire/roadway frictional connection conditions at a suitable force level.

Resetting forces during cornering can also be simulated in this way. When the steering wheel is moved, the steering wheel motor counters the movement direction and the movement torque to a level that can be fixed as required, regardless of whether the axle resetting forces of the vehicle achieve ideal values or not. Even an end stop can be simulated with a blocking torque in the steering wheel motor, without a mechanical stop in the upper steering column being needed.

Disturbance forces acting on the steered wheels, for example, tire imbalance, pothole effects, etc., can simply be selectively faded out or simulated at the steering wheel with any required intensity. This can be

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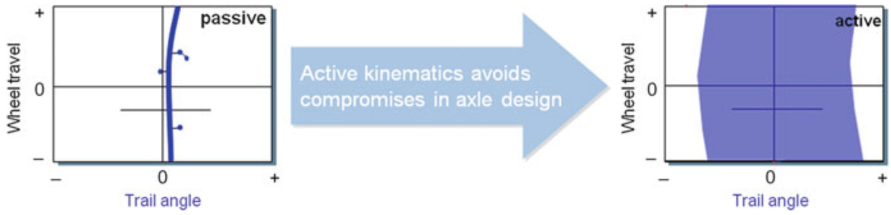

Fig. 27 Cf. passive and active kinematics

scaled in any way required as part of the design of the control software and would in the case of traditional steering systems have required at least design measures for the mechanics or hydraulics.

In the same way, the steering system can be adapted optimally to any vehicle using the parameterizable software. Even self-steering behavior, such as oversteering or understeering, can be influenced in this way, to impose on every vehicle model the required brand character, also known as "blend-by-wire." It is even conceivable to accommodate to the personal driving style of the individual driver by individually controlling his preferred steering parameters.

As regards driver assistance and stabilization functions, it is of course possible to implement all the solutions already described and practiced in electromechanical power steering and in active/superposition steering, such as variable speed-dependent ratio, steering lead, yaw rate control, yaw moment compensation, side wind compensation, automated parking, etc. To that extent, it is possible with this combination to represent most of the steer-by-wire functions.

Thanks to the complete mechanical decoupling of steering wheel and steering gear, these functions will doubtless be of even higher quality in the long term. Fully automatic lane keeping and fully automated evasive maneuvers without the participation of the driver in conjunction with all other vehicle systems in the braking and driving fields can be achieved. In the final analysis, autonomous driving is indeed possible.

With the aid of single-wheel steering (each front wheel is individually steered by an electrically operated actuator, and the rigid connection using a tie rod is dispensed with), the wheel angle can be designed, using only the control algorithms filed in the software of the control unit, so individually that today's mechanical multi-link axles could be replaced by simple and inexpensive wheel suspensions.

But until this technology is introduced, the latest statutory regulations need to be changed and the cost/benefit ratio must evolve toward an acceptable and profitable range.

The opportunities for introduction in vehicle concepts newly designed from scratch, such as electric and hybrid vehicles in which electric motors are used directly as the wheel drives, are certainly greater than in classic vehicles with combustion engines.

6 Rear-Axle Steering Systems

The use of rear-axle steering could avoid many of the compromises resulting from the design of passive axles. The resultant adjustment range opens up the potential to do so (see Fig. 27):

For the end customer, this results in considerable improvements in the properties influenced by the chassis. Depending on the driving situation, driving stability, agility, or maneuverability is optimized. Driving pleasure, and the feeling of comfort and safety, is improved, while the properties of driving dynamics can be experienced with greater awareness.

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DOI 10.1007/978-3-319-09840-1_32-1

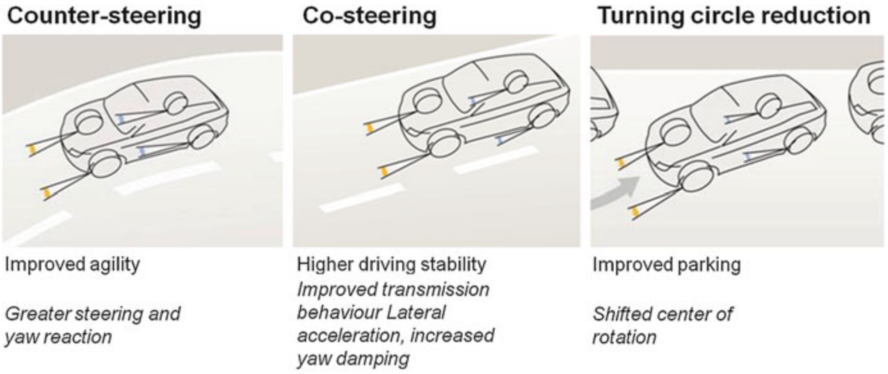

Fig. 28 Functional advantages of rear-axle steering

6.1 Basic Functions and Customer Benefits

The following basic functions and objectives for the use of rear-axle steering can be distinguished (see Fig. 28):

