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Steer-by-wire system of an agro-hybrid vehicle with single wheel drive

For landscape preservation a compact, remote controlled implement with modern and efficient drive technology has been developed. The new implement carrier offers good maneuverability, a low center of gravity and enables soil-protective steering modes. This paper focuses on the wheel-speed and steering models of this vehicle equipped with single-wheel drive, which enable best possible operation in different steering modes.

Abstract
Landtechnik 69(2), 2014, pp. 78–83, 6 figures, 2 tables, 10 references

■ Machine productivity can be gained by increasing working widths, more powerful engines and faster process speeds. Such huge machines can hardly be operated in alpine regions. A crucial issue in the cultivation of steep slopes is to assure the operator's safety. Consequently, a remote controlled implement carrier has been developed, where the operator can stand at a safe place, while the machine works in rough terrain. Firstly, the machine is utilized for applications as mowing, mulching and snow blowing. Based on the typical properties of the machine it is expected, that the application range will expand rapidly.

System Architecture
Electric drives are promising for dedicated applications in agricultural engineering due to their good controllability and high efficiency. Besides, new functionalities and machine concepts can be realized [1-3].The presented implement carrier basically is a serial-hybrid-vehicle [4; 5], for general data of the vehicle see **Table 1**. An internal combustion engine (ICE) drives two 24 VDC-generators. The electric energy is stored in conventional lead-acid batteries. The control unit actuates the four wheel-motors. Therefore the ground speed can be controlled infinitely variable. The PTO is driven by the ICE via a mechanical gearbox (**Figure 1**). The hydraulic system has been replaced completely. The steering and implement lifting movements are done by

means of electric linear actuators. The chosen architecture enables hybrid-functions like recuperation or a pure electric drive. Besides, several steering modes as front-axle-, rear-axle- or all-wheel-steering and crab-steering are possible.

The chassis includes a central swivel joint, which enables front and rear axles to be twisted by 35°.

This allows best possible ground contact of the tires and equal load distribution. In the introduced concept with single wheel drive the maximum traction power is limited by the power of the wheel-motors and not by the power of the internal combustion engine. Coupled implements can be lifted by an electric lifting device (categories 0 and 1) and operated through a mechanical PTO-drive due to efficiency reasons.

As every single wheel is equipped with a separate electric motor, mechanical differentials are not needed. But their functionality must be emulated in any driving situation. Therefore it is necessary to integrate the steering kinematics model and the wheel speed model into the control strategy. The required formulas for individual wheel-speeds are derived from actually required vehicle speed and steering angle.

Steering
Both axles of the vehicle have steering actuators, which allow several steering modes. In recent publications vehicles with various steering modes have been introduced, comprising axle-drive or single-wheel-drive [6-8]. In the current project the steering modes all-wheel-steering, front-axle-, rear-axle- and crab-steering have been implemented, as both steering actuators can be commanded independently from each other. The ideal steering kinematic turns the wheels tangential to the requested path. At constant steering angle all trajectories have the same instantaneous centre point of velocity P. Therefore the inside wheels must have a higher steering-angle than the outside wheels. This principle is known as Ackermann-steer-

Table 1

Hybrid vehicle specifications

VKM-Leistung/*ICE power*	30 kW
Nennleistung der Radmotoren *Wheel motors' nominal power*	4 x 1,3 kW
Zapfwellendrehzahl *PTO speed*	540 und 1 000 U/min 540 and 1 000 rpm
Gesamtmasse (ohne Geräte) *Total mass (w/o implement)*	660 kg
Radstand/*Wheel base*	1 302 mm
Wenderadius (Vierradlenkung) *Turning radius (all wheel steering)*	1 200 mm
Fahrzeuglänge/*Vehicle length*	2 380 mm
Fahrzeughöhe/*Vehicle height*	950 mm

ing [9]. The difference between inside and outside steering angle gets bigger as the track width increases and the wheelbase decreases. With single-wheel drive every drive has to be controlled with respect to the wheels' steering angle. Vehicle speed, steering mode and mean steering-angle are remote controlled. Steering-actuator positions and individual wheel speeds have to be compiled accordingly. The vehicle speed v_K is referred to the reference point K, which is at the vehicle center line, perpendicular to the instantaneous center P. The steering trapezoid is designed to meet best the Ackermann-principle in all-wheel-steering mode. Following calculations have been done for all-wheel-steering mode.

