Future Trends for Automotive Steering Systems

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This paper illustrates future trends of steering system development approaches. Starting with a brief introduction and overview of existing steering system concepts, the focus is directed to the general benefits and challenges of steer-by-wire systems. These aspects were taken into account while developing and realizing the research vehicle concept 'SpeedE' at the Institute of Automotive Engineering at the RWTH Aachen University.

***Key Words**: Steering system development, wheel individual steering, steer-by-wire, large steering angle, functional safety*

1. Introduction

It has been a long way from the first vehicles being equipped with a steering wheel to today's state of the art steering systems. While for a long period of time hydraulic power steering (HPS) systems were considered the optimum solution for all vehicles, the progress in steering system development throughout the last decades has led to a paradigm shift towards electric power steering (EPS) systems. By today, EPS systems have a wide market penetration starting from A-segment up to the heavy passenger vehicles with high wheel loads such as SUVs. Higher allowable electric power demand facilitated by the upcoming 48 V voltage level will increase the deployment rate of EPS systems even further.

EPS systems are characterized by a significantly lower energy consumption compared to HPS systems and thus contribute to the reduction of CO_2-emissions. Since they are CPU controlled, they also offer a huge potential for additional functions. These enhance safety, driver comfort and enable advanced driver assistance features, e.g. speed dependent power assist or automated parking assistance. Besides these benefits, several challenges needed to be mastered to obtain an accepted replacement of the HPS systems. Especially much effort had to be spent in order to reach sufficient steering feel and functional safety. Both aspects can be considered as solved for current steering systems.

EPS systems facilitate an individual design of the steering torque feedback within large boundaries but current demands go beyond this degree of freedom. In order to holistically design steering feedback, it is also desirable to realize a variable steering angle transmission ratio. In fact, the first systems that were able to independently vary torque and angle transmission ratios were superimposed steering systems incorporating an additional gear set to enable the variable angle transmission ratio. It took another decade and some changes in legislation until the first real steer-by-wire system was introduced in a series-production vehicle[1].

This paper gives a brief overview on the state-of-the-art of passenger car steering systems and provides an outlook into the future of automotive steering systems. The focus is laid upon the main steering system at the front axle; rear wheel steering systems will not be discussed, in spite of the fact, that they will also play an important role in the future.

2. State of the Art Steering Systems

Today, the direction of development for steering systems is evidently towards electric power steering (EPS) systems. The pressure to introduce EPS systems for all segments is high enough to make e.g. BMW introduced a separate 24 V power-supply system to enable electrical steering systems for all variants of the 5-series launched in 2010[2]. Today, it is obvious that the future for automotive steering systems will be electrically powered.

2. 1 Electric Power Steering Systems

In the late 1980s, first EPS systems were introduced in series passenger vehicles. Contrary to the usual innovation process and due to limited steering rack forces of the first systems, EPS systems first appeared in small passenger vehicles with lower axle loads and limited rack forces. Currently, depending on cost, package and performance requirements several different types of EPS systems can be found across the different vehicle segments (**Fig. 1**).

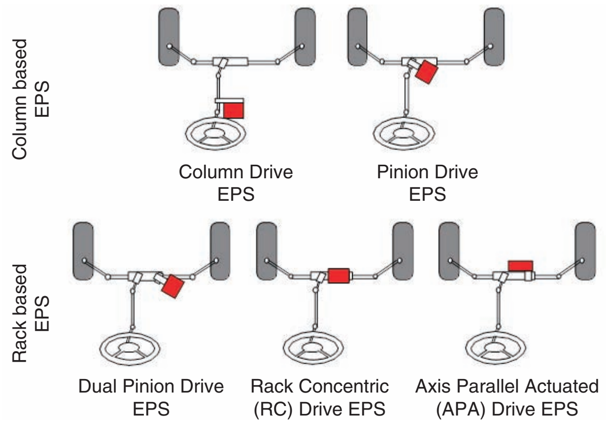

Fig. 1 Overview of common EPS types[3)]

While column and pinion drive EPS systems make use of the existing rack and pinion gear to induce the assist torque, the variations on the bottom of **Fig. 1** require an additional gear set. In a dual pinion setup, a second rack and pinion gear is included in the system, whereas RC and APA Drive EPS systems consist of a ball screw which is actuated either directly by a hollow shaft motor (RC) or by a tooth belt drive (APA). Currently, APA Drive EPS systems are able to realize the highest rack forces.

