Potentials and Challenges for the Application of Active Sidesticks – Case Study "SpeedE"

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Summary

The Institut für Kraftfahrzeuge Aachen of RWTH Aachen University and the School of Transportation Design of Pforzheim University have presented a new research vehicle named SpeedE. Amongst other innovations, the vehicle is equipped with a new steering system with individually steered front wheels and high achievable steering angles controlled by active sidesticks and a vehicle dynamics controller embedded into a functional safety concept.

This paper presents the development of the active sidestick components and the implementation of the forward and feedback control into the vehicle dynamics controller.

1 Introduction

The research vehicle SpeedE which is developed in close cooperation between the Institut für Kraftfahrzeuge Aachen (ika) and the School of Transportation Design of Pforzheim University is approaching a new design in steering systems. Individual wheel steering actuators with high achievable steering angles combined with a steer-by-wire system controlled by active sidesticks and an innovative vehicle dynamics controller offer a new potential in steering functionality on the one hand. On the other hand the system complexity and its integrity are leading to new challenges which need to be handled in the future.

Although x-by-wire systems have already been state of the art in aviation industry for decades, they have not yet found their way into the automotive industry. Revision 2 of the ECE R79 from 2005 has edited the advantages of steer-by-wire systems compared to conventional steering systems with a mechanical link between operation device and steered wheels. Hence, the way for steer-by-wire systems has been cleared from the legal point of view.

This paper is focusing on the development of active sidesticks embedded in a functional safety concept. Concepts for the functional implementation into the vehicle dynamics control system are presented. Moreover, the cockpit including human-machine interface and dashboard can be rethought in terms of passive and active safety by the use of active sidesticks. The implications of the functional safety concept on the active sidestick concept are presented and explained in detail. Furthermore, concepts for the forward and feedback control system and the connection to the vehicle dynamics controller are explained.

2 Research Vehicle SpeedE

The Institut für Kraftfahrzeuge Aachen (ika) introduced the research vehicle SpeedE at the Aachen Colloquium Automobile and Engine Technology in 2011 (see Fig. 1). This new generation of full-electric vehicles is combining the advantages of electric mobility and the complex requirements for efficiency and safety.

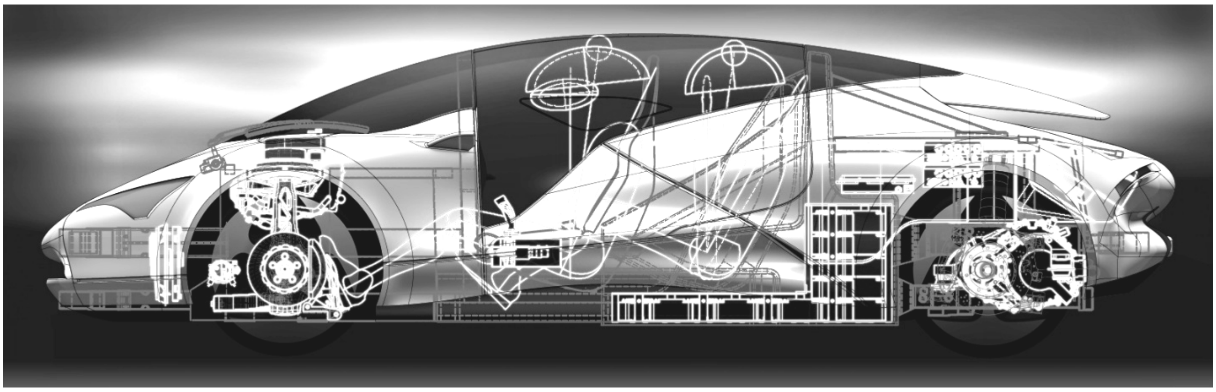

Fig. 1: Vehicle Concept SpeedE

The interior and exterior purpose design was realized in a close cooperation between ika and the School of Transportation Design of Pforzheim University [1]. The vehicle, which is propelled by two electric engines located closely to the rear wheels, accommodates three passengers. The driver is sitting in the front center of the vehicle, the two passengers in a shifted rear position. The steer-by-wire system consists basically of two individual steered wheels and two active sidesticks.

System integrity is achieved by new approaches in functional safety. Previous proposals discuss the system-specific deployment of redundant components and network architectures which is disadvantageous regarding system weight, package space and costs. The SpeedE steer-by-wire system deals with this challenge across system boundaries by utilization of degraded operating states as described in [2].

