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Sustainable Agriculture in an Electrified World

Cradle-to-Grave evaluation of different propulsion systems

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Abstract

Electrification is arriving in the agricultural industry and is seen as the holy grail for CO_2 emission reduction and sustainability increase, but technology progress in all sectors is needed for the entire lifecycle including production. Future pathways for renewable energy and fuel production needs to be developed and upscaled and issues like indirect land use for the production are to be considered. Therefore, to get a clear picture on sustainability of different propulsion systems, a cradle to grave evaluation is done for four different powertrain systems for a standard multi-purpose tractor. The evaluated four powertrains are conventional powertrain with diesel engine, parallel hybrid configuration in combination with alternative fuels, battery electric system and a fuel cell powertrain.

Introduction to Sustainability

With the increasing importance of sustainability supported by the sustainability goals of the UN [1] as well the circular economy a holistic approach is needed among all disciplines and life-cycle steps. The product sustainability covers the areas of raw materials, production, energy generation, in-use as well as recycling. The overall target is to reduce harmful emissions as well as CO_2. All powertrain options have potential to contribute to a more sustainable future mobility. Nevertheless, the potentials are specific to each powertrain type and to the phase in the life cycle.

Current emission legislation is focused on tank to wheel. In the long term an extension of the legislation to well to wheel and later to cradle to grave is expected. The legislative change will come in the passenger car segment first and will reach the off-road area in a later stage.

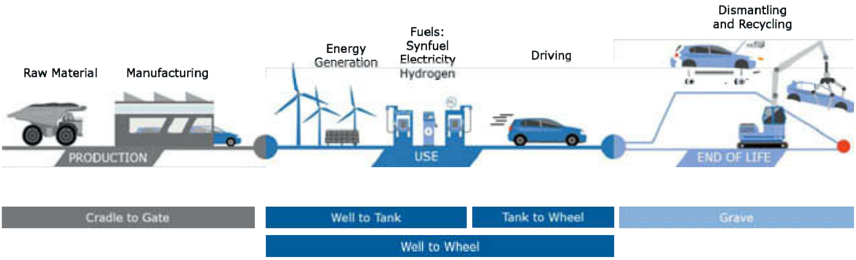

Fig. 1: Sustainability in all life-cycle steps

The road to Zero Emission: Competition of powertrain technologies

The vehicle's powertrain is currently undergoing its most lasting change in history. Alternative technologies to the conventional ICE based powertrain are pushing into the market for passenger cars and commercial vehicles – on the one hand to reduce the fuel consumption as requested by new regulations and on the other hand to meet the increased customer demand for sustainability at optimized costs.

Contrary to the situation in the on-road industry, there are currently no comparably strict CO_2 restrictions for the NRMM industry. However, it has to be assumed that the emissions of agricultural vehicles will also be regulated on the way to a CO_2 neutral Europe by the year 2050. This will have a correspondingly large influence on the machines that are today to a large amount driven by diesel engines. Considering this background, OEMs are paying great attention to the optimization of existing powertrain systems and the possible implementation of alternative technologies. [2]

Considering the powertrain from tank to wheel as well as from well to wheel, there are different possibilities for CO_2 reduction as well as avoidance. Within this paper four different technologies, namely conventional powertrain with diesel engine, parallel hybrid configuration in combination with alternative fuels, battery electric system and fuel cell powertrain are investigated.

The following example shows the technology evaluation for a standard multi-purpose tractor with a system power of 100HP and a vehicle weight (considering a conventional system) of 3,8 ton. This application is characterized by a diversified load profile due to a wide range of use cases. For the analysis of lifecycle emissions, a total vehicle operating time of 8000 hours is assumed.

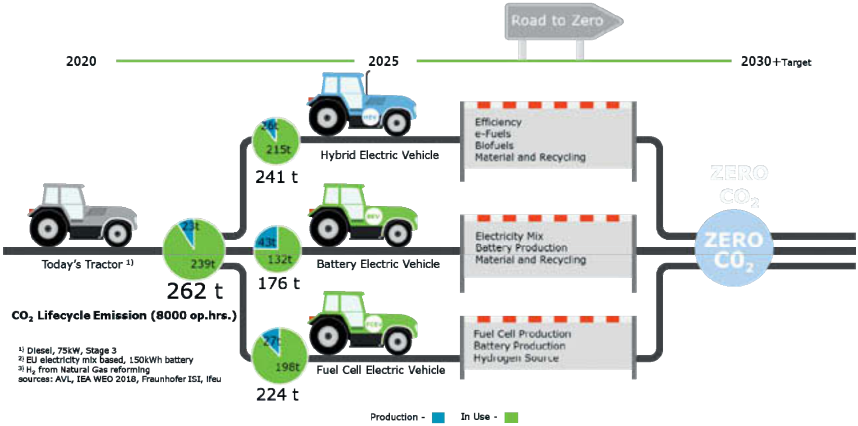

Fig. 2: Comparison of powertrain technologies

Today's Tractor, as shown in Fig. 2, is characterized by a 75kW Stage IV engine. CO_2 emissions of 23t in production are relatively low compared to CO_2 emissions in use of 239t.

As a first step towards emission reduction a P2 hybrid electric system is investigated, characterized by a 75kW Stage V engine combined with a 20kW e-drive system and a 20kWh energy storage system for boosting, recuperation and limited pure electric drive. The CO_2 emissions in production of 26t are higher for the hybrid system then for today's tractor, but the emissions of 215t in use are lower.

A further step towards emission reduction is the full electrification of the tractor. In this example the tractor is characterized by an electric system power of 75kW and the energy is provided by a 150kWh battery storage system. The CO_2 emissions of 43t in production are rather high, the emissions of 132t in use are the lowest. Those in use CO_2 emissions are caused by electric power generation and transportation. An EU electricity mix is used for battery production as well as in use phase.

The last investigated architecture is the fuel cell electric vehicle, characterized by a 70kW PEM system and a 20kWh energy storage system. The installed electric drive system power of 75kW is identical to the pure electric system. The CO_2 emissions of 27t in production are comparable to the hybrid electric system as well as the CO_2 emissions of 198t in use. Steam methane reforming from natural gas is used for the hydrogen production.

The details on the investigation and the backgrounds will be discussed in the following chapters.

ICE based powertrain

State of the art powertrain for NRMM is still ICE based because of its benefits in terms of packaging space, availability, range and refuelling. This is due to the situation with available fuel stations usually existing on the farm. The topology for the example vehicle can be seen in Fig. 3.

The combustion engine offers still potential for improving efficiency. This is possible by optimization of the turbo charging system, further improvement of combustion, higher compression and minimisation of heat losses. This would correspond to a CO_2 reduction in use in medium single-digit percentage range compared to a today's engine, depending on the load profile.

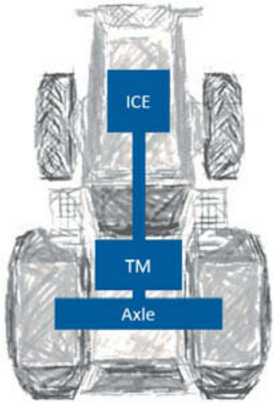

Fig. 3: ICE based powertrain (simplified)

Parallel hybrid powertrain

Fig. 4 shows a P2 hybrid powertrain for the example vehicle, being characterized by an e-drive system between engine and transmission. Hybrid architectures can increase efficiency through recuperation or load point shifting. Such measures can lead to CO_2 reduction in the low double-digit percentage range, especially for small to mid-sized tractors with diversified operating profile. For further emission reduction the use of alternative fuels, so-called e-fuels, shall be considered.

The replacement of fossil liquid fuels by other alterative fuels like biofuels or synthetic fuels reduces the CO2 footprint for the in-use phase. Synthetic fuels have two main challenges to overcome, the challenge of the overall process efficiency and the challenge of the costs. Any improvements in both areas will make them a more viable option in the future. Furthermore synthetic fuels will have a huge impact, as also the existing fleet will contribute to a CO_2 reduction.

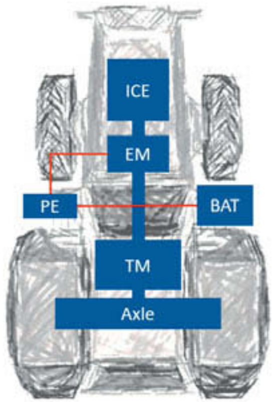

Fig. 4: P2 hybrid powertrain (simplified)

Battery electric powertrain

Fig. 5 shows a battery electric powertrain for the example vehicle, being characterized by a central e-drive system for traction and a one or two speed reduction gearset (depending on the use cases). The battery system dimensioning has to be a trade-off between costs, packaging, weight and vehicle operating time. The electrical range with nowadays technology is not comparable to operating times of diesel driven vehicles.

In tank to wheel analysis, battery electric vehicles seem to be an attractive solution for standard multipurpose tractor for CO_2 avoidance. The diversified use cases can be covered by a battery of the size of 150kWh, considering opportunity charging during the day.

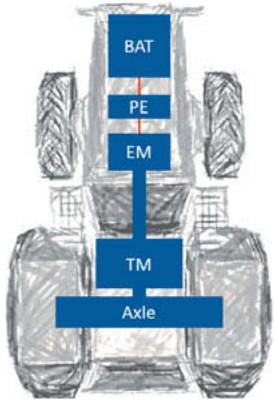

Fig. 3: Battery electric powertrain (simplified)

Regarding battery production and recycling, advanced battery production methods as well as the usage of green electricity are main influencing factor to reduce the CO_2 footprint in the energy intensive battery manufacturing process. Proper recycling of the materials will reduce the raw material usage in the long-term. Recycling of the batteries needs to be already considered in an “easy-to-recycle” architecture in the battery design phase.

Fuel cell powertrain

Fig. 6 shows a fuel cell powertrain for the example vehicle, being characterized by a central e-drive system for traction and a one or two speed reduction gearset (depending on the use cases). The power generation is done by a PEM fuel cell and a battery system to buffer the dynamic load points. The sizing of fuel cell and battery shall be a compromise between lifetime and costs. [3]

In tank to wheel analysis, fuel cell drives are seen as interesting solutions for mid to big sized applications since operating time and energy density are higher

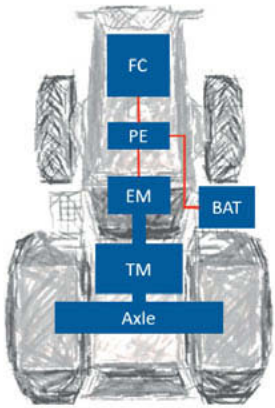

Fig. 4: Fuel cell powertrain (Simplified)

compared to battery electric solutions. However, the technology still features several challenges regarding integration (cooling and packing), refuelling infrastructure and TCO.