All of those design solutions enable the steering system to realize numerous steering functions. These can be clustered into three sets i.e. basic steering functions, enhanced steering functions and advanced driver assistance functions.

Basic steering functions contain the main power assistance to control the required steering wheel torque in a certain driving situation. Additional functionality around the torque equilibrium that directly influences the steering feel, e.g. friction and inertia compensation may also be accounted to this group.

Enhanced steering functions are features that are beyond the scope of steering feel. This includes an active return of the steering wheel to straight line driving position as well as an assisted straight line drive, which compensates necessary steering torques due to road banking or constant cross winds.

Finally, advanced driver assistance functions accumulate features that either enable automated steering in certain situations such as automated parking, trailer back-up assist, and lane keeping or sophisticated driver feedback, e.g. lane departure warning.

2. 2 Superimposed Steering Systems (SIS)

To further enhance steering system functionality, it is necessary to provide a direct influence on the steering angle. This can be realized by adding a degree of freedom in the steering column that is actuated by an electric motor and controlled in a way that an angle is added to the steering wheel angle (**Fig. 2**). Functional Safety concepts for these systems usually include a locking mechanism. In case of a system fault, the system may be degraded to a standard steering system with a fixed steering angle transmission ratio.

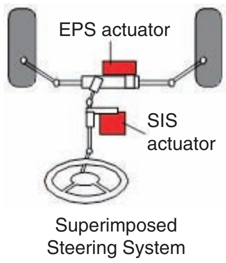

Fig. 2 General setup of a superimposed steering system

Superimposed steering systems allow a multitude of additional functions. The most evident is a speed dependent transmission ratio from steering wheel angle to wheel steering angles. Furthermore, it can also be integrated into the vehicle dynamics control system.

While in control theory, a system consisting of an EPS and an SIS can be tuned arbitrarily regarding steering wheel angle and torque demand, it should be noted that in reality the performance is limited due to certain boundary conditions, e.g. the reaction torque in the steering wheel needs to be supported by the driver.

2. 3 "Conventional" Steer-by-Wire Systems

A Steer-by-Wire (SbW) is characterized by a lack of mechanical connection between the steering wheel and the steering gear and therefore, the wheels themselves. Besides one or more electric motors that actuate the steering rack, an additional actuator may be introduced in order to generate a variable feedback torque at the steering wheel (**Fig. 3**).

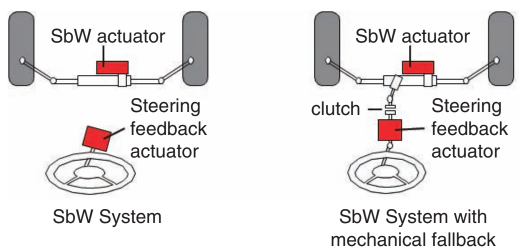

Fig. 3 Setup of a general steer-by-wire system and another with mechanical fallback

Advantages offered by such a system are[4]:

- free configuration of steering angle ratio and torque assistance;
- maximum potential for steering functionality, also improving active safety;
- suspension design without regarding effects on steering feedback;
- improvement of passive safety by omission of steering column;
- improved package situation due to omitting the steering column;
- reduction of variants, i.e. left and right hand drive steering position;
- simplification of vehicle assembly;
- introduction of innovative human-machine interfaces (HMI).