Electric actuators integrated into an innovative suspension system turn the front wheels individually up to a steering angle of approximately 90°. The operation of the steering system is carried out by means of two active sidesticks, which behave as if they were mechanically coupled. The use of active sidesticks offers the possibility to rethink

- the functional relationship between operating device and steering system respectively vehicle dynamics,
- the vehicle architecture aiming at advantages in conception, e.g. regarding modularity, and production and
- the design of the operating device and the ergonomics of the operator’s working place.

On the one hand, the individual deployment of the wheel steering angles guarantees high vehicle maneuverability. Moreover, it offers a high functional potential regarding vehicle safety, comfort and efficiency as well as an optimal utilization of the side force potential at the front axle. On the other hand, the deployment of individual steering angles challenges the active sidestick feedback control system. Thus, the two active sidesticks have been built up to investigate different concepts of the forward and feedback control system of the SpeedE research vehicle.

3 Active Sidestick Concept

After having taken over a crank-like device from horse-driven coaches, Alfred Vacheron was the first engineer to improve the complex vehicle operation in a redesigned 1893 Panhard 4hp in the race Paris-Rouen in 1894 [3]. Later, the steering wheel became commonly and exclusively the operating device to influence the vehicle direction for another century. The steering gear and the ideal force transmission have improved the effort of setting the vehicle course and lead to the steering wheel's success.

In the history of automotive design, numerous futuristic vehicle concepts have dealt with rethinking the human machine interface. Some of these concepts used and investigated in detail the idea of integrated sidesticks (e.g. [4], [5], [6]). The SpeedE concept is the first vehicle to combine a wheel individual steering system with high achievable steering angles and active sidesticks embedded into a vehicle dynamics controller. The following chapter presents the sidestick design and the forward and feedback control concept.

3.1 Overview Sidestick Design

A study has been carried out to find the optimum position for the sidesticks in the SpeedE passenger compartment. The test group consisted of 46 subjects (32.6% female, 67.4% male) ranging from 21 to 63 years. The study resulted in an optimal sidestick handle bar position of 240 mm in x- and 315 mm in y-direction with reference to the Seating Reference Point (SgRP). The optimal height for the arm support is 370 mm [8].

One important engineering goal is a minimum of required package space for sidestick integration. As the sidesticks are positioned next to the driver's seat, especially the sidestick box width is virtually fixed to a maximum of 100 mm. The length is limited to 210 mm.