Hydrogen is produced via different production routes. Each production route has its specific characteristics regarding CO_2 footprint, costs and social acceptance [4]. 95% of the current production is covered by steam methane reforming out of fossil sources, referred to as grey hydrogen. Green hydrogen, hydrogen production from electrolysis using renewable electricity sources has a close to zero CO_2 WTT footprint. Besides the high investment costs the operation costs are mainly driven by the costs of electricity.

Following the overall target of CO_2 reduction, the production of green hydrogen shows the highest future potential over all other production methods on the long-term.

Summary and conclusion

With an operation lifetime of 8000 hours the CO_2 emissions in use are considerably higher than CO2 emissions in production. Therefore, electrification is a measure to reduce emissions. By implementation of a P2 hybrid system, CO_2 emissions can be reduced by 10% compared to a today's tractor with diesel engine. Full electrification would lead to a CO_2 emission reduction by 33% compared to a today's tractor with diesel engine. However, the electrical range with nowadays battery technology is not comparable to operating times of diesel driven vehicles. Fuel cell systems would lead to a CO_2 emission reduction by 15% compared to a today's tractor with diesel engine. However, the technology still features several challenges regarding integration (cooling and packing) and TCO.

Production and transport processes still have potential for CO_2 reduction. Within the next decade more efforts will be made in the optimization of production processes and system efficiencies. It is expected, that engine technologies will be developed further and efficiency values of 50% and more will be possible. Also energy storage system technologies will be improved in efficiency and energy density. Regarding Hydrogen, renewable Hydrogen is part of national energy planning and lifecycle emissions are to be improved significantly. Those measures and further developments will lead to further CO_2 reductions in use and in production.

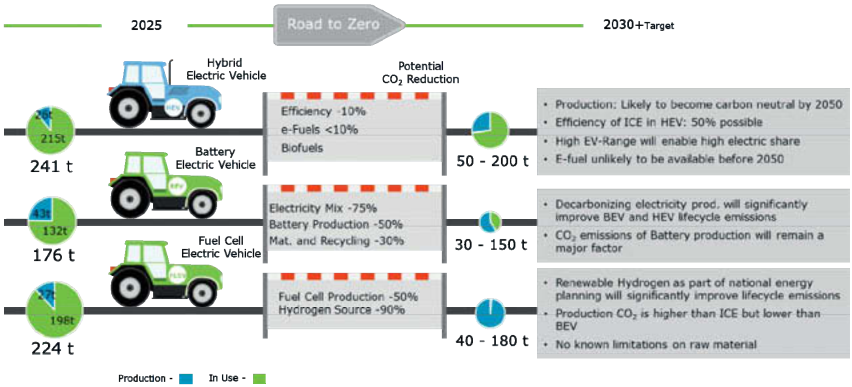

Fig. 5: Potential for further CO_2 reduction

Every technical innovation has its optimal use in a specific application. Markets and their usage patterns are very diverse and so are the technical solutions. The exciting task is now to apply the right solution. A broader view on the total spectrum of use cases and applications is necessary and will lead in the end to a coexistence of different propulsion systems.

For sustainable agriculture a cross industries approach is required. The CO_2 challenge requires to make use of renewable energy production. Green electricity can be used directly or converted and stored chemically. Upscaling of today's green hydrogen and e-Fuel production and distribution systems are needed. Both can have a significant positive effect on CO_2 reduction.

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Understanding the opportunities and challenges of self-driving, electric field tractors using dynamic discrete-event simulation

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Abstract

There is increasing interest in the application of battery electric vehicles (BEVs) for fieldwork in the agricultural sector. Self-driving systems are proposed as a solution to the challenges of BEVs and as a way to realise the opportunities created by them. To investigate the characteristics of systems with self-driving BEVs, a discrete-event model of a Swedish grain farm using small, self-driving BEVs for fieldwork was used for simulations. The results showed adequate capacity compared to diesel counterparts, as well as lower annual costs, weight and energy use. The results also showed the need for a well-dimensioned system and that a certain energy carrying capacity was needed in order to complete the allotted tasks in a reasonable time. The study concluded that when combined with autonomous drive, BEVs for fieldwork in an agricultural setting show great promise.

Introduction

In recent years, there has been a surge in interest in electric vehicles (EV) over the entire transport sector, including the agricultural sector [1]. However, though successful applications of battery electric vehicles (BEV) have been shown for farm loaders [2], specific operations [3] and non-road heavy work machinery in other sectors, there is still a lack of market solutions for electric agricultural field work. Some of the criticism of the idea of an agricultural BEV for fieldwork includes the intricate and complex set of tasks [4], the low energy carrying capacity of the battery, leading to effective working hours [5] being too few and long recharging time leading to expensive downtime [6]. A proposed solution to these problems, and with additional synergetic benefits, is vehicular autonomy [7-9]. Decoupling the productivity of the vehicle from the driver not only negates most negative effects of the BEV while highlighting its benefits, it also allows for additional potential benefits in management, system design, soil health, energy use and economy. Simulations were run with the aim of understanding the dynamics, benefits and challenges of such a system compared with contemporary manned diesel tractors.

Method

A theoretical 200 ha grain farm in the Uppsala region of Sweden was modelled. Four types of grain (barley, oats, winter wheat and spring wheat) were grown on equal areas and with suitable, conventional field operations as described in [10]. The vehicle system was focused on comparing a manned 250 kW diesel tractor with several 50 kW traction BEVs for general agricultural fieldwork, excluding harvest. Charging stations of different powers (10-100 kW) and technology (conductive charging (CC) and battery exchange systems (BES)) were used. The battery energy content was varied between 25-150 kWh. The BEVs were assumed to be autonomous at level 4 or above on the SAE J3016 definition [11], but still needing occasional monitoring.

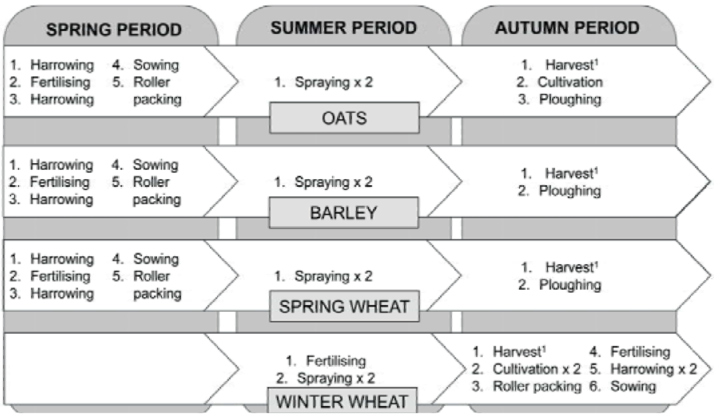

Fig. 1: Field operations for the different kinds of grain and working periods used in the simulation. [1]Harvest was not included in the model but is shown in the scheduling for clarity.

The models used for the simulations were a dynamic discrete-event model with state based decision making algorithms, as described in [10], built in MATLAB Simulink. In addition, to get a more complete system picture a timeliness model described by [12] and a cell-based battery degradation model were included. To analyse costs, the average-interest method described in [13] was used, with component costs from [14]. As well as dynamics and costs; production capacity, battery ageing, weather impact, soil compaction and energy used were also analysed. Five different scenarios were simulated, as described in Table 1 below, using the settings described in [10].

Table 1: Scenario descriptions and input for the simulation

	D1	BED	CC1	BES2	BES3
Fuel	Diesel	Electricity	Electricity	Electricity	Electricity
Number of vehicles	1	2	2	2	2
Autonomous (24 h/d)?	No (10 h/d)	Yes	Yes	Yes	Yes
Vehicle power (kW)	250	50	50	50	50
Energy content (kWh)	1,315 (130 L diesel)	50	50	25	100
Refuelling method	Diesel pump	BES	CC	BES	BES
Chargers/pumps	1	1	1	2	2
Number of batteries	-	4	2	8	4
Notes	Diesel system	Base case for BES	Base case for CC	Many small batteries	Few larger batteries

Results and discussion

The results from the simulations can be seen in Fig. 1 and Fig. 2. Fig. 1 shows that the BEV systems had 43-72% lower energy use compared to the D1 case. It was also shown that the total number of active days was similar between the D1, BED and CC1 cases, indicating equal capacity. The BES2 case showed a significantly higher active time requirement due to the low energy content carried, which made effective field work difficult, as can be seen in the high amount of time spent on transport from the charging stations to the fields. BES3, which compared to the base case (BED) had larger batteries and more chargers, boasted the lowest time required, offering a good balance of fast charging and an effective amount of energy carried. In all cases the weather had a large impact, between 46-57% of the time was spent waiting for better weather and field workability.

The cost analysis is shown in Fig. 2 and shows the investment cost as well as the annual operating cost for the different systems. In comparison to the D1 scenario, the BEV systems contained more investments in infrastructure, as well as components for the autonomous systems and battery-electric drives. This generally increased the investment cost in comparison to conventional diesel systems, although, due to the smaller size of the tractors, that investment was significantly lower, which resulted in CC1 having the lowest investment cost, as there were no need for investment in extra batteries or a battery exchange system. In the annual cost, the BEV systems showed a decreased cost for maintenance, fuel, operation and time, resulting in a generally lower annual cost compared to D1. However, in the case of BES2, the annual cost was high and the production capacity was low, marking it as an unprofitable system choice. The BES3 system showed the lowest annual cost due to a low time and operation costs, weighing up the higher investment cost associated with large battery packs.

Vehicle weight and tire pressure is considered to be one of the main contributors to harmful soil compaction [15, 16]. The proposed BEV system was calculated to weigh 3,200-3,600 kg per vehicle, excluding implements. Comparing this to the weight of a 250 kW tractor (11,400 kg for a John Deere 8R250), an opportunity for reduced tire pressure and consequently reduced soil compaction was presented.