Many different solutions for steer-by-wire concepts have been published in academic literature throughout the last decades, but the potentials were not rated high enough to overcome the challenges and the development effort associated with the introduction of steer-by-wire systems until Infiniti announced the first series SbW system for the Q50 in 2014. As depicted in **Fig. 3** (right), the Direct Adaptive Steering (DAS) System of the Q50 features a steer-by-wire system with a mechanical fallback. A steering column is still present in the vehicle but separated by means of a clutch which can be closed in order to reach the safe state. According to Infiniti[1], the main advantage of the DAS system over an SIS system is the possibility to reduce the feedback of short wave length road excitation and unwanted disturbances from the engine to the steering wheel. Necessary rack forces are low pass filtered and used for the calculation of the feedback torque. While the comfort is increased by this measure, some automotive journalists criticize a lack of road feedback and a rather artificial steering feel, e.g.[5].

3. Future Trends for Steering Systems

When observing the current discussion around steer-by-wire systems, some parallels can be drawn with regard to the discussion on early EPS systems. Much scepticism is present with respect to necessary development cost, quality of the artificial driver feedback and the feasibility to design a safe system.

Early solutions that lead the way to the Infiniti SbW concept could not demonstrate the full potential of SbW systems as they were mainly designed to prove that realizing a SbW system is feasible at all. Therefore, it is necessary to unlock the full potential of SbW systems, e.g. package and assembly cost advantages as well as notable additional functionalities.

Today, the scepticism towards the development of a reliable and safe system has decreased notably due to the expected rise of automated driving vehicles that requires redundant steering actuators anyway. To increase market penetration, the functional potential needs to be such, that it can be experienced by any driver. At the same time, production costs need to be limited e.g. by more sophisticated redundancy concepts. Wheel individual steer-by-wire systems offer the potential to achieve both - innovative steering functionality and acceptable costs.

3. 1 Sophisticated Redundancy Concepts

While mechanical systems are considered inherently safe, a mechatronic system can fail without prior signs of damage or wear. Thus, regarding SbW systems without a mechanical fallback, a functional safety concept needs to incorporate redundancies.

The safety goal is to maintain control over the vehicle with no or only manageable interruptions. This can be achieved by either introducing redundancies that are able to fulfil the original functionality without limitations, thus providing a fail-operational behaviour, or maintain a restricted functionality as a degraded state. The concept of degraded states is very common for automotive systems. In EPS and SIS systems, the actuators are simply deactivated when a fault is detected. The driver needs to be able to still steer the vehicle with a passive system without power assist, although while the comfort is largely reduced and any active steering functionality is absent.

Today, it is common to design functional safety concepts on system level only. Transferring this practice to SbW systems leads to a significant number of double or triple components that are likely to consume much of the package potential and add extra mass and cost. Most critical in this regard are the actuators. While certain common-cause faults that will lead to a complete system failure, such as energy supply or communication, need to be avoided by deploying diversified redundancies, redundancies of other components need to be assessed carefully, whether it is possible to allow a degraded state which is still safe but less disadvantageous.

3. 2 Wheel Individual Steer-by-Wire

Wheel individual steering actuation is characterized by the missing mechanical link between the two steered wheels. Consequently, two separate actuators are necessary as depicted in **Fig. 4**. In general, such a steering concept facilitates the greatest functional potential, since the steering angle of both wheels can be individually controlled in order to increase driving safety, reduce rolling resistance and assist the driver in performing his driving task. Moreover, the Human Machine Interface (HMI) can be redesigned like it was done in aviation with the introduction of fly-by-wire.

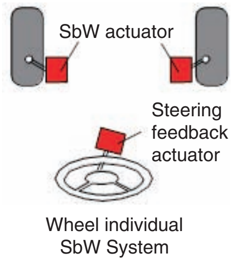

Fig. 4 Setup of a wheel individual steer-by-wire steering system

3. 3 Steering HMI

Since 1894[6] the steering wheel has been the state of the art human-machine-interface (HMI) for controlling the steering system and is a very present element of every series vehicle today. While on a short- and mid-term basis this is highly unlikely to change, in the long run it seems possible that for automated vehicles this HMI concept could become outdated. Once the driver becomes a passenger in most driving situations, the steering wheel as known today may be perceived as disturbing and occupying space that could be used more reasonably. Already in the past, this idea has led to various concepts, which are often based on control elements located on one or both sides of the driver, and therefore named as sidesticks[7].