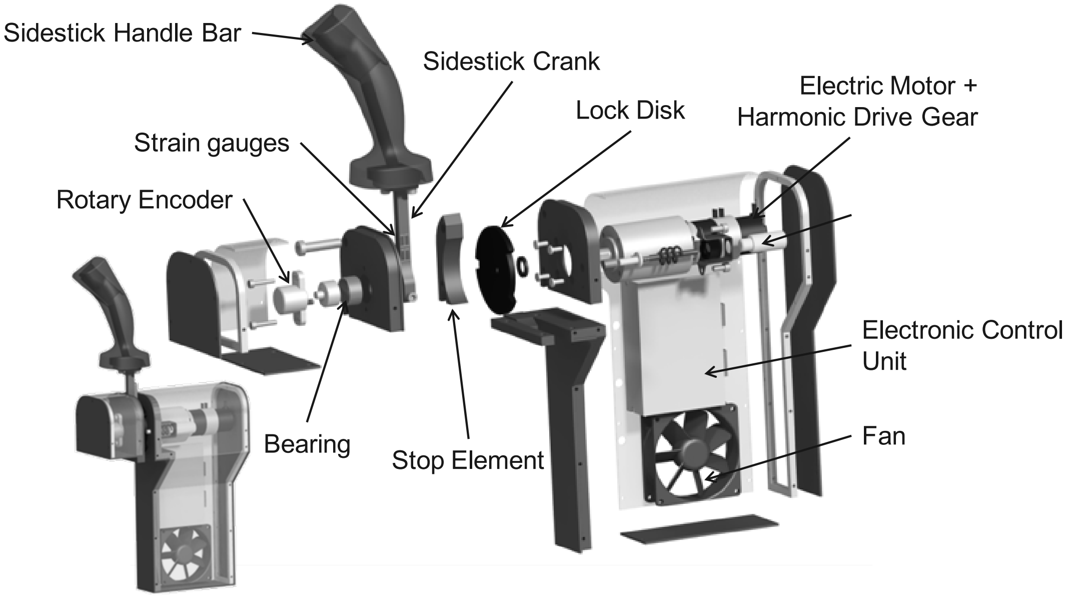

Fig. 2: Sidestick components

Fig. 2 shows the assembly of one sidestick unit. The main sidestick component is the electric motor combined with a harmonic drive gear. This combination is advantageous because of the self-locking ability which originates from a high gear ratio of 100. Therefore, the electric motor weight can be reduced to 0.8 kg while achieving a maximum output torque of 28 Nm. The sidestick crank has an effective length of 150 mm between the pivot point and the driver`s hand, thus the motor will be able to support a total driver hand force of more than 185 N. The angle of the sidestick bar end has got an offset and is inclined by 10° to the driver position due to ergonomic reasons. The maximum sidestick feedback angle is limited to ±30°. Additionally the sidestick is able to swing 180° to facilitate the driver’s entrance and exit of the vehicle. This results in a total angle of 210° which is swept through by the sidestick crank (see Fig. 3).

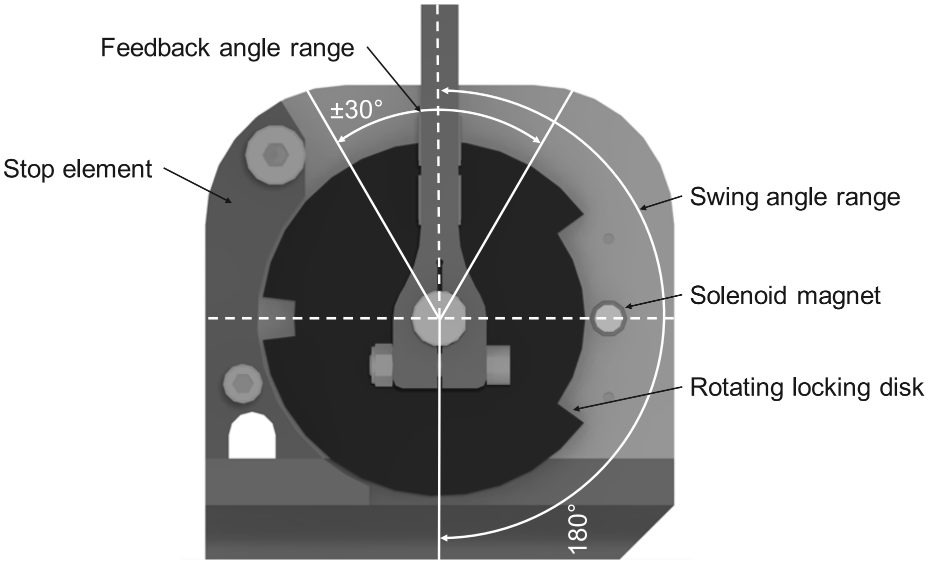

Fig. 3: Sidestick feedback and swing angle ranges

By means of a stop element, the total angle is limited to 220°. Furthermore, two states in operation mode are locked by a solenoid magnet which moves a pin in a rotating locking disk. In hinged position at 180°, the sidestick crank is fixed. Additionally the permanent magnet blocks the operating angle at ±30°. The locking mechanisms have been designed as safety elements, as e.g. a hinging down sidestick during vehicle operation has to be avoided.

3.2 Forward Control System

According to [6] an active operating device is defined by the active modification of the cutting force between handle bar and operator hand realized by a controllable actuator of any kind. Hence two different types of control systems are becoming apparent: an active operating device with

- displacement as control variable and force feedback, and
- force as control variable and displacement feedback.

[6] motivates the second solution as the principle which is most common to every human since childhood. Applying a force to an object causes the effect of object acceleration/movement. In summary the forward control concept uses the driver's hand force to calculate the steering angle and the sidestick angle is used as a feedback channel informing the driver on relevant system or vehicle states.

The sensor selection has been developed on the basis of a functional safety concept. Thus, the components are considered as safety elements. The force is detected with four strain gauges on each side of the sidestick crank. The sidestick crank has been designed to achieve a maximum strain of 870 µm/m which results in the best achievable strain gauge resolution (see Fig. 4).