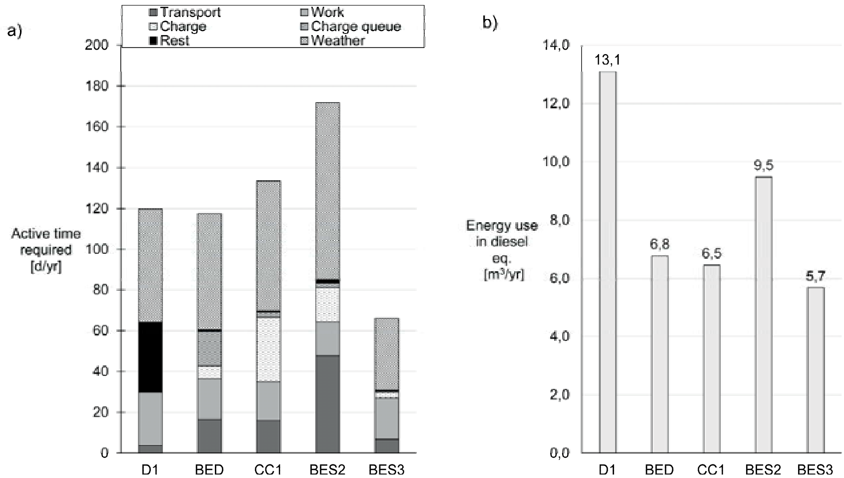

Fig. 2: Active time requirement and time distribution (a), and energy use (b) in the different simulated **scenarios.**

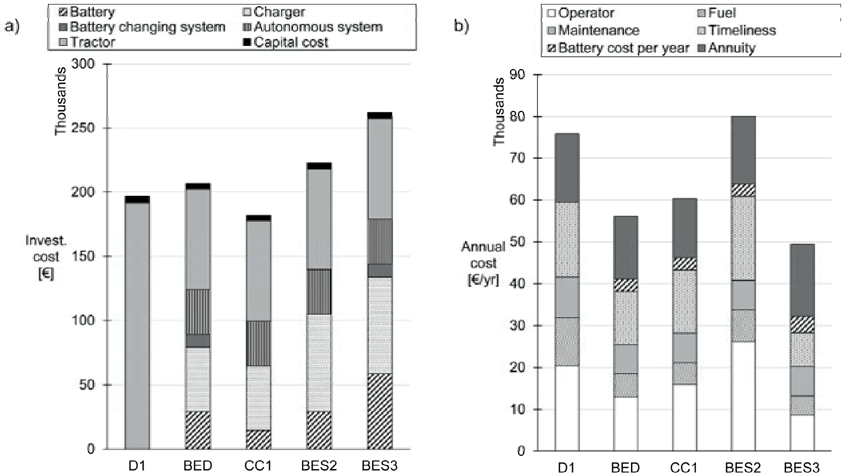

Fig. 3: Cost analysis of the different scenarios, showing investment cost (a) and total annual operating cost (b) for the relevant system components and costs.

Conclusions

The results showed that the BEVs could have equal capacity to the diesel system, when looking at the time required to complete all field operations. It was also shown that energy use is lower with BEVs due to the increased driveline efficiency associated with electric drives. The BEVs generally had a larger investment cost, but lower annual cost due to reduced costs of fuel, maintenance and operation, as well as the tractor investment costs. In cases with small (25 kWh) batteries, the energy carried was not enough to ensure effective fieldwork and resulted in a high amount of time spent on transport, and high costs overall. The scenario with larger batteries performed well and had the lowest annual costs, as well as good capacity, showing the importance of good energy carrying content and adequate charging speed/exchange rate to avoid queueing.

The cost increases attributed to BEVs were mitigated by the cost decrease resulting from the autonomy, showing synergy between the technologies. In addition to cost, energy use and capacity, the combination of self-driving BEV tractors also showed the possibility of smaller tractors and therefore lower soil compaction, and freedom in the choice of charging technology and system structure, as several different BEV scenarios showed favourable results compared with the diesel scenario.

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Design and analysis of a magnetic-electrical power split gearbox for application in an agricultural vehicle

PhD thesis handed in at TU Berlin January 2020 [1], supervised by Prof. Dr. Meyer, TU Berlin, still to be published

Matthias Lang, John Deere GmbH & Co. KG, Mannheim

Abstract

Continuously variable transmissions have been established in agricultural vehicles besides manual and power shiftable transmissions within the last few years. With continuously variable transmissions, the vehicle speed can be adjusted independent from the speed of the combustion engine, usually making use of a controlling element for superpositioning of speed. As of today, this controlling element usually is formed by a mechanical circumferential gearbox unit whose output speed is controlled by two independent input speeds, specifically the one of the combustion engine and the one of a variable drive, usually a hydraulic motor. The hydraulic motors in these arrangements are expected to be replaced by electric motors in the future. Furthermore, scientific research in the last few years has shown that circumferential gearbox units can not only be realized using a mechanical principle but also using a magnetic one. An electrical motor in these arrangements can be integrated directly into a magnetic circumferential gearbox unit, leading to a significant reduction in part count. The question arises, whether there is a concept for an electric power split transmission with a magnetic circumferential gearbox unit and inbuilt electrical machine and whether this concept can be integrated in tractor transmissions of current and fictitious future tractor generations in terms of technical feasibility, space claim and economics. It was shown that there is such a concept, providing diverse opportunities to emphasize dedicated design goals when designing new transmissions. This concept is therefore suitable for application in certain power and technology classes of tractors. These results are compliant to the current state of the art regarding engineering research, as the transmissions drafted during concepting work show many similarities to existing power split transmissions that are equipped with mechanical circumferential gearbox units and hydraulic motors. There is a tendency in automotive to qualify magnetic circumferential gearbox units for application in hybrid power trains, underlining their basic usage potential. Especially for expected future developments in agriculture regarding electrification of mounted implements that need to be powered by the tractor, the

drafted transmission concepts provide attractive solutions. A single one of these concepts was selected, built and studied. One part requiring additional empiric research is the detailed investigation of the alternative concepts developed.

Motivation

Besides manual and power shiftable transmissions, there is a trend towards continuously variable transmissions in agricultural vehicles visible within the last years [2]. With continuously variable transmissions, the output speed can be adjusted seamlessly to any input speed. Continuously variable transmissions can be classified as mechanical, hydraulic or electrical. Hydraulic continuously variable transmissions have been established in agricultural vehicles and are commercially sold by various tractor companies [3].
In 2019, John Deere presented the first electrical continuously variable transmission for the use in an agricultural vehicle [4].

State-of-the-art of science and technology

Power split units in continuously variable transmissions are usually mechanical planetary gearsets. Recent developments have shown that a circumferential gearset can not only be realized using a mechanical principle, but also using a magnetic principle [5]. A magnetic circumferential gearbox unit in three shaft operation consists of two shafts with radial magnetic pole pairs and a modulating ring between them.

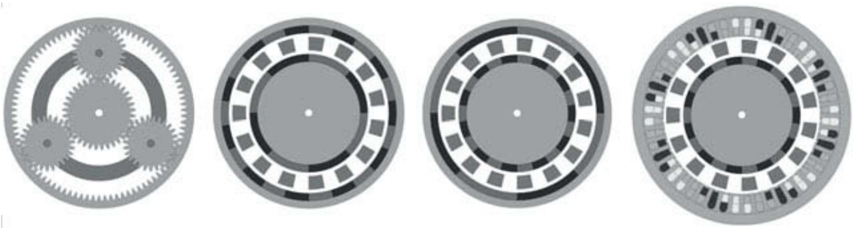

Fig. 1: Development of the magnetic-electrical power split unit from the mechanical planetary gearset

The speeds and torques of the magnetic pendant are only dependent on the number of pole pairs, which itself is not dependent on the diameter of the component. As such, it is possible to switch positions of the high speed and the low-speed component, leaving the high speed component accessible from the outside. It is then further possible to remove the outer (hollow) shaft equipped with permanent magnets and replace this component with a fixed stator

that can create a rotating electromagnetic field. This concept was originally invented by Atallah and Howe [6] and later spun off into the company Magnomatics Ltd., holding a number of patents on this topic. §11 Abs. 2 PatG covers the rights for research and testing.
In the light of these recent developments, the question arises whether there is a concept for a seamless, magnetic-electrical power split transmission for the use in agricultural vehicles that integrates an electrical machine directly in a variator.

Requirements and goal statement

The requirements for the transmission that was to be developed were that all shift points should be fully seamless. No component, would be allowed to change speeds during a shifting event. Only a single magnetic-electrical recirculating gearset combination should be used to keep costs controlled. The vehicle should be able to use all gear ranges in forward and reverse operation and the transmission should enable "powered zero". That is an output speed of 0 rpm at constant input speed, witch clutches engaged but the variator superpositioning the speed to 0 rpm.

Design of a magnetic-electrical power split gearbox

Putting all the requirements for the transmission together, a schematic for the transmission was developed using the "WOLF-schematic" [7]. It serves to identify the location and connections of sum shafts and differential shafts and can be used to determine relative turning directions. The result of this basic design schematic , was that such a transmission would need to have two variator sections. A variator is a circumferential gearset that can superposition speeds and combine torques. This can either be a classical mechanical planetary gearset or the above-mentioned magnetic-electrical unit. The two circumferential gearsets need to be connected in a way that the combustion engine of the vehicle is connected to both variators, whereas one of the two output shafts is also connected to both variators and the other is connected to only one variator. Because of the nature of the design, only one variator can be directly controlled, meaning that the other output shaft is controlled by operating the transmission as a complex, linked planetary gearbox. Still, the "WOLF-schematic" of this transmission leaves a number of design options. One of the options, seeming the most promising one, was selected to be detailed, manufactured, assembled and tested.
To detail this concept, the basic variator design was extended by a common range gearbox having two gears and an additional reverse module.
Comparing the final concept, especially the "WOLF-schematic" of the transmission to existing hydraulic power split transmissions, it became clear that the fundamental design concept and

schematic is the same as some transmissions that have been in the market for several decades and therefore can be described as trusted technology.

Analysis of the transmission

Using matrix calculation methods presented by Stangl [8], the speed and torque of every component of the transmission was calculated for the designated operating points. Based on the speeds and torques at these points, loss models were introduced to calculate overall transmission efficiency.

From this point, a series of fictitious electrical power split transmissions was created using available hydraulic power split transmissions and theoretically replacing the hydrostats in these transmissions with electrical machines. These fictitious transmissions served as a baseline to compare the efficiency, as they can be expected to be developed out of their hydraulic predecessors within the next decades.

Comparing the calculated transmission efficiency of the developed transmission with the fictitious electrical power split transmissions using all the loss models developed in this work, it could be shown that the efficiency is expected to be higher as compared to the efficiency of the fictitious electrical power split transmissions.

Construction and test operation

To verify the efficiency calculations and the loss models, the core part of the transmission, namely the variator section consisting of the two coupled variators including the magnetic-electrical power split unit was detailed, manufactured, assembled and put to test. The test results showed good correlation with the calculations, reaching even higher efficiency in some points while being slightly off at high speeds.