4. The steering system of the research vehicle SpeedE

The aforementioned development trends motivated the Institute of Automotive Engineering (ika) at RWTH Aachen University to develop the innovative research vehicle 'SpeedE' (**Fig. 5**) which has been initiated by Lutz Eckstein in 2011. By putting innovative features of electric vehicles into focus of the design process, the prototype aims at displaying the advantages of electric vehicles beyond zero emission driving. For ika and its partners, it is a platform to show and further develop new ideas for systems and components, independent of any car manufacturer.

Beside the propulsion which is realized by two wheel-individual electric motors on the rear axle, one of the main topics of research in this context is the innovative steering system, which is meant to be an outlook into future steering technology. The steer-by-wire system comes with one steering actuator per steered wheel on the front axle allowing large wheel-individual steering angles up to 90° that enables a high manoeuvrability of the vehicle. The steering wheel as input unit of conventional steering systems is replaced by two sidesticks placed left and right of the driver's seat.

Fig. 5 ika research vehicle SpeedE (CAD model and real vehicle)

4. 1 Wheel Individual Steering

Because of the individual wheel steering, it is possible to adjust the wheel angle independently and depending on the current driving situation. A steering angle of up to 90° can be achieved and thus a very high manoeuvrability of the vehicle. Also, the individual wheel steering angles facilitate an increase of the driving safety as well as the full utilization of the lateral force potential of the front axle. The maximum wheel steering angle in a parking situation is depicted in **Fig. 6**.

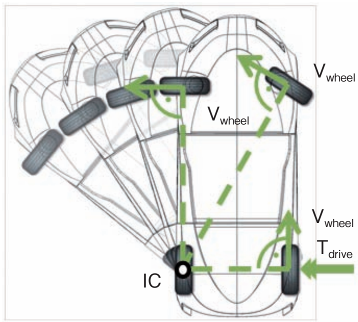

Fig. 6 Maximum steering angles at the front axle of the research vehicle SpeedE

In the depicted sketch, the left wheel is turned in by 90° and the right wheel by 60°. The wheel's velocity vectors correspond with the wheel planes, since, due to the low speed while parking, no significant side slip angles develop. This means that the instantaneous centre of rotation (IC) of the vehicle movement is located at the rear inside wheel. For the parking situation shown in **Fig. 6**, only the outside rear wheel is driven.

In order to achieve these large wheel steering angles, a double-wishbone suspension concept is chosen and modified according to the requirements. **Figure 7** depicts the suspension concept.

Fig. 7 Wheel individual steerable front axle of the research vehicle SpeedE

Two steering actuators are mounted between the upper control arms and the wheel carriers. A 48 V electric motor combined with a reduction gear is implemented as the steering actuator. An important requirement of the reduction gear is a high rotational stiffness and highest possible freedom of play. In this concept, this is accomplished by a strain wave gear with a high transmission ratio. With this concept, a cardan joint connects the upper control arm with the wheel carrier[8].

4.2 Functional Potential

The design unlocks new and innovative functionality potentials. This includes vehicle dynamics functions such as a variable Ackermann geometry, a maximum utilization of tire lateral force potentials and intelligent response strategies to special situations[9].