– Turning circle reduction/parking assistance: improved maneuvering and parking
– Agility function at low and medium speeds: more driving pleasure, improved handling, sportier driving characteristics, less steering effort, and so greater comfort
– Stability function at high speeds: considerably increased driving stability and safety and improved subjective feeling of safety

6.2 Function Principle

Rear-axle steering offers in principle two intervention options (see also Fig. 28):

6.2.1 Counter-Steering

Counter-steering reduces the turning circle, and the result is a reduction in the necessary steering wheel angle. In driving physics terms, this is the result of "virtual wheelbase shortening." From the viewpoint of driving dynamics, counter-steering initially increases the effective yaw moment. The driver feels an improved maneuverability and agility.

6.2.2 Co-steering

In the case of co-steering, a definite improvement in driving stability can be experienced. The reason for this is the synchronous buildup of the cornering forces at both axles, so that the time until a stationary lateral dynamic state is achieved is shortened. Furthermore, the yaw moment is reduced and limited in its dynamics (less overshooting), which directly improves driving safety. From the driving physics viewpoint, this is a "virtual wheelbase extension."

6.2.3 Driving Dynamics Borderline Area

The maximum potential when the rear wheels are steered can be used in the borderline area in the event of understeering. The rear axle has not yet reached its gripping limit here and can generate additional cornering forces. During oversteering, by contrast, intervention is not reasonable, since the rear axle is already at its grip limit and there is no potential for an increase in cornering forces. Below the physical borderline area, both driving-dynamics situations can be equally well corrected.

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DOI 10.1007/978-3-319-09840-1_32-1

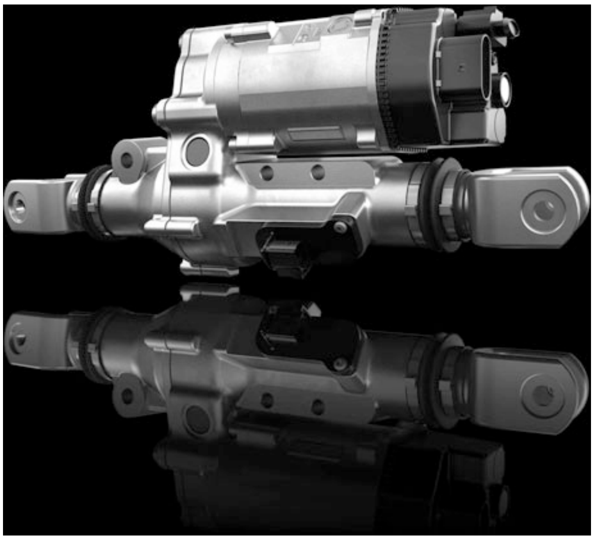

Fig. 29 Central actuator system (ZF Friedrichshafen AG)

6.3 System Design/Structure of System

The systems on the market can be classified into two basic types:

6.3.1 Central Actuator Systems

Structure similar to that for front-axle steering with a centrally arranged actuator (see Fig. 29). The rear wheels are here "mechanically coupled."

6.3.2 Dual Actuator Systems

Structure with two wheel actuators installed in the axles instead of tie rods/links. There is no "mechanical coupling" of the rear wheels here.

6.3.3 Subsystems

– Mechanical:
  Mechanical housing assembly, transmission stage (e.g., toothed belt), transmission gear (e.g., ball screw or trapezoid screw), etc.
– Mechatronic:
  electric motor, sensors, cable harnesses/plug connections
– Electric/Electronic:
  control unit with power electronics
– Software:
  operating software (low level), steering function (high level)

6.4 Interlinking/Expanded Functionality

Due to the increasing number of active driving-dynamics systems, intelligently interlinking them is becoming a necessity. This results in further functional potential. This is illustrated in the following by way of example:

Electric Power Steering The parking assistance systems already available today can be improved with the aid of the increased maneuverability due to rear-axle steering systems.

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Active Steering By a functional interlinking of active front-axle steering (variable ratio) and rear-axle steering, the overall steering behavior of the vehicles can be variably determined by both axles.

Electronic Stability Systems (Brake) The function of stability control systems can also be expanded by rear-axle steering. Steering interventions can be made well before the borderline area (and hence also before engagement of the brake) and barely perceptible for the driver. This is referred to as the so-called soft stabilization.

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