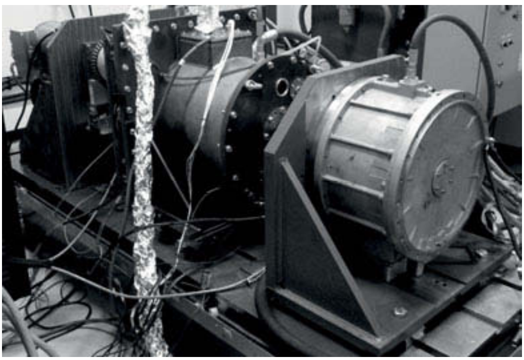

Fig. 2: Transmission on test stand

Results of the test operation and comparison to other transmissions

The newly developed transmission reaches higher efficiency compared to the fictitious electrical power split transmissions and enables additional possibilities in the design process because of greater design freedom resulting from the position of the high speed component in the magnetic-electrical power split gearset. The overall design space is expected to be smaller as compared to the fictitious electrical power split transmissions, while the electrical machines are expected to be scalable in terms of power requirements. Additionally, the magnetic-electrical power split gearbox integrates an inherent overload protection as slip will occur when torque on the component exceeds its design limits. Service and repair are expected to be more difficult than for the fictitious electrical power split transmissions using only standard electrical machines because of the overall higher complexity of the system that also leads to a more complex failure diagnosis. High magnetic forces that can occur during assembly are another challenge that needs to be addressed.

Judging from all the mentioned advantages and disadvantages, there is no clear recommendation on the future use of a magnetic-electrical power split gearbox in an agricultural vehicle, which is a common outcome for basic research projects. It is recommended to detail the other "WOLF-schematics" that were found within the scope of this work to increase the understanding of the overall system and to increase the design possibilities. It is yet to be seen how future developments in the area of magnetics and power split transmissions, as well as electrification of accessory equipment will influence this research.

Summary and outlook

Summing up this work, it could be shown that there is a potential to replace common mechanical planetary gearsets with magnetic-electrical gearset combinations including an electrical machine. Using a systematic synthesis by applying the "WOLF-schematic", it could be shown that such a design is possible. It is also to be expected that there will be more electrical power split transmissions in the future as they naturally evolve from the hydraulic power split transmissions that are widely used in agriculture vehicles.

With future focus on electrification of accessory equipment, there is potential to further cut down on one electrical machine in the vehicle, as electrical offboard power can be produced at every operating point using the integrated electrical machines in an electrical power split transmission in input coupled architecture. This is not possible for every operating point when output coupled architecture is used.

Within the scope of this work, it could also be shown that using a wide combination of loss models for all the different components within a transmission can be a quick way of obtaining good overall efficiency predictions, despite the individual loss models being quite simple.
Within the frame of this work, a detailed cost analysis could not be done. Also, there is still a lot of potential in the technical design of the modulating ring and its segments. Different stator winding schemes and the impact of surface magnets versus buried magnets are left for future research, as are the exact thermal and electrical operating limits.
Regarding further potential, the underlying requirements should be reviewed again, for instance with the quick response time of electrical machines compared to their hydraulic counterparts it could be possible to develop a transmission whose shifting points are not fully seamless. If future tractors will at some point be realized without a power take-off shaft because accessory equipment is fully electrified, this would free the transmission of design limitations resulting from the need to have a power take-off shaft going through the entire transmission.

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Development of a 3-speed gearbox in electric powertrain

Ground drive transmission for a commercial vehicle

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Abstract

This paper describes design, development and characteristics of a 3-speed gearbox. The gearbox is designed to be used in an electrically powered commercial vehicle with a maximum permissible weight of 44 t. With this drive system the vehicle meets the performance specifications required. Three mid-tier companies have bundled their competences to put the drive system into operation within 8 months.

Specification

The vehicle is based on an existing vehicle with a diesel engine from Iveco. It is used for local and long-distance traffic. Other possible applications are garbage collection or sweeping.

Technical data:

maximum permissible weight:	44.000 kg
range:	400 km
max. gradeability with max weight	17 %
gearbox ratios	I1 = 5,7:1 I2 = 2,6:1 I3 = 1:1
Lh B10 lifetime	> 20.000 h
development time till trial use	one year
electrical drive motor	Danfoss PMI 540-T2000 with 320 kW and 2600 rpm

Approach

In our cooperation, 3 SMEs with different strengths and focal points work together on a complex goal, the development of a 3-speed manual transmission:

- Antriebstechnik-Roth GmbH, Neunkirchen: Development company
- Eforce one AG, Switzerland: Manufacturer of electrically driven commercial vehicles (customer)
- Pulsgetriebe GmbH & CO. KG, Karlsruhe: Development and production of gearboxes

The goal is to design cooperation, process and communication in such a way that the specific competences of the three project partners are bundled in all project phases! The size of the companies enables very short decision-making processes. In addition to the professional competencies, this is the success factor for a short and goal-oriented development work.
It was important for this plan that the sympathies and respect in the team are present on all sides. Within 8 months, we were able to put the first transmission into operation - including the concept development.

It was also clear that due to the planned annual quantity, the approach differs significantly from the automotive industry. The project is planned and implemented according to the Pareto principle in order to achieve a practical and economical solution.

Powertrain

Overall system

The overall system consists of the electric drive including battery and power electronics, the 3-speed manual transmission, the drive shaft train and the rear axle.

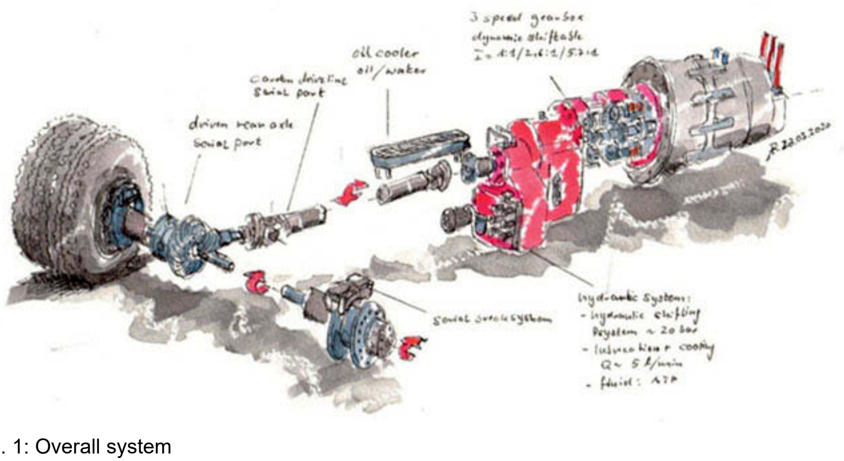

Fig. 1: Overall system

Main gearbox

After a valuation of various drive concepts, a planetary gear drive of Wilson design was chosen. One of the main requirements is a high efficiency in third gear because of a high duty cycle. This is achieved by directly coupling, so there are no sliding and rolling losses on the gears.

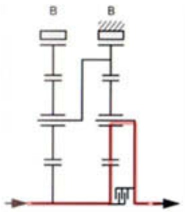

Fig. 2: gear 1

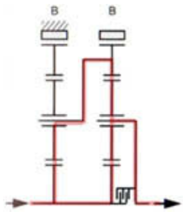

Fig. 3: gear 2

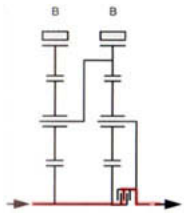

Fig. 4: gear 3

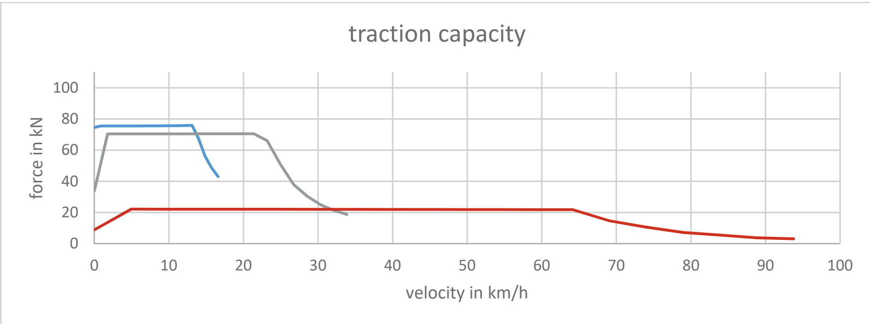

Fig. 5: Operation diagram

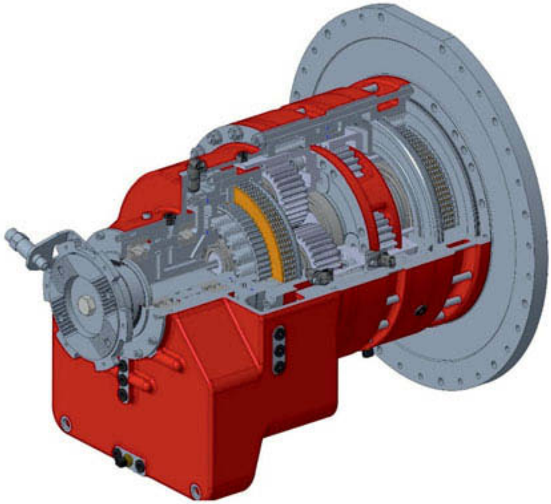

Fig. 6: 3-speed gearbox

Gearbox control

System

The vehicle has various decentralized control units. Therefore, the requirement is that the control unit responsible for the transmission is placed directly at the transmission. The communication with the higher-level control unit should take place via CAN.

The transmission control unit should take over the following tasks:

- Enabling gear changes on demand and managing synchronization in the shift process
- Checking the sensors and their cabling when the vehicle is started
- Monitor communication link to higher-level control
- Monitor gearbox conditions (pressures, temperatures, speeds) and enable diagnostics

Controller

When selecting the suitable transmission control unit, the robustness with a high protection class was decisive - in addition to the performance - since the control unit is exposed to direct environmental influences such as road dirt at its installation location. With its IP 69K protection class, the selected control unit meets this requirement to a high degree.

All required sensors and actuators can be connected to the controller via the 30 inputs/outputs of the controller.
The programming of the control unit is done by means of freely available Codesys, so that the customer can also make adjustments to the software without having to purchase expensive software solutions.

Changing gears

The gear change takes place in several steps, which are shown in the flow chart. The most important task is the synchronization during the shifting process. The control unit separates the power flow on request of the superordinate control and calculates the synchronization speed, which is necessary for an almost frictionless power flow shift in the new gear. This speed is sent to the higher-level control unit, which in turn sends this speed as a request to the vehicle's drive motor. This happens every 50 ms during a shifting process, so that it is possible to react to dynamic driving conditions. When the drive motor has reached the synchronization speed, the power flow is established.