The basic requirements of steering kinematics depend on the driving speed or more precisely on the lateral acceleration. At lower speeds, distortion free and slip angle free wheel rolling motion is advantageous. When cornering at high speeds, slip angles at the wheels result in lateral tire forces in order to support the centrifugal force. The utilized tire friction coefficient is a criterion for the driving dynamics safety potential. At higher vehicle velocity, to exploit the same friction potential for the outer wheels, which experience higher wheel loads as the inside wheels in a curve, the outer wheels slip angle should be greater than the inside wheels[10]. Conventional steering kinematics tries to partially fulfil both steering demands with a compromise (at dynamic steering design). The wheels are kept almost parallel up to a steering angle of about 20° and only with larger slip angles the Ackermann geometry comes into effect[3]. With single wheel steering, this compromise is resolved.

Furthermore, the wheel individual steering allows intelligent system reactions to special driving situations such as braking on μ-split. In this situation the unequal braking forces on both vehicle sides result in a yaw momentum that needs to be compensated by the driver in order to go straight. Returning to a homogenous μ-high surface will lead to another yaw impulse, which is even harder to control by the driver. It is possible to completely suppress the yaw impulse by setting the tire slip angle on the low coefficient side in the direction of the high coefficient side and with the same toe-in than the wheel on the μ-high side. If the car is leaving the μ-split in this configuration, the lateral forces on the front axle balance and the yaw rate response due to the yaw impulse is almost completely avoided. Subsequently, the lateral displacement response is also suppressed and the vehicle safety can be significantly increased.

4.3 Functional Safety Concept

The research vehicle SpeedE implements an innovative approach to functional safety[11]. The safety goals of the steer-by-wire system are defined based on parameters on vehicle level, for example based on the lateral displacement of the car and not based on the steering angle error. This offers a larger number of opportunities to reach the safety goals and does not limit the solution space needlessly. For the SpeedE steering system, five safety goals were derived from the results of the Hazard Analysis and Risk Assessment. All safety goals aim to keep the lateral displacement of the vehicle within an acceptable range.

As one example in the SpeedE steer-by-wire system, faulty steering interventions caused by one of the steering actuators are compensated by counter-steering on the other steered wheel and torque-vectoring interventions on the rear axle. Although more complex on the functional side than a redundant steering actuator, this measure covers a large number of possible causes for this hazard and is thus situated close to the top event in the corresponding fault tree. The cross-domain nature (using the wheel-individual propulsion) makes this measure even more efficient, because expensive and bulky redundant actuators as known from other safety concepts for steer-by-wire systems are not required.

5. Conclusion

The history of steering systems for passenger cars has taken a typical course for the development of complex subsystems in automotive industry. Once a certain technology is established and the development cost are spent, it takes substantial time and good reasoning to replace the mature technology approach by new and innovative solutions. Over decades hydraulic power steering systems were considered to be the optimal solution. EPS systems were looked at sceptically especially concerning functional safety and steering feel quality. It took the pressure to reduce CO_2-emmisions to pave the way for a wide market penetration until it has reached upper class vehicles and SUVs.

Today, the early issues are successfully solved, accepted and considered state of the art. To allow implementation in heavier vehicle classes, higher voltage supply levels are introduced and will become more popular once 48 V supply is widely spread. Already, research and development departments are working on more enhanced features and adding again complex amendments. One goal is to achieve so called steer-by-wire functionality, i.e. the possibility to independently influence power assist and steering angle transmission ratio. With one exception, current available systems avoid the implementation of real steer-by-wire. The arguments against steer-by-wire systems are similar to the arguments against early EPS systems. The development effort appears to be too high, the steering feel may not be sufficient and functional safety might be impossible to achieve. Again a catalyst is required in order to allow the breakthrough of a new technology. For steer-by-wire systems this might very well be the ambition to realize automated driving.

In long term view, steer-by-wire systems will become fully integrated into vehicle dynamics control algorithms and more sophisticated functional safety concepts will make mechanical fallback levels unnecessary enabling full package and assembly advantages of steer-by-wire-systems. Sooner or later, additional potentials can be unlocked by wheel individual steering systems and revolutionary Human Machine Interfaces. With ika's SpeedE, one research vehicle considering all innovative aspects of future steering systems has been introduced already.

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