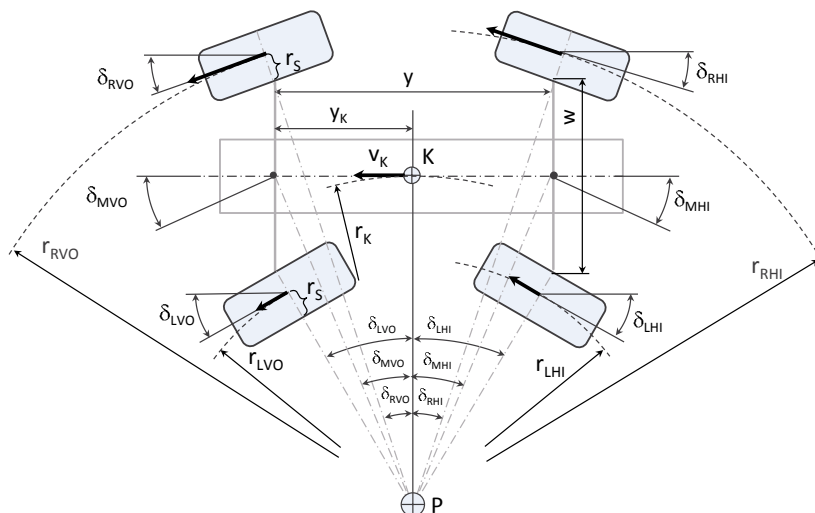### Calculation of Ackermann-steering angles

The stated mean steering angles are applied to the front and rear axle. They have the same absolute values (**Figure 2**):

Fig. 1
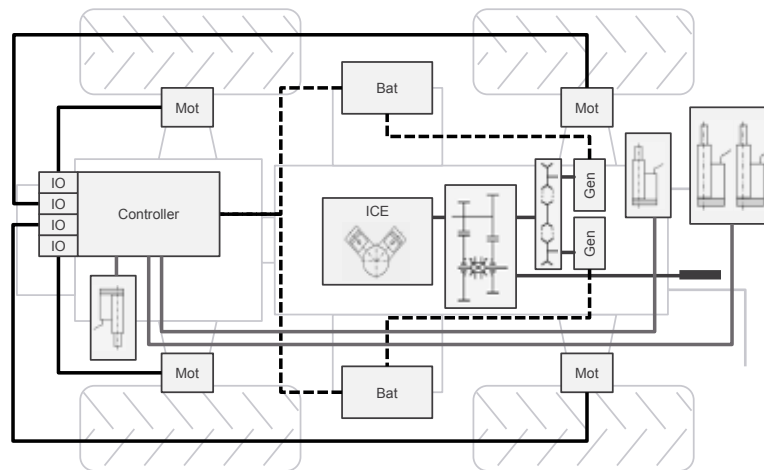
System architecture of the hybrid implement carrier with variable electric traction drive and two-speed mechanical PTO-drive

Fig. 2

Steering angles can also be found nearby instantaneous center P

$$|\delta_M| = |\delta_{MVO}| = |\delta_{MHI}| \tag{Eq. 1}$$

The individual wheel-steering angles can be calculated by using the cotangent-function of the mean steering angle, the wheelbase and the track width reduced by scrub radius (**Figure 2** and **Table 2**):

$$\delta_{RVO} = arccot\left(cot(\delta_M) + \frac{w}{2 \cdot y_K}\right) \tag{Eq. 2}$$

$$\delta_{LVO} = arccot\left(cot(\delta_M) - \frac{w}{2 \cdot y_K}\right) \tag{Eq. 3}$$

The same result is derived by Saxinger in [10], with the difference, that he used the tan-function:

$$\delta_{LVO} = \arctan\left(\frac{2 \cdot y_K \cdot tan(\delta_M)}{2 \cdot y_K - w \cdot tan(\delta_M)}\right) \tag{Eq. 4}$$

$$\delta_{RVO} = \arctan\left(\frac{2 \cdot y_K \cdot tan(\delta_M)}{2 \cdot y_K + w \cdot tan(\delta_M)}\right) \tag{Eq. 5}$$

With all-wheel-steering mode the inside wheels have the same value of steering angle, and so the outside wheels have:

$$|\delta_{LHI}| = |\delta_{LVO}| \tag{Eq. 6}$$

$$|\delta_{RHI}| = |\delta_{RVO}| \tag{Eq. 7}$$

The calculated steering angles of each wheel are illustrated in **Figure 3**. For left cornering with a vehicle mean steering angle of 20°, the inside wheels (left front and rear) have to be turned by 26,1° respectively -26,1° and outside wheels (right front and rear) by 16,1° respectively -16,1°, to meet the Ackermann-conditions. The linear actuators for steering at the front- and rear axle have to be commanded accordingly, whereas the actuator at the front axle has to be pushed out from its neutral position and the rear actuator has to be pulled-in. The required lengths (strokes) can be calculated by using trigonometry (**Figure 4**).

