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Steer-by-wire steering system with enhanced functionality for rear steered vehicles

Christoph Dillmann, Bernd Johanning

Rear-steered self-propelled harvesters are the central elements of modern harvesting chains in agriculture. But on-road control of rear-steered machines can be complicated at the present stage of development. Main reasons include chassis design for enhanced soil protection, current top speed of 40 km/h and system-related disadvantages in the dynamics of driving. To maintain the vehicle on track and to stabilize it, a lot of experience and high concentration is required from the driver. Driving dynamics systems can relieve the driver and, hence, make driving at high speeds safer and more comfortable. The project described in the following introduces a steer-by-wire steering system with configurable steering characteristics, which can be adjusted to the different advantages of the driver and provides driving state-dependent information through the steering wheel to the operator.

Keywords
Steering system, steer-by-wire, rear wheel steering, driving safety, mobile machines

Rear-steered self-propelled harvesters, e. g. forage harvesters, are the key elements of modern harvest chains in agriculture. In order to ensure the profitability of these machines a rapid movement between the fields is needed. This led to a cross-vendor increase of the driving speed from 25 to 40 km/h whereby driving dynamics and driving safety in mobile machinery are gaining more importance. In this context the following systematic disadvantages of rear steered machinery have to be stated:

- Negative self-steering gradient
- Missing steering wheel return forces
- Decoupling of driver and vehicle

According to DIN 70000, the self-steering behavior of vehicles is described by the self-steering gradient (EG):

$$EG = \frac{d\delta_H}{da_y} \cdot \frac{1}{i_s} - \frac{d\delta_A}{da_y} \qquad \text{(Eq. 1)}$$

In driving tests the EG is often determined by steady-state circular motion with constant radius, as in this case the Ackermann steering angle δ_A remains constant and thereby the derivation of the lateral acceleration a_y equals zero. Within constant steering ratio i_s the EG can be read from the required steering wheel angle curve (Figure 1).

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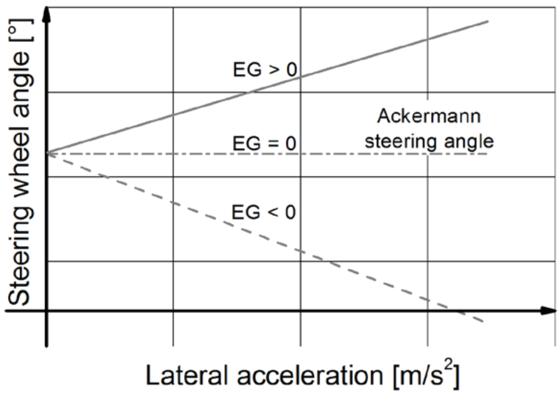

Figure 1: Required steering wheel angle at constant path radius according to Schindler (2007)

In the case of a vehicle with negative self-steering gradient and the associated oversteering driving behavior the steering wheel angle δ_H must be withdrawn when increasing lateral acceleration. The stability limit is reached when the steering wheel angle is reduced to zero. Moreover, the vehicle becomes unstable. Thus, rear-wheel steer machines are to be driven safely only up to a vehicle-specifically critic driving speed (Herold and Wallbrecher 2013).

A further disadvantage of rear wheel steered vehicles is the negative self-alignment force M_{SR} acting on the steered rear wheels. This is caused by the cornering forces F_S transposed from the middle of the tyre contact patch onto the pneumatic trail n_R (Figure 2). Unlike the autonomous resetting into the centre position within a front steer system, this leads to an enlargement of the steering angle. Even though a huge caster angle as well as a big kingpin inclination at the rear axle enhance the driving safety, it also causes a stability problem at higher speed (Zomotor 1987).

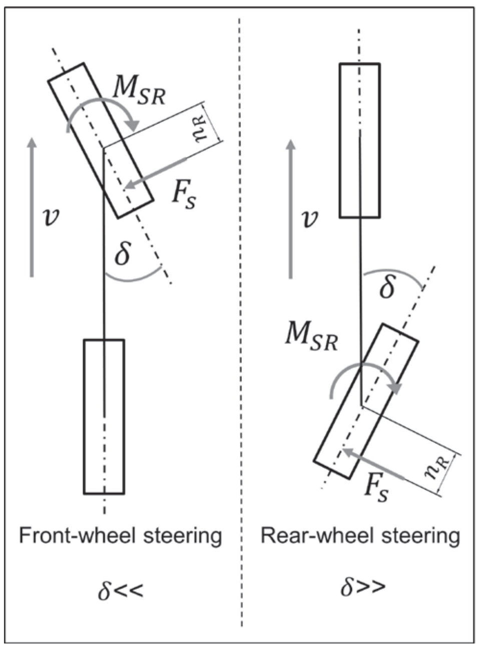

Figure 2: Tire aligning torque of a front-steered and a rear-steered vehicle

In order to counteract the autonomous enlargement of the steering angle, mobile machines are equipped with hydrostatic steering systems which clamp the steering cylinder hydraulically at constant steering wheel angle. However, this leads to a strong decoupling of driver and vehicle without giving a feedback of the driving dynamics. Figure 3 displays the course of the steering wheel torque over the steering wheel angle at constant speed. Throughout the whole range of steering wheel angle, the steering wheel torque remains constant throughout varying lateral accelerations; thus, the haptic feedback provides no information to the driver about the driving dynamics.