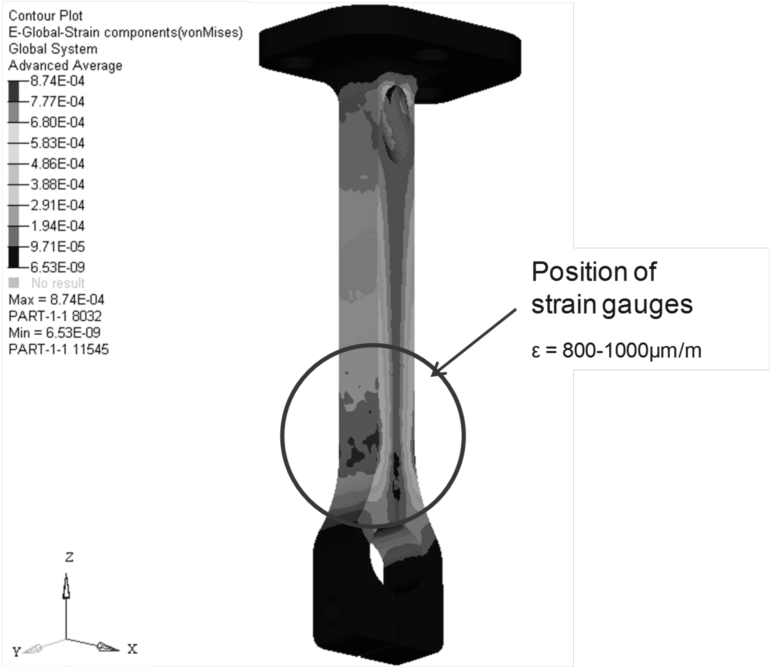

Fig. 4: Sidestick crank with 30 Nm bending load

Four strain gauges, two of each side, are connected to one Wheatstone bridge in order to compensate e.g., temperature influences. As the force is measured twice with the principle of electrical resistance, the motor torque is taken into account as a third element to cross-check the result of the two strain gauge circuits. In summary, the driver's hand force of one sidestick is detected three times with two different measurement principles. Additionally, the force of both sidesticks is summed up and serves as the control variable. Hence, the vehicle can be driven with either the right, left or both hands which results in an increased redundancy. From the system integrity point of view, the hand force detection has to be guaranteed in any circumstance.

For the calculation of the desired steering extent, the driver's left and right hand forces are summed up. The signal is filtered and amplified with a basic and a velocity dependent amplification factor resulting in a desired steering angle of the front axle (see (1), [6]).

$$\delta_{St,des} = \frac{K_{St}}{1 + K_{St,v} \cdot v} \cdot \sum F_{Sidestick} \tag{1}$$

The maximum achievable front wheel steering angle of the SpeedE research vehicle ranges from 90.5° at the inner to approximately 60° at the outer curvature wheel. In order to guarantee a smooth operation for the driver, the driver's hand forces are transformed into one wheel steering angle based on the single track model [7] which ranges from +74.1° to -74.1° (see Fig. 5).

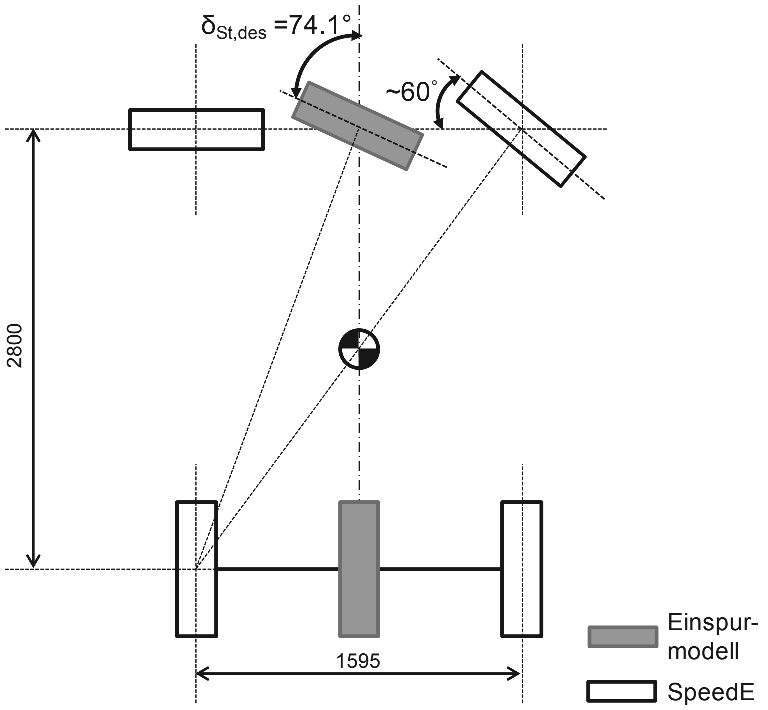

Fig. 5: Maximum SpeedE steering angle and transformation to single track model for basic steering functionality (Ackermann)

Depending on vehicle speed and driver hand force the achievable desired steering angle may be electronically limited according to Fig. 6. The values are exemplary and can be changed during the system application.