Calculation of wheel speed

All pivot axles are without camber. As the radio-controlled vehicle speed refers to point K, the pole distance is calculated first:

$$r_K = \frac{y_K}{tan(\delta_{MVO})} \tag{Eq. 8}$$

After that the track radii of the individual wheels are calculated:

$$r_{LVO} = r_{LHI} = \frac{y_K}{sin(\delta_{LVO})} - r_S \tag{Eq. 9}$$

$$r_{RVO} = r_{RHI} = \frac{y_K}{sin(\delta_{RVO})} + r_S \tag{Eq. 10}$$

The vehicle movement with a steering angle can be assumed as rotation about the instantaneous center point P. Hence, the individual wheel speeds are:

$$v_{LVO} = v_{LHI} = v_K \cdot \frac{r_{LVO}}{r_K} \tag{Eq. 11}$$

$$v_{RVO} = v_{RHI} = v_K \cdot \frac{r_{RVO}}{r_K} \tag{Eq. 12}$$

The default vehicle speed can be multiplied by a factor to obtain the required wheel speeds for the requested cornering. The speed ratios refer to the requested vehicle mean steering angle (**Figure 5**). A positive value of the mean steering angle refers to left cornering during forward drive. Which means that the inside wheels (left vehicle side) must have slower speed than the outside wheels (right vehicle side). As the steering trapezoid is optimized for all-wheel-steering, the Ackermann conditions are just approximated for the remaining steering modes. The individual wheel speeds are calculated in a way, as if the mechanical steering kinematics would fully comply with

Table 2

List of abbreviations

δ_M	Fahrzeuglenkwinkel/*Vehicle steering angle*
δ_{MVO}	Mittlerer Lenkwinkel an der Vorderachse *Mean steering angle at the front axle*
δ_{MHI}	Mittlerer Lenkwinkel an der Hinterachse *Mean steering angle at the rear axle*
δ_{RVO}	Lenkwinkel am rechten Vorderrad *Steering angle at the right front wheel*
δ_{LVO}	Lenkwinkel am linken Vorderrad *Steering angle at the left front wheel*
y_K	Radstand/*Wheel base*
w	Abstand der Lenkachsen (links-rechts) *Distance of the king pins (left-right)*
δ_{LHI}	Lenkwinkel am linken Hinterrad *Steering angle at the left rear wheel*
δ_{RHI}	Lenkwinkel am rechten Hinterrad *Steering angle at the right rear wheel*
r_K	Kurvenradius des Fahrzeugbezugspunktes K (Polabstand $\overline{PK}$) *Turning radius of the vehicle reference point K (pole distance $\overline{PK}$)*
r_{LVO}	Kurvenradius am linken Vorderrad *Turning radius of the left front wheel*
r_{LHI}	Kurvenradius am linken Hinterrad *Turning radius of the left rear wheel*
r_{RVO}	Kurvenradius am rechten Vorderrad *Turning radius of the right front wheel*
r_{RHI}	Kurvenradius am rechten Hinterrad *Turning radius of the right rear wheel*
v_{LVO}	Geschwindigkeit am linken Vorderrad *Speed at the left front wheel*
v_{LHI}	Geschwindigkeit am linken Hinterrad *Speed at the left rear wheel*
v_{RVO}	Geschwindigkeit am rechten Vorderrad *Speed at the right front wheel*
v_{RHI}	Geschwindigkeit am rechten Hinterrad *Speed at the right rear wheel*
r_S	Lenkrollradius/*Scrub radius*