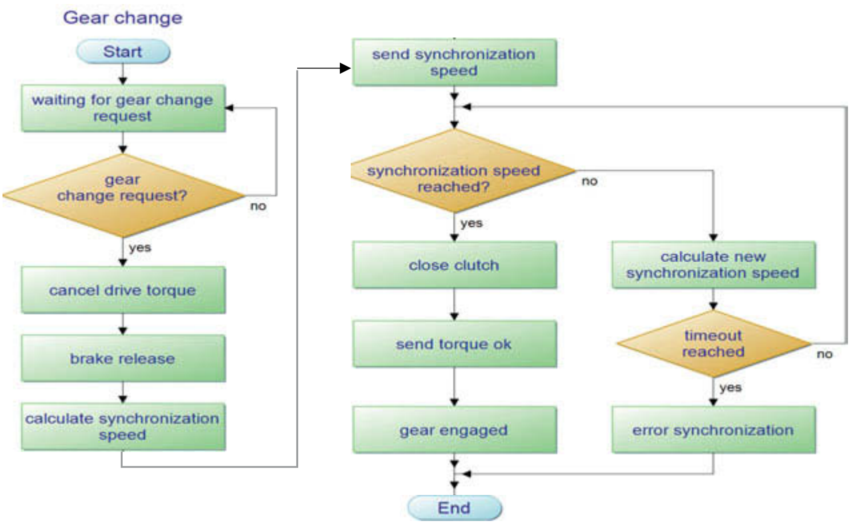

Fig. 7: Shift operation 2 <->3

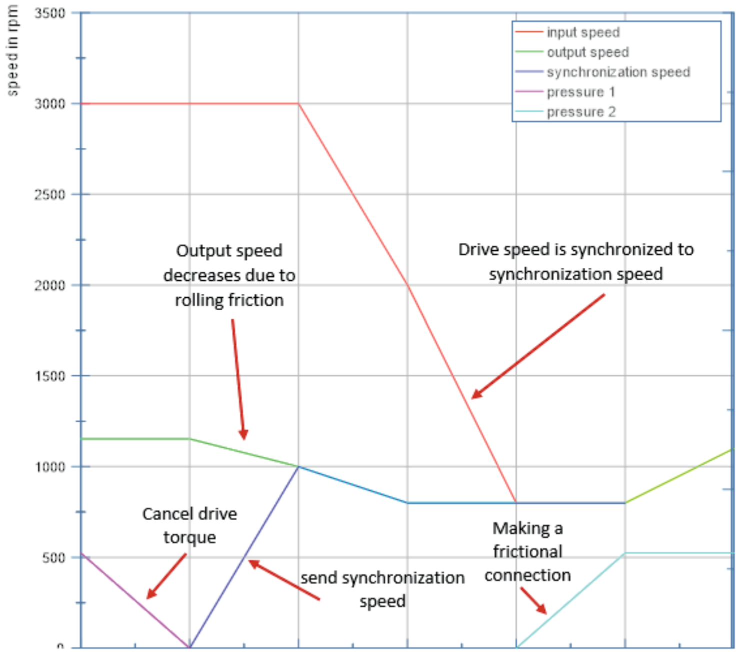

Fig. 8: Gear change

Validation

Test bench testing

All operating points - known from the specification - were run through in the test bench program.

Non-load test

By means of finely resolved drag torque measurements the efficiency was partially optimized. By changing the clearance, relief bores and oil feeds, temperature behaviour and drag torques could be reduced. The temperature distribution was also observed and improved in this program.

Dynamic load tests

To confirm the contact patterns and to investigate possible fretting corrosion, the known dynamic operating points were mapped in the test program:

- Dynamic test run with maximum torque
- Dynamic shifting
- Test runs with attached electric machine

The developed transmission control system was tested, parameterized and optimized at test bench.

Fig. 9: Dynamic test rig

Practical testing and parameterization

After the integration of the prototype in the vehicle, the parameterization of the transmission control was carried out in the vehicle - together with eForce. The same applies to the implementation and adaptation of hydraulics and cooling. Several transmissions are evaluated in different profiles by Pulsgetriebe and Antriebstechnik-Roth after driving operation.

Summary

- By bundling the competencies of three companies, a 3-speed transmission for a 320kW commercial vehicle was put into operation after a development time of only 8 months.
- With a limited development budget - compared to the automotive industry - a very good and practical result was achieved
- In the market running vehicles, with the new 3-speed transmission, a performing very good
- The entire powerpack is offered by eForce to the open market

Farmers' expectations in Precision Farming Technologies – Transfarm 4.0 online survey 2019

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Abstract

The use and dissemination of precision farming (PF) technologies in agriculture, especially in Central European (CE) countries, shows potential for improvement. The Interreg project TRANSFARM4.0 was started in 2019 to support technology transfer to farms. Ten partners from five CE countries (IT, HU, SLO, PL, AT) pursue the goal of advancing precision agriculture through technological improvements in this project. In order to achieve a better dissemination of PF technologies in practice, it is necessary, among other things, to work out the challenges in technology transfer and also to take into account the practical requirements of farmers. Therefore an online survey was carried out in 2019 in order to better include the requirements of farmers in the analysis. As a result, 236 farmers located in the five CE project partner countries could be questioned in order to draw conclusions for further future PF innovations and improvements.

Introduction

In the online survey of the Transfarm4.0 project [1], or TF survey for short, the term precision farming was initially described for a uniform understanding for the farmers and read as follows: Precision Farming (PF) summarizes methods which take account of local differences within arable land as conditions, state and their capacity. In short, it is about using the right PF treatment in the right place at the right time [2], in order to stabilize or increase yields, save resources and operate more sustainably overall [3]. PF includes, for example, applications as fertilization, plant protection, or site-specific soil cultivation. In most cases, this requires the use of high-precision GPS systems and application technologies in order to cultivate the areas in a location-specific and targeted manner.

Precision Livestock Farming (PLF), on the other hand, deals with data processing and analysis of animal-related data to optimize feeding, work processes, husbandry, animal health and animal welfare.

While PF technologies are available for EU farmers, they are not being used sufficiently.[4]

The Northwest-European countries such as Germany, UK, or France have a larger share of employed PF technology with about 20 % of the farms. In contrast, in Italy only about 1 % of the arable land is cultivated with PF systems [5], or only 6 % of Austrian farmers used precision farming systems in 2016 [6]. Ultimately, in the CE countries mentioned, economic as well as ecological advantages of the existing PF technologies are not used sufficiently. This TF survey was carried out, in order to work out the causes of this development and also improvements for the five CE countries from the farmers' point of view. Due to the abundance of results, only a few of the central results of the main questions can be discussed below.

General information about the survey

The aim was to reach around 40 farmers per country, around 200 in total. The farmers questioned were more or less familiar with the subject of precision farming. The TF survey for CE farmers was divided into three main parts. The first part dealt with general information about the farmers and their farms. This information was used to also take into account social factors (especially age and education) and farm factors (especially farm size and main farm focus). The second part of the survey contained eleven closed questions and five open questions. The third and last part of the survey included a short opportunity to evaluate the TF survey.

Extract of results in general

In the following, the results are shown as a whole (all countries on average). Overall, results from 236 farmers could be obtained. The majority of the farmers surveyed are male (75 %) and between 30 and 59 years old (73 %). Around a quarter (26 %) have a high school education and around half (53 %) of all participants have a university degree. In summary, about a quarter (24 %) of the farms had a farm size of less than 10 ha, 28 % have a farm size of 10 to 49 ha, 37 % have a farm size of 50 to 199 ha and farms with 200 ha and more are represented with 10 %. Around three quarters of the farms, based on the forestry area, have none (43 %) or less than 10 ha of forest (36 %).

The largest share in total, with two thirds of all farms, focus on cash crops (29%) and permanent crops (37 %). In Italy and Hungary in particular, the share of permanent crops, due to the specialization in viticulture, is the highest with 88 % and 80 % respectively. In comparison, the highest proportion of cash crop farms is in Austria with 66 %.
Around three quarters (74 %) of all participants manage their farm conventionally, the rest (26 %) are organic farms. In general, around two thirds (64 %) of the farmers run a full-time

farm and around a third (36 %) are part-time farmer. Likewise, less than one third (28 %) of the farmers surveyed do have a farm in less-favoured areas.

Extracts of results in special

Extracts of the results from some of the main questions (1, 2, 3, 4, 7, 8, 12-16) are shown below.

11 % of farmers stated that they are not interested in precision farming (PF). The largest proportion with 40 % are those farmers who are not yet using precision farming technologies, but plan to do so in the near future. 16 % of those questioned started using precision farming applications on their farm. Furthermore, a majority of those questioned (18 %) stated that they are beginners in PF but wanted to become a professional in the field of precision farming. 8 % of the farmers said they are advanced users of PF applications. In addition, 7 % see themselves as professional users in the field of PF for years.

In the following professionals and their farms are considered in more detail. In the survey 17 farmers stated that they are professionals in the field of PF for years. After a closer look at the general information from the first part, the following statements can be made. 88 % of the professionals are male (15) and two are female. About one third of the professionals (35 %) are between 40-49 years old, one quarter each stated to be between 30-39 and 50-59 years old. In the field of education, more than two thirds of the professionals (70 %) have at least a high-school education (35 % each with high-school or university degree). Nearly one-fifth of the professionals (18 %) have a skilled worker education.

In terms of the size of the professionals, the majority (29 %) have a farm in the range of 100 to 199 hectares. The three company size ranges "under 10 ha", "50-99 ha" and "200-499 ha" are represented by just under one fifth (18%) each.

The most frequent main farm focus, with 41 %, was permanent crop, followed by cash crop with 35 %. 12 % of the professionals manage a forage production livestock growing farm.

About two thirds of the professionals (65 %) manage their farm conventionally, and one third (35 %) organically. Four out of five professionals (82 %) run their farm on a full-time basis, the rest on a part-time basis (18 %).

Around a third of the farmers each stated that PF applications in daily practice on their farm were "important" to "very important" (36 %), neutral (29 %) or "less important" to "not important" (36 %).

Around two thirds of the farmers surveyed stated that they would use (more) precision farming technologies on their farm if the costs were lower. In Austria this was even 84 %. 44 % of farmers would agree with the same statement if the technology would be simpler / more reliable. 37 % would use (more) PF, if they were better educated in this area.