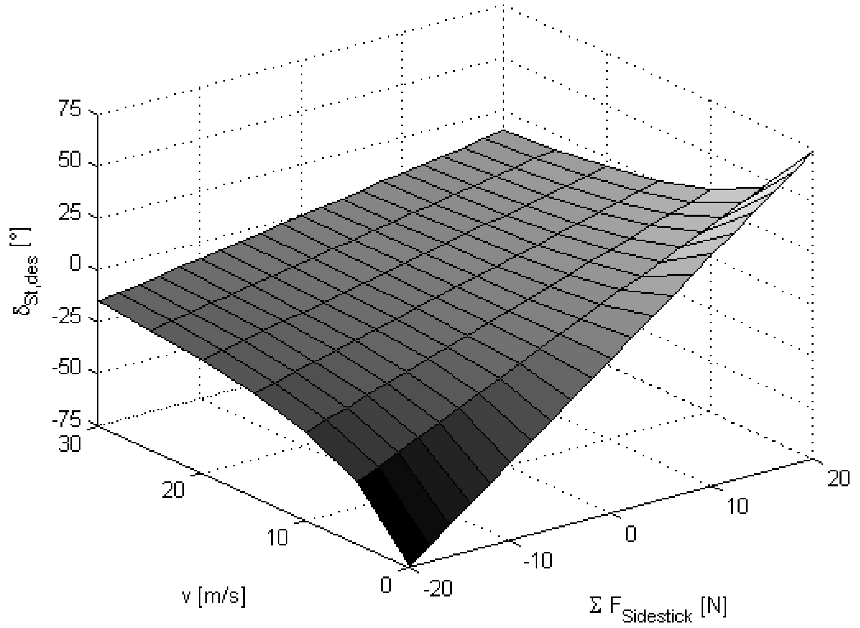

Fig. 6: Maximum achievable SpeedE steering angle depending on vehicle speed and driver hand force

Fig. 7 shows the overview of the forward control system from the driver hand force up to the wheel actuator. The desired steering angle of the single track model is converted into the left and right wheel steering angle using a modified Ackermann algorithm. This algorithm allocates the optimal wheel steering angle depending on the vehicle velocity and the lateral acceleration. Thereby e.g. a tension free rolling of the vehicle at low speed and a good longitudinal and lateral axle force exploitation at all speeds can be achieved.

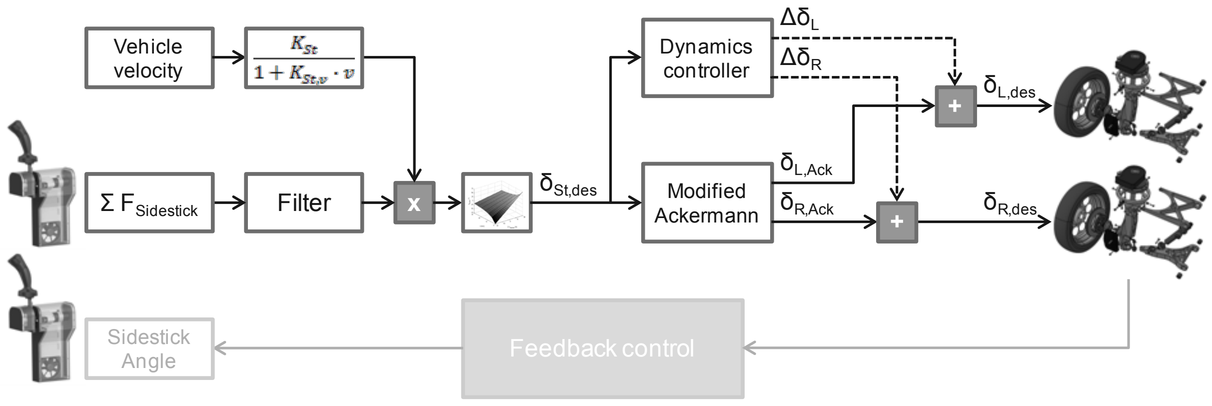

Fig. 7: Overview of forward control concept

The dynamics controller of the vehicle influences the steering angle values of the wheels in order to stabilize the vehicle in critical situations (e.g. oversteer), increase its agility (e.g. understeer) or optimize the rolling resistance. This is done by adding additional steering angles on top of the desired steering angles calculated by the modified Ackermann algorithm.