Fig. 3
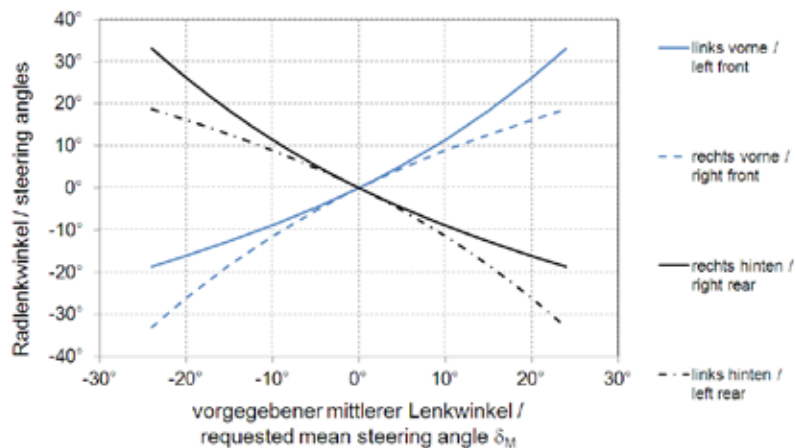
Steering angle of each wheel at given mean steering angle

Fig. 4
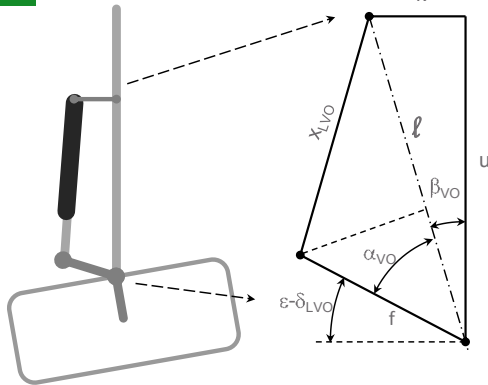
Kinematics at the front steering actuator

Ackermann-steering. Tests in practice with front-, rear- and crab-steering have shown good controllability.

Simultaneous Control of Traction Drive and Steering

Each one of the wheel motors has to be controlled separately. Additionally the commands for traction-motors and steering have to be synchronized in time. Otherwise e.g. still standing wheel-motors could interrupt or prevent the linear actuators from moving. A common and well-known industrial SPS-system was used for the implementation of the controller strategy. It has several analog and digital in-/outputs and a CAN-Bus for the communication with external hardware.

Handling

The requested vehicle speed and steering angle are commanded by a radio control unit. The up/down-angles of a joystick define the direction and requested velocity of the vehicle. The maximum speed can be defined with a control knob at the remote control panel. The steering mode can be selected by hitting one of four steering buttons. The steering is done by left-/right-movement at the second joystick. An electro-magnetic clutch connects the internal combustion engine with the PTO-shaft to power an implement. The clutch can be operated by the remote control unit. The lifting/lowering of an attached implement is done by forward/backward movement of the second joystick. The internal combustion engine can be started and stopped from distance and the rev-value can be set. Together with implements some further more functions are possible. A display is installed on-board, where system information, as e.g. steering angle, battery state of charge and engine temperature, can be indicated.

Control concept

The controller algorithm has to deal with following major tasks:

- Compute requested values of linear actuators dedicated to the front and rear axle based on trigonometry, see **Figure 4**
- Compute required values for angular velocities of the traction drives from equations 11 and 12

Figure 6 illustrates the control concept of the vehicle with its inputs and outputs (IO's, **Figure 1**). The grey blocks represent inputs from measured position-increments of the steering actuators within the control loop. The blocks marked yellow are outputs of the control loop which transmit the target values to the servo-controllers of the single wheel drives respectively to the controllers of the steering actuators. The orange colored blocks characterize procedures for unit-conversions or calculations of the steering direction. Green blocks indicate calculation of the default values of the steering actuators. The blue blocks represent calculations which are essential for the target values of the rotary speed of the single wheel drives.

The blocks VR_Joy and LR_Joy are input values of the remote control unit and refer to forward-/backward- and left-/right-movements of the joysticks at the RC-panel. The rotary speed controller WGR calculates the steering-speed with respect to the chosen steering mode. The steering angle-speed-controller for the front (FVO) and the rear (FHI) transform the outputs of the WGR in linear trajectories of the operator-defined steering angle-speeds (**Figure 6**). The limits of the steering angle are supervised continuously.