Overall, farmers consider the following five data sources to be most relevant for their farm in descending order: 64 % field data (vegetative stage of plants, soil analysis, etc.), 61 % weather data (forecast, temperature, rainfalls, etc.), 50 % production data (yield, harvest quality, etc.) and each with 42 % machine or equipment data (engine, consumption, components aging, etc.) and data for the allocation of production inputs (amount of water, fertilizer, etc.).

CE farmers gave “very high or high potential” for all PF methods available for selection, each with more than 50 % approval. In particular, site-specific chemical plant protection (69 %), site-specific mineral fertilization (NPK, etc.) with 63 % and site-specific tillage (60 %) as well as site-specific mechanical weed control (60 %) can be mentioned here.

In comparison, “low or no potential” was assigned to adequate irrigation (46 %), site-specific sowing (44 %) and site-specific organic fertilization (liquid manure, manure) with 41.5 %. Regarding the result of adequate irrigation, however, it should be noted that especially in Italy with 83 % a "very high or high potential" is seen for this PF method.

The initial investment (82 %), the compatibility of different systems (59 %) and the operation costs (58 %) are seen as "strong or slightly inhibiting" for the use of PF technologies. The improvement of the quality of work (80 %), the reduced workload (78 %) and the facilitation of documentation (73 %) speak as "slightly or strongly promoting" aspects for the use of PF technologies.

In the course of the project, experimental small projects, so-called case studies, were started in 2020, which focus on the three areas of ISOBUS applications, remote and proximal sensing and big and smart data management to improve decision-making in agriculture. The open questions of the TF survey (12-16) aimed to find out which innovations or improvements farmers will require in the future, especially in these three areas.

It can be stated that in connection with ISOBUS applications innovations or improvements are required by farmers, especially in terms of compatibility, user-friendliness, facilitation of documentation, reduction of workload and training/knowledge. With regard to improvements in the area of remote and proximal sensing (satellites, drones, sensors), among others for farmers, improved and affordable sensors, increased use of satellite data and drones, simplified handling of the generated data, better and easier usability and higher precision are of great importance. There should also be further improvements in terms of making work easier and data security and sovereignty in relation to the use of robots and FMIS. With regard to improvements in the area of Big & Smart Data Management applications, the farmers are particularly interested in compatibility, user-friendly operation, ease the handling of the data, reduction of workload and the use in an FMIS. Aspects for improvements in the area of field robotics could also be obtained. In particular, the application in the field of chemical crop protection should be intensified. An improvement in the technical equipment of robotics has to take place, as well as an expansion in the area of permanent crops, especially viticulture, and in general an expansion in the area of application from sowing, cultivation to precise harvesting. In addition to the aforementioned areas, further improvements has been mentioned, which include increasing user-friendly operation of the technology/software and its reliability, improvements in the used technology/sensors, environmentally relevant aspects, especially in relation to soil cultivation and plant protection, the area of education and knowledge transfer and, finally, the improvement of the legal framework.

Summary

236 statements from farmers on the subject of precision farming technologies were obtained. Among other things, aspects of their application, the importance of the PF technology or PF data in practice and potential for improvement were collected. In addition, it was possible to determine which aspects inhibit or promote the use of PF technologies in the CE countries.

In terms of the age of farmers, all age groups rather have a greater interest in PF technologies than no interest at all. Although the majority of farmers do not currently use PF, they plan to do so in the near future. Similarly, more of the surveyed farmers are already using PF technology than farmers without interest in PF. The largest age group that is beginners but wants to become a precision farming professional or has been a professional for years is found in the 40-49 age group. The largest percentage of advanced users of PF applications, who are not yet professionals, is found in the age group of 30-39 years. Approximately 17% of the 50-59 year olds are not interested in PF and therefore represent the largest group with this negative attitude in terms of the response option.

Around two thirds of the farmers questioned stated that they would use (more) precision farming technologies on their farm if the costs were lower. This was followed by improvements in technology to make them more reliable or simpler, and ultimately better education in the use of PF technologies.

Field data, weather data, production data, machine or equipment data, and data for the allocation of production inputs were considered to be the most relevant PF data from farmers. The initial investment (82 %), the poor compatibility of different systems (59 %) and the running costs (58 %) are cited as particularly inhibiting aspects for the use of PF technologies. The results and individual aspects must be taken into account in the further work steps in the Transfarm4.0 project so that ultimately industry and politics can take appropriate measures and instruments to increase the spread of PF technologies in agriculture, especially in the CE countries.

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Cyber Threats and Cyber Risks in Smart Farming

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Introduction

Cyber threats and attacks are on the rise across different industries. The farming sector has not been hit by sophisticated attacks at least as far as these have become public knowledge. However, ransomware attacks have caused damage to agricultural businesses and with the proliferation of precision farming or smart farming devastating cyber-attacks could certainly happen in the future. We discuss the typical cyber threats and risks using the case study of an Automatic Milking system (AMS). These systems automate the milking process in such a way that only minimal interference by humans is necessary. Connected to the Internet they can be remotely monitored and managed. However, connectivity poses a threat. Taking this as an example we discuss the cyber threats and the risks involved. Proper security controls have to be deployed and best practices from other domains like the automotive industry can be helpful.

Digitization and Automation in Agriculture

Information systems play a critical role to increase yield as well as product quality, improve efficiency and reduce losses. Interconnected smart sensors, the increased deployment of Internet of Things (IoT) devices and solutions and a high degree of automation of operational technology in planting, fertilizing, deployment of pesticides and harvesting ease the daily work and make it possible to manage huge farms with minimum human labor.

Tractors and harvesters can maneuver independently in a geofenced structure and have reached a high degree of autonomy. Research on special harvesting equipment and the deployment of robots is underway to even handle delicate plants with robotic equipment. All these devices can be monitored and controlled remotely through the Internet. Predictive maintenance and remote diagnostics allow to minimize downtime and optimize the usage of costly equipment.

In summary, digitization allows for real-time control, better yields, optimal timing, higher efficiency, scalability, reduce costs, and fewer downtimes. Furthermore, it provides more freedom as many processes can be controlled and monitored without the farmer to be physically present.

Cyber security threats

Smart farming is vulnerable to attacks on IT and specific cyber-attacks that target sensitive assets.

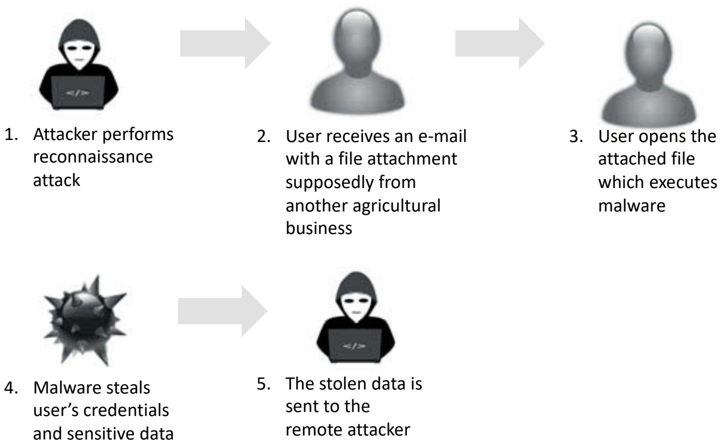

Fig. 1: Steps in a Ransomware Attack

Although, agriculture has not been the target of sophisticated attacks on the operational technologies, like many other industries, agricultural businesses have been targeted by ransomware. These attacks are often preceded by social engineering to gain access to critical systems. If this access is achieved, a malware is deployed that encrypts all files on the system rendering them useless without the proper password. The attackers blackmail the victims and demand a ransom fee often to be paid in bitcoins. However, even after paying, the victim cannot be sure to recover the critical information. Fig. 1 summarizes the different steps of a ransomware attack.

Multiple ransomware attacks were reported on agricultural businesses. Some of the recent ones had a crippling effect:

- In April 2019 a malware attack hit Fleury Michon (French Agri and Food company) and brought the IT systems to a halt for 5 days [1]
- The ransomware attack on the computer software of the Australian wool trade halted sales for over a week in early 2020 [2]
- In April 2020 the Danish Agro group fell victim to a ransomware attack which affected various critical IT systems that controlled feed factories, ordering and logistics [3]
- In July 2020 an Israel's watering system was attacked, shutting down agricultural pumps [4]

A cyber threat is the potential exploit of a vulnerability in IT, control and communication systems that enable precision agriculture. Information systems might have known vulnerabilities that can be used for an attack. The risk depends on the likelihood of a cyber-attack successfully performed and the criticality of the asset targeted. The damage scenario can range from the nuisance to deal with a SPAM mail to a catastrophic failure in an operational technology like irrigation, spraying, fertilization or automated milking. Also, attacks could target an autonomous tractor with potentially life threatening consequences.

Any cyber security measure has to start with a clear understanding of the critical assets under attack. In smart farming or precision agriculture, these assets can be grouped into the following categories:

- IT systems (like herd management, ERP for agricultural businesses, collaboration tools)
- Agricultural machines/vehicles (harvesters, tractors, etc.)
- Operational Technology (OT) for irrigations systems, seed distribution, milking, feeding, etc.
- Automated systems for variable rate sowing/planting, fertilizing, spraying, weeding and irrigation
- Control systems for facility and Heating, Ventilation and Air Conditioning (HVAC)
- Biogas plants
- IoT equipment (distributed sensor networks, etc.)

Attacks could target the integrity of data, the availability of a resource, the privacy of a sensitive information, and they could try to gain unauthorized access to operational technology or inject inaccurate information.

Critical assets could be vulnerable to [5]:

- Data exposure
- Unauthorized access (e.g., unmanned aerial systems/drones)
- Inserting inaccurate information in sensors
- Remote control attacks on critical systems like HVAC to change the temperature for livestock or plant environment
- Denial of service (DoS) attacks on communication networks

An attacker can exploit a vulnerability trying to enter the system without authorization, tamper with sensitive information, or disrupt the operation with a denial of service attack.
IoT sensor networks, integrated IT systems as well as App and Internet enabled systems create a large attack surface (see fig 2). Each element of this attack surface has to be analyzed in detail, the threat to the associated key asset has to be modelled, and the risk quantified. Based on this, a proper cyber security protection level can be chosen.

Cyber security controls will harden the system and make it more resilient to cyber-attacks. Similarly, a proper management system has to be defined which allows to prevent, detect, respond and mitigate cyber-attacks.