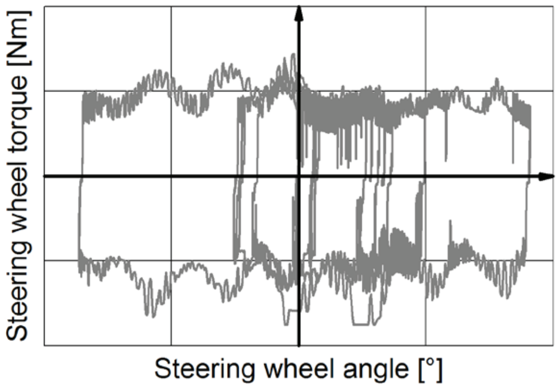

Figure 3: Characteristic of a fully hydraulic steering system

Derived from the presented disadvantages the research aim of this project funded by the BMBF is to improve lateral dynamics at fast-moving, rear-wheel steering machines. Using the example of a forage harvester, an active dynamic driving system should be developed allowing safe driving speeds of 40 km/h or higher.

Solution concepts

In this context two solutions are worth being considered: the driving dynamics modification of the lateral dynamics as well as the improvement of the driver´s awareness concerning the steering response depending on the haptic feedback (Schmidtke 1993). With regard to the disadvantages mentioned above following solutions are revealed:

1. Regulated speed difference on the front wheels (Skid-Steer-Principle) which allows autonomous minor steering movements or can be used as support for the rear wheel steering. Such feature can either be realized through the regulation of hydraulic adjustment (hydraulic motors) or through immediate braking of one front wheel.
2. Steering movement of front wheels with minor steering angle and same influence possibilities concerning driving dynamics as seen in point 1.
3. Active driver seat adjustment (rotation around the vertical axis respectively seat tilt) as feedback or rather to intensify the perception of the current driving situation and reaction. A continuation of this approach could lead to an active motion of the whole cabin.
4. Electro-hydraulic steering with the additional functionality of speed and steering angle dependent steering ratio and steering wheel torque.

5. Active-controlled steering wheel return forces for the realization of an automatic straightline tracking and steering wheel return after cornering. This approach aims at the haptic perception of the driver and ensures an improvement of the steering response, particularly at high speeds.

The above-mentioned concepts do not claim to be exhaustive and are openly discussed in the research project. This paper provides first insights into the concepts 4 and 5 which lead by the integration of a new steering assistance facility to an improved perception of the driver.

Test vehicle

The test vehicle, a forage harvester type BiG X V8 from Krone, has been equipped with a steer-by-wire (SbW) system. The major components of this steering system (Figure 4) are a proportional valve and a steering simulator which consists of an absolute encoder, an electromagnetic brake, a gear unit as well as an engine with complying engine electronics. The actual angle of the steering axle is received with an angle sensor and, like the other signals, processed with a rapid-control-prototyping system (RCP system). In addition, a 3/2-way valve has been installed to switch between SbW and fully hydraulic steering system ensuring a quick change between the two steering modes on hydraulic level. The steering simulator is mounted on the steering column of the forage harvester and is activated by replugging of the steering wheel. Thus, a direct comparison of the two systems is possible without costly set-up times.

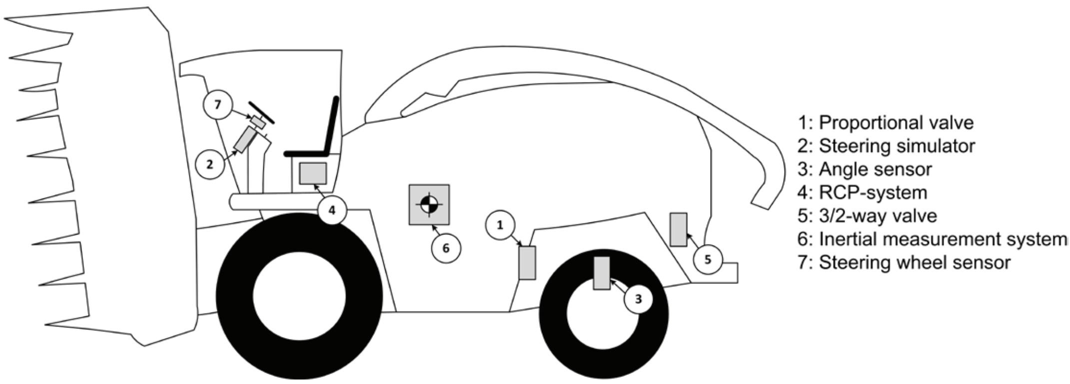

Figure 4: Schematic arrangement of the components in the test vehicle

Besides the functionality components mentioned above, a further measuring technology is installed. An inertial measurement system measures the vehicle dynamics parameters such as the speed, pitch-, roll- and yaw angles and accelerations in the machine´s centre. A steering wheel sensor detects steering wheel torque, steering wheel angle, velocity and acceleration.

Through the SbW system synthetic moments can be generated on the steering wheel. Different sensor signals, such as the steering wheel angle or the lateral acceleration can be used as input variables in order to characterize the course of the amplitude of the steering wheel torque and the steering ratio. The modeling of driving situation-specific steering wheel and return forces at the wheel for active middle position after cornering or in order to produce a straight-line tracking ("Groove" effect) are possible. Different solutions concerning the perception of the driver can thus be tested with this test vehicle.

Test objectives and execution

The aim of the experiments is the determination of parameter combination that conveys a positive steering feeling to the driver in the particular driving situation. According to Wolf (2008) steering feeling can be defined in a narrower and a broader sense. Within the driving tests, the steering feeling is regarded in the narrower sense, which involves mainly the steering wheel torque and the steering wheel angle and thus is targeted on the haptic perception at the steering wheel. Despite different approaches to objectify the steering feeling, the evaluation of the steering system is based on a subjective assessment as this still represents the best tool for evaluating the steering and driving behavior (Koch 2010).

The driving tests are carried out by normal drivers who unlike trained test drivers neither can reproduce subjective opinions of steering characteristics nor compare the multiple variations (Barthenheier 2006). Therefore, a relative evaluation is carried out between two pairs in the variation of each parameter. During the test scenarios the test subjects are exposed to typical driving situations, which they have to assess according to certain criteria. Within the parking scenario, the following characteristics in terms of driving comfort, driving safety and feedback of the dynamic driving state are evaluated:

- initial steering torque
- steering torque curve
- required steering wheel angle

Preferred forms and limits of such parameters are known for the automotive sector (Wolf 2008, Heissing and Brandl 2002) as well as simulations of the driver´s behavior, which correlate parameters of the driver model with subjective judgments of drivers (Henze 2004, Zschocke 2009). However, due to different steering concepts and speed ranges, these findings cannot be applied directly for rear-steered mobile machinery. Therefore, parameter studies were conducted in order to identify meaningful combinations of steering ratio, steering torque and steering wheel return and thus limit the number of variants, so that verification by normal driver can be realized.

Figure 5 shows two steering wheel torque curves for various speeds. The torque increases when turning in a curve to the end limits. When deflecting out of the corner there is a small, constant counter-torque up to the neutral position, which is marked by a steep torque on both sides. At speed 2, the end stop has not been reached.

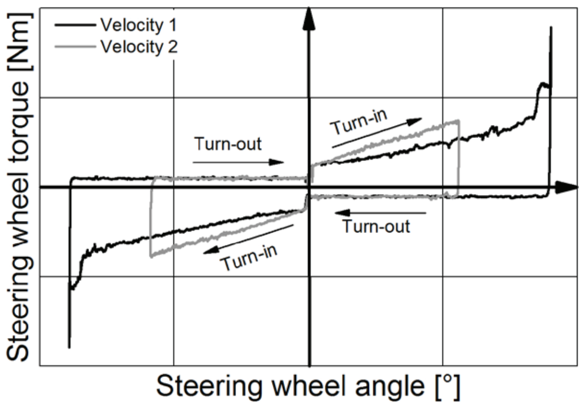

Figure 5: Steering torque curve of the SbW system

Conclusions

The system-related disadvantages of a rear wheel steered machine with fully hydraulic steering system require a lot of skills and experience in guiding such machines. The integration of a steer-by-wire system with the additional functionality mentioned above shows a great potential to improve the driver´s perception.

It has already been identified by driving tests within a small group of subjects that a better driving feeling can be achieved through the implementation of the active center position and the distinctive torque in the centre position. This has to be confirmed in further test series in order to find out a driver-specific steering wheel torque characteristic regarding the above mentioned criteria.

The concept presented here is limited to the road trip. Safety aspects and steering wheel torque during the work process where other criteria apply, are initially not considered. With regard to a subsequent series approval and the optimum design of the overall system, further studies are necessary.

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