The application parameters of the forward control have been adjusted according to [6] and the new requirements of the SpeedE research vehicle. However, the final tuning needs to be performed on real hardware.

3.3 Feedback Control System

As already motivated in the previous chapter, the sidestick angle is used for providing a feedback to the driver with the aid of the electric motor. The motor feedback system is based on an optical incremental encoder. A sensor using the Hall Effect principle has been implemented with the aim of cross-checking the effective sidestick angle. Thus, the feedback control system is designed redundant with two different working principles. In case of a feedback failure, the electric motor output shaft needs to be fixed. [6] has shown that the driver is still capable to drive with isometric (fixed) sidesticks. The driver behavior in such a failure mode will be investigated after the sidesticks have been build-up.

[6] has chosen the course curvature κ as the most appropriate parameter to feed back. This is defined based on the curve radius R or on the single track wheel steering angle δ_{St}, the self-steering gradient SG and the vehicle velocity (see (2)).

$$\kappa = \frac{1}{R} = \frac{\delta_{St}}{l + SG \cdot v^2} \tag{2}$$

The goal is to use a parameter which corresponds to the visual human perception and describes the lateral vehicle dynamics behavior. At the same time, the parameter should be decoupled from longitudinal vehicle dynamics in order not to vary the sidestick position while accelerating or decelerating. Following this argumentation, the feedback controller of the SpeedE research vehicle uses the curvature as the value to be transformed into the sidestick angle (see (3)). The amplification factor K_R is determined based on the maximum sidestick angle range.

$$\delta_{Stick} = \kappa \cdot \mathrm{K_R} \tag{3}$$

Fig. 8 gives a functional overview of the feedback control system. A major challenge in developing the feedback control of the SpeedE research vehicle is, due to the individual wheel steering angles and the corrections by the dynamics controller, requiring a sufficiently correct estimation of the course curvature. First of all, depending on the driving situation and the vehicle side slip angle, the measured steering angles do not reveal where the vehicle is really heading to. Secondly, the measured steering angles of the wheels cannot be simply fed back to the driver, because the vehicle dynamics controller often sets additional angles in order to stabilize the vehicle (e.g. steer back during oversteer situations). The vehicle dynamics controller's activity shall not or not entirely be perceivable by the driver. In this way the driver feels that he is always in control of the vehicle, regardless of the dynamics controller interventions.

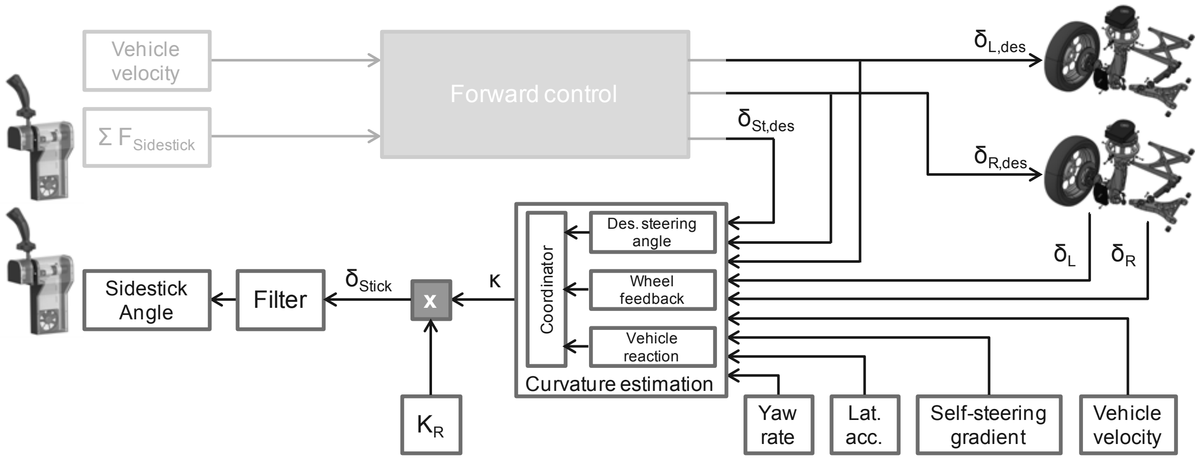

Fig. 8: Overview of feedback control concept

The curvature estimation algorithm considers three feedback strategies and coordinates them into one curvature value. The three strategies are based on:

- the desired steering angle of the single track model
- the actual wheel angles
- the vehicle's dynamic state (e.g. yaw rate and lateral acceleration)

The simplest strategy is to route the driver input (desired steering angle) back as the sidestick angle using the single track model. The curvature is thereby calculated considering the velocity and the self-steering gradient of the vehicle (see (2), (3)). In most of the driving situations this calculation is correct, since the vehicle dynamics controller is regulating the steering angles in order to exactly follow the desired driving trajectory. The disadvantage of this strategy is that the driver has no feedback on the real vehicle or wheel behavior (e.g. steering towards curbstone).

The second feedback strategy uses the measured steering angles and compares them to the desired angles. The difference between the desired and the measured value provides information on the present wheel force and position. This delta can be subtracted from the desired steering angle and regarded in the course curvature estimation. This strategy has the advantage of feeding back the dynamic extent of the vehicle dynamics controller interventions. This can be of interest for some driver types.

The vehicle behavior determined by using the lateral acceleration and yaw rate is the most accurate feedback possibility for determining the curvature during steady-state cornering on even roads. Non steady-state cornering, instable driving situations or roads with lateral inclination are a challenge for such an algorithm, since more complex vehicle dynamics models are necessary to estimate the vehicle´s trajectory on the basis of the available sensors.

The coordinator adds up the information from the three strategies and calculates the curvature depending on the current driving situation. The weighting of each strategy is being varied in order to have an optimal curvature feedback.

The optimal road curvature estimation coordination algorithm will be elaborated and applied after the sidesticks have been built up, on real hardware and using real driving situations and various types of drivers.

4 Summary and Outlook

The steering system of the research vehicle SpeedE is equipped with individual steered front wheels with high achievable steering angles. It is designed as a steer-by-wire system controlled by active sidesticks. The system additionally comprising a vehicle dynamics controller is embedded in an overall functional safety concept.

At the same time the implementation of active sidesticks offers all advantages of steer-by-wire systems and opens new possibilities in the design of the cockpit including the dashboard and the human machine interface. The forward control is realized by detecting the driver’s hand forces, which are then transformed into a steering angle based on a single track vehicle model. A modified Ackermann function then calculates the wheel steering angles depending on the driving situation, in order to achieve a tension free rolling at low speeds and a good longitudinal and lateral force exploitation at all speeds. The vehicle dynamic control functions finally adds correcting steering angles in order to keep the vehicle stable and agile.

However, due to the single-steered wheels and the integration of a vehicle dynamics controller the sidestick feedback to the driver is challenging. The sidestick angle is calculated on the basis of the current curvature of the vehicle´s trajectory. The curvature is the most appropriate value for the description of the lateral behavior as it is velocity-independent and corresponds to the visual perception of the driver. The determination of the course curvature is done depending on the driving situation. The algorithms are based on the desired steering angle, the measured steering angle and the measured vehicle driving state, e.g. yaw and lateral acceleration reaction. A final application of the functionalities can only be done with real hardware and using several driver types.

The active sidesticks have been built-up in order to test and tune the proposed control concepts in combination with a simulated SpeedE vehicle model. The optimal forward and backward control application will be elaborated based on driving tests in the near future.

5 Definitions, Acronyms, Abbreviations

Abbreviation	
ika	Institut für Kraftfahrzeuge Aachen
SgRP	Seating Reference Point
des	desired
St	steering
Ack	Ackermann
Stick	sidestick
L	left
R	right

Definition		
δ	[°]	angle (steering)
$\Delta \delta$	[°]	delta angle (steering)
κ	[1/m]	course curvature
F	[N]	force
K_{St}	[°/N]	steering amplification factor
$K_{St,v}$	[1/v]	vehicle velocity steering amplification factor
K_R	[°m]	feedback amplification factor
v	[m/s]	vehicle velocity
SG	[°s^2/m]	self-steering gradient
l	[m]	wheel base

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