The additive value of the rotational speed – caused by changing speed of the steering angle, which enables steering

Fig. 5
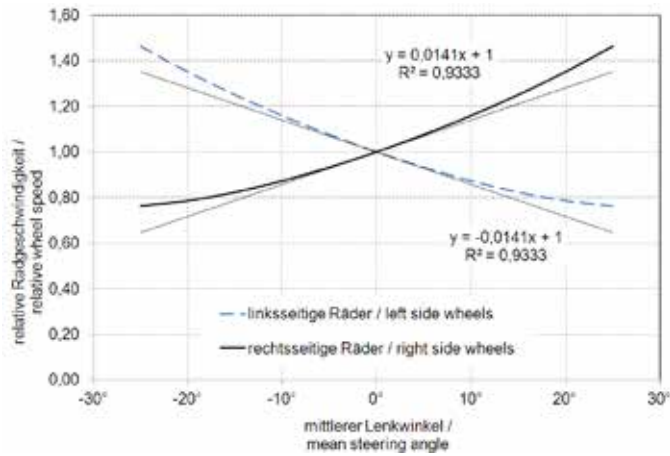
Relative wheel speed at various mean vehicle steering angles in all-wheel steering mode

in stillstand, is calculated in the block RDLG. The calculation of the speed factors is implemented in the block GF. The traction-control TR uses the multiplicative speed factors from GF and the additional wheel speed from FFC and calculates the individually required wheel speeds.

Conclusions

In the new vehicle concept of a hybrid implement carrier for the cultivation of steep slopes an internal combustion engine powers the PTO-shaft mechanically. The infinitely variable traction drive using electric single wheel drive is designed as serial

Fig. 6
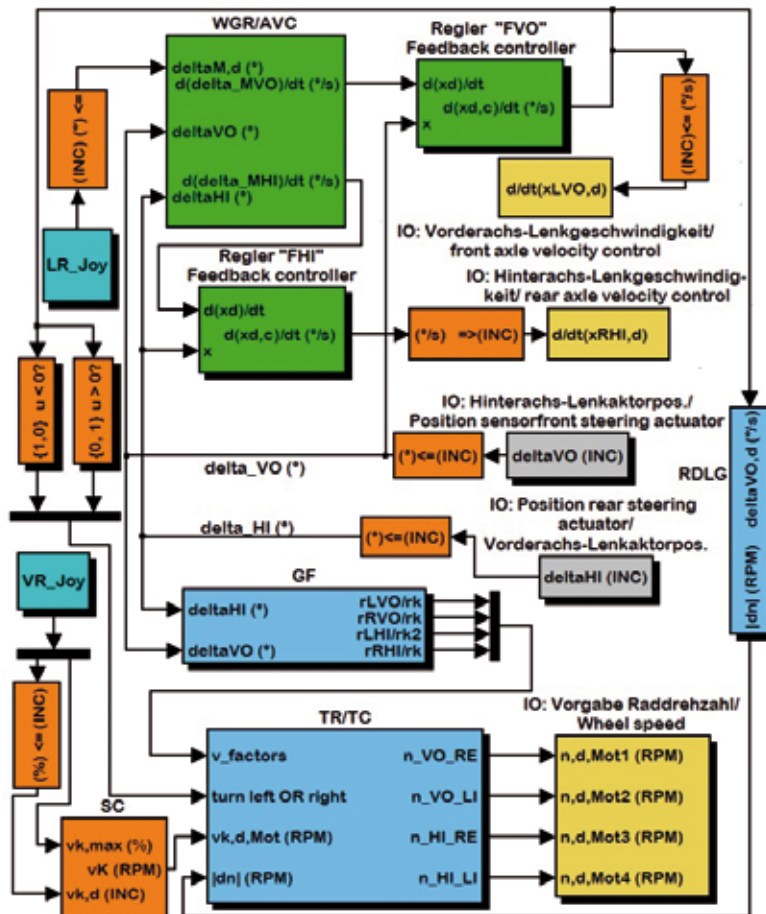
Closed loop control for steering of an agro-hybrid vehicle with single wheel drive

hybrid. Actually four steering modes have been implemented. A hydraulic system is dispensable. A so called comfort-steering-mode is considered in the future. There the instantaneous center is located next to the implement, which prevents it from moving sideways under gentle steering movements. The steering movements and the power lift are operated electrically. The required single-wheel speeds are calculated according to the Ackermann principle and have been integrated into the control. A future perspective of the presented hybrid vehicle is autonomous driving in fields. Therefore a GPS-system must be added to the system. The paths can be predefined on a computer application in a first step. Hence, e.g. plant protection applications could be done driverless.

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