Fig. 2: The Attack Surface of an industrial control systems explained in the Hacking Village at DEFCON (photo: Roland Haas)

Automatic Milking Systems (AMS)

An Automatic milking system (AMS) or voluntary milking system (VMS) is a type of agricultural robot, that automates the milking process. It comprises collecting and routing animals, inspection and cleaning of the udder, attachment of milking equipment to teats, extraction and quality check of the milk, measurement of vital health parameters, removal of milking equipment, and guiding the cattle out of the boxes. Often, it includes devices for massaging the back of the udder to stimulate the milk extraction.

The AMS is connected to a herd management software to track cows, measure weight and health status and optimize the throughput. An important function of the AMS is the disposal of low-quality or tainted milk.

An AMS works as follows:

- The cows enter the AMS, often voluntarily on their own
- Each cow takes between 8 to 10 mins to be milked while fed with special food
- A single AMS box could cater to 60+ cows per day
- The milk robot cleans the udder, attaches the vacuum pumps and starts the milking process

- Twice a day a main cleaning process is performed
- A herd management system tracks the cows, monitors the health status and processes Key Performance Indicators (KPIs)
- Special precaution has to be taken that no contaminated milk enters the dairy production chain
- If the cow is being treated with antibiotics, the cow has to be milked just before a major cleaning cycle. The milk will be disposed of and the herd management system will keep track of this. It is crucial that all pipes and funnels are free of antibiotics residues.

The attack surface of the AMS comprises:

- Internet and Mobile App connection
- USB ports
- Malware inflicted connected IT system
- Diagnostic ports and so forth

Possible cyber-attacks could be

- Denial of service shutting down the AMS temporarily
- Ransomware attacks on connected IT systems
- Tampering with the integrity of data and the delicate control mechanisms
- Eavesdropping on sensitive information (yield, health status of cattle, etc.)

More sophisticated attacks could even try to compromise the calibration and quality check mechanism with the ultimate goal to contaminate the food chain/milk production. Threats and attacks have to be analyzed with respect to the consequences and ultimately the damage that can be caused. A denial of service attack on the AMS system, the herd management and a tampering with the delicate information flow could mean:

- Cows cannot be milked in time causing a loss of milk production and discomfort to the animals
- Tainted milk enters the dairy production chain
- A manipulated vacuum pump could cause inflammation to the udder
- Unhealthy animals could not be detected
- Downtime of the system will cause severe backlogs as an AMS/VMS could literally operate 24/7

- An attack on the cleaning mechanism could cause the spread of germs/pathogens from the inflamed teats from one unhealthy cow to others

The damage (loss of production, reduced yield, discomforted and unhealthy animals, etc.) has to be quantified in terms of a monetary loss. The worst case arises if milk with antibiotic residues is delivered to the dairy/milk processing corporation which not only causes high penalties, but also a lasting loss of reputation.

Threat analysis and Risk assessment

A threat analysis starts with understanding the key stakeholders and assets that are vulnerable and need to be protected. With the increasing connectivity, automation of production, e.g., automatic feeding and milking of cows, and the use of information technology the attack possibilities have increased tremendously. An asset could be a specific information and data set, a critical system and/or resource (like the automatic feeding system for livestock) or an interface to other critical systems.

Likelihood ↑ / Impact →	1 - Negligible	2 - Minor	3 - Moderate	4 - Significant	5 - Severe
5 - Very Likely		Medium		High	High
4 - Likely	Low		Medium		High
3 - Possible	Low		Medium	**Medium to High**	
2 - Unlikely	Low			Medium	
1 - Very Unlikely	Low	Low		Medium	Medium

Fig. 3: Risk Matrix for evaluation of the AMS cyber threats

A risk matrix as depicted in Fig. 3 shows the severity of the damage vs the probability that the triggering event occurs. In the above example concerning the risk of an attack on the milking system the automatic milking machinery could stop functioning, or the embedded Supervisory Control and Data Acquisition (SCADA) could be manipulated to introduce tainted milk into the production process. Milk would go to waste and the discomfort to the livestock could have lasting consequences. If the system would fail for several days, the damage would be much higher because cows might have to be milked by hand, and a sizable part of the production would go to waste. Overall, we would classify this damage to be 4 in a scale of 1 to 5 (meaning

5 is the most severe damage). The other dimension is the probability of the attack to occur and succeed. This, of course, depends on the attackers (knowledge, budget, resources) and the sophistication level needed to do the attack. However, with modern exploit kits even untrained cyber attackers (e.g., script kiddies) can cause a lot of damage. Complex infrastructure attacks happened in the past and it is a well-known fact that many industrial control systems are directly accessible on the Internet because diagnostic ports are left open without password protection.

The AMS exposes multiple attack surfaces. It is connected to other systems like herd management, and is controlled by a standard industrial control system using certain protection mechanisms. In a detailed threat analysis, one would have to screen all elements of the attack surface meticulously and check the vulnerabilities and how they could be exploited in an attack [6]. Cyber Security tests like pen tests could further provide evidence for classification of the risks. In the case of the AMS we would quantify the likelihood of a successful attack to be moderate (category 3 out of 5) which leads to an overall risk assessment of *medium to high*.

The threat analysis has to categorize all threats systematically and try to quantify the risks in such a way that proper measure can be introduced.

Cyber Security Controls/Hardening the system

Based on the risk assessment and the potential attack vectors, several security controls can be chosen to harden the system and prevent a cyber-attack. These measures range from simple, but often surprisingly effective actions like proper awareness trainings, password policies and the reduction of attack surfaces (e.g., closing USB ports) to more sophisticated measures like encrypting communication channels, separating network subnets, malware protection, firewalls and intrusion detections systems. As always, cyber security is not a one-time effort, but a process that needs constant evaluation and feedback. A best practice from the automotive industry uses a *defense-in-depth* approach where each layer from semiconductor to Internet-connected external interfaces is protected separately; effectively containing a breach in a particular layer and preventing it from spreading through the whole system. In the case of the AMS, this could mean several protection layers for sensors, embedded control units (ECUs), bus systems, and SCADA to harden the system. One of the most important aspects is the management of cyber risks as cyber security does not follow an implement-once-and-forget approach, but it is a moving target and needs a continuous effort.

A Cyber Security Management System (CSMS) provides the proper framework for managing the risks of a constantly changing threat scenario. The concept of a CSMS for agricultural technology is further discussed in a second paper [7].

Best practices and lessons learned can be exchanged with the automotive industry. But even the most rigorous analysis, sophisticated protection scheme and high awareness might still leave vulnerabilities. In this case, a cyber insurance can help to handle the financial damage. There are several general cyber insurances to choose from and some are tailored to the smart farming sector.

Summary and Outlook

Digitization and precision farming have transformed agriculture and increased efficiency tremendously. However, smart farming like any other domain with connected systems, and integrated information systems is vulnerable to cyber-attacks. Several attacks, especially ransomware attacks, have been documented. Sophisticated attacks on the infrastructure are possible and the high automation of farming machinery with unmanned drones, autonomous harvesters and self-driving tractors leads to similar threats and risks than the automotive industry faces with robo taxis.

This paper gives an overview of some of the key threats and cyber risks and we showed, how they could be dealt with in a systematic risk management approach. As a practical example we analyzed the potential cyber threats to an Automatic Milking System. These systems are very complex and are capable to automate the milk extraction process to such an extent, that the farmer can monitor the operation remotely when cows enter the AMS boxes voluntarily. The monitoring is done through the Internet.

Also, security measures that can be deployed to prevent cyber-attacks are discussed. In a second paper, we suggest and further outline the introduction of a CSMS to track the risks and respond adequately to cyber threats. Cyber security for smart farming is not an isolated domain. Lessons learned and best practices can be exchanged with other verticals, especially the automotive industry. Better training and knowledge dissemination for farmers is essential and targeted offerings for the industry to protect the key assets should be developed [8].

Further work will focus on the in-depth threat analysis and risk assessment of the AMS system and the design of a lean CSMS for protecting these assets. We also plan to apply the approach to other critical and highly automated operational technology in agriculture like irrigation, fertilization, pesticide distribution and autonomous machinery like tractors, harvesters and drones. Finally, the interface to other critical infrastructures and the food processing industry is an important field for further research as terrorist attacks could target the agricultural industry as part of a wider, orchestrated attack.

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Automatic logging and situation-related evaluation of manufacturer independent machine data

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Abstract

The results of the project BiDa-LAP are presented in this work. The development of a manufacturer-independent data management system for agriculture is the aim of the project. In this article the project is presented in detail. Besides the introduction of the project partners, the focus is on the presentation of the data loggers and the developed decision support system. The core algorithms for the evaluation and optimization of machine utilization are also addressed. In 3 years almost 10.000 hours of work processes from various machines were recorded and with big data tools analysed. With the recorded data different evaluation algorithms could be developed and tested.

Introduction

In today's agriculture, comprehensive documentation of the fieldwork plays an important role. It is needed for various reasons like managing, and legal purposes. Data loggers or smart devices are used to record the work process of a farm machine. The recorded work logs are saved and processed in a farm management information system (FMIS). Different service providers offer various systems and data loggers. There are two challenges, that these providers still have to face.

Firstly, the compatibility of the data loggers and the machine park of the famers. Although there have been efforts made for the unification of the machine data like ISOBUS, farmers still depend on the machine manufacturers in some way. Either you have to use the cloud service or the data logger provided by manufacturers for example, which is problematic, cause most farmers in Germany and other European Countries have a diverse machine park. Data exchange is almost impossible due to the proprietary data systems.

Secondly, the unused potential of the GPS-tracks and the belonging machine data. Discovering optimization opportunities and supporting the user in decision making has not been in the focus of the service provider yet.

Facing these challenges is the core of the project “BiDa-LAP – innovative usage of big data in agricultural processes”, supported by the Federal Ministry for Food and Agriculture. The aim of the project BiDa-LAP is to develop an electronical system, consisting of a platform architecture and mobile data loggers with the possibility to interact with smart devices. The system will be available as an operational and strategic decision support system for farming and service companies. It is designed to assist the user in decision-making through various indicators (e.g. organizational, economical and sustainable).

The project BiDa-LAP and its results are presented in this work. Therefor the four project partners are introduced and their subprojects are explained. The data loggers will be presented, which have the capabilities to record automatically and continuously GPS-Track and machine data, like fuel rate or actual torque.

After that, the subproject of the TU Berlin is described in detail. The main aim of the TU was the development and implementation of algorithms for visualization and evaluation of the work processes. Different algorithms for various use cases will be presented, which can analyse and evaluate the processes profoundly.

Project partners

The project consortium consists of two universities and two medium-sized companies.

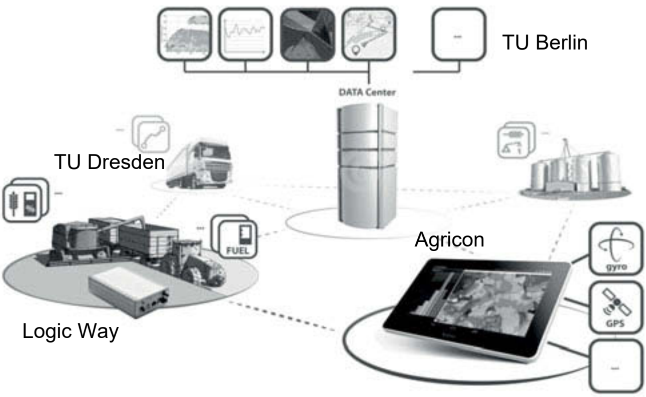

Fig. 1: The project partners and their field of work in the project BiDa-LAP

Logic Way delivers a part of the server architecture and the manufacturer independent data loggers, which will be presented in the next part of the work. Agricon is a solution provider in precision farming. They support farmers in the optimal use of machines, equipment and working time. In this project, they provide the other part server architecture, the farm management information system (FMIS) and the agricultural know how. The Technische Universität Dresden, department Agricultural Systems Technology, manages the data loggers and the farm test. The algorithm development for optimization and decision-making support is the main task of the Technische Universität Berlin, Chair Machinery System Design, as well as the development of a smart phone app to collect additional data. All partners have worked together before on the prior project LaSeKo [1], in which the first prototypes of the data loggers were developed.

Data loggers

Logic Way has improved and updated the prototypes form the project LaSeKo significantly, which includes software and hardware. The loggers (CPU: ARM Cortex A8) run Linux and have USB ports for Wi-Fi and Bluetooth, interfaces for CAN bus and GPS antennas and an LTE modem is also built in.

For the acquisition of machine data, a modular and highly flexibly configurable acquisition and transmission software (DCS) has been developed and continuously enhanced, which is used on the communication modules of the new generation. As a result, data from different sources (CAN bus, GPS-position, time data, directly connected sensors, etc.) can already be combined on the acquisition device, aggregated in normalized form and made available for transmission. An adaptive filtering of the data contents for machine and position data has also already been integrated so that both the amount of data to be transmitted and the loss of information associated with the filtering are minimized.

In addition to the acquisition of operating data from the existing machine interfaces, the possibility of injecting data from smart devices (smartphone, tablet) and network-compatible sensors into the acquisition data stream was implemented in order to feed additional factual information into the process - such as fuel quantities or filling levels that are not acquired with existing machine sensors.

For operation with changing attachments and machine configurations, a dynamic configuration management system was put into operation - in addition to the DCS - which records and provides the available data depending on the currently used machine configuration. [2]

Since February 2018, this new device series has been available for field tests and is used in continuous operation. For the devices in operation up to now, the continued usability could be ensured by repairs and software adaptations.
Reference and demonstration data sets were derived from the data recorded with different devices, which are used for tests and trials of the technical data recording infrastructure. Thus, reproducible test situations and results are enforced.

Situation-related evaluation

Focus of the evaluation is the machine usage and the optimization it by the means of time and resources. The experimental farm is a large agricultural enterprise producing animal and plant and energy. Several crops are cultivated and various machines are used during the different production processes. For each operation, like seeding, tillage, fertilization or transport, different parameters are interesting for evaluation and optimization.
Since the algorithms for evaluation are used in the FMIS, it is advantageous to be able to automatically assign an instrument to the automatically recorded operations. This saves a lot of work for the user and after recording, the operation can be instantly analysed because the situation, the specific work process, is known then. A classification algorithm was developed, which is able to assign an instrument to a work log using the recorded GPS and timestamps as well as the field diary and crop rotation (if existing). The algorithm can differentiate between transport and field work by machine learning approach, which uses the calculated work width and machine speed. After a suitable attachment is assigned by a logic, which uses the crop rotation and the field diary.
An evaluation scenario was developed for each situation. The scenario for the most common situations on the test farm will be explained in the following.
Tillage: Tillage is in general a process with high energy consumption. Even minor optimizations can lead to noticeable savings. To make the optimization potential visible, not just typical statistical values like area output ha/h and fuel consumption per hectare l/ha are calculated, also the actual working width and the load distribution are assessed. Due to the measuring frequency of 1 Hz the working width can be determined very precisely by vector calculation and the user obtains a representative overlap value for each process. A typical engine load distribution for a ploughing process is shown in Fig. 2.

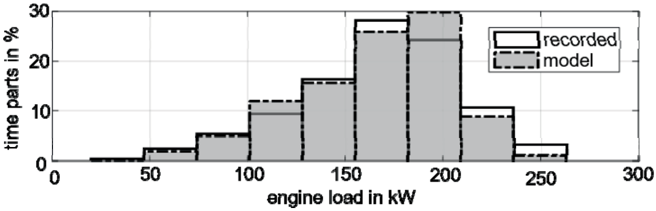

Fig. 2: Real and estimated engine load of a ploughing process

Additionally, a model based on various datasets like weather, ground, machine and height data, was build, which has the capability to estimate the engine load for a process [3]. The estimated engine load from the model for the same ploughing process is also presented in Fig. 2. Although the model is still in development, it already shows good results for different operations. The model could recommend adjustments of the driving behaviour or also an alternative machine-tool combination for the planned process that may have a better load distribution then the used machine. A better load distribution of can lead to fuel savings up to 26% [4].

Fertilization with organic fertilizer: For fertilization processes with manure, the overlap and the area output are calculated again. The energy consumption cannot be calculated because of proprietary machine data. Due to the always known GPS-positioning it can be determined very exactly when the manure tank is refilled. The amount of liquid manure applied can be determined with that. There is usually only a need for optimization in the overlap and the standing times, but these were rather low in the test operations and do not need to be further discussed at this point.

Seeding: Typical statistical values are also first determined for these processes. When examining the work logs, it became apparent that there were very large deviations in the area output. The range and deviation of all recorded seeding processes are displayed in Fig. 3 in the boxplot for “recorded data”.

To analyse these deviations, a regression model was built, which based on various parameters and uses a support vector machine [5]. To determine the reasons more exactly, only processes with the same machine and instrument were analysed. It is hereby important to examine how big the impact of the environmental characteristics of the company are or if the machine operator is the only influence on the deviations.

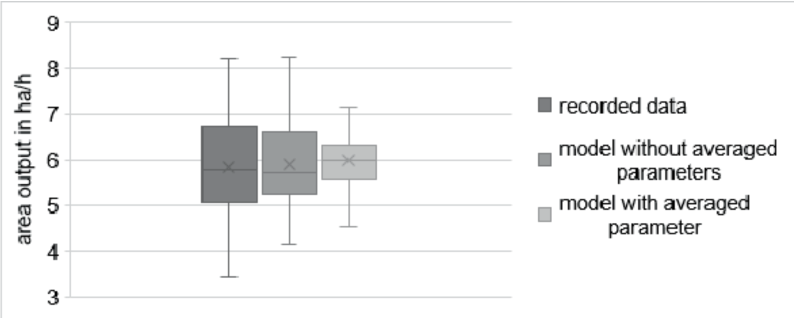

Fig. 3: Box diagram of the area performance of the recorded data, as well as the calculated area output of the SVM without and with averaged environmental parameters

The regression model includes these two main effects using parameters like driving speed, stop time, turning time and height profile, soil data (moisture, clay, slit and sand ratio), track length and field geometry. All parameters are extracted from open data bases. A comprehensive statistical analysis was conducted to verify the regression model. The result was also presented in Fig. 3 (“model without averaged parameters). For each process, the regression model was able to reproduce the area output well.

The next step is to adjust the environmental parameters. For this purpose, the averaged parameters of all processes are assigned to each recorded process. The area output is then calculated using the regression model and the adjusted environmental parameters and the original operator parameters. The recorded and the corrected area output are also shown in Figure 3 as box diagrams. The box is bounded by the upper and lower quartile, the total extent represents minimum and maximum of the considered size. It can be seen that the spread of the corrected area output has become considerably smaller in contrast to the recorded one. The original area output ranges between 3.5 ha/h and 8.1 ha/h, the corrected area output only between 4.5 ha/h and 7.0 ha/h. It reflects the deviation of the area output, which is caused solely by the operator. This also means that the environmental parameters have a considerable influence on the area output and must always be considered when examining the efficiency of work processes.

With this model, it is also possible to calculate the possible savings, if the driving parameters are optimized. In theory, savings around 2% are imaginable, if working speed, stop and turning times are optimized [5]. It is important to mention here, that the fuel consumption and the quality of the work are not part of the regression model, because the data base was not consistent enough for this. This will be examined in the subsequent project BiDa-LAP II.

Transport: In transport processes, other parameters play an important role for the evaluation than in the types of work listed so far. If a transport process is automatically recognised by the logic, significant breakpoints are determined by a cluster algorithm. In recent test data sets, this algorithm shows good results for detection of the Poi's. These points of interest (Poi) can also be added by the user. Some examples for Poi's are grain silos, manure dispensers, loading and unloading points in the field and the farm itself.
With the GPS-tracks it is now possible, to calculate the driven distance, average speed and average time needed between two Poi's. To gain more knowledge about the driven route, the openrouteservice API (openrouteservice.org) is used. It provides route-planning and it can consider the slow speed and the agricultural roads, which are sometimes taken. This makes it possible to compare the route taken in terms of distance travelled and alternative routes. Furthermore, it can be evaluated whether the taken route was practical or whether alternative routes might have been more favourable. It is also possible to determine whether more or fewer vehicles should be used to transport a resource, possibly to save costs or time.

Conclusion

The results of the project BiDa-LAP were presented in this paper. The electronic infrastructure including the data logger was successfully set up and put into operation. During the project many promising approaches for evaluation algorithms were developed by the TU Berlin. It could be shown that many evaluation options and optimisation potentials are available and can be implemented. However, only some of these algorithms are currently being used on the test server. The aim of the successor project BiDa-LAP II is to make all algorithms ready for series implementation and usage. In addition, further data like satellite data and novel evaluation approaches as well as multimodel approaches will be included.

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Data insight and expert knowledge combined to maximize uptime

Combining telemetry, warranty and diagnostics data on machine status allows for new concepts for early failure detection and to-the-point issue resolution

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Abstract

The AGCO Machine Monitoring Center (MMC) monitors individual machines and the entire AGCO fleet to increase customer satisfaction and machine uptime as well as to reduce Total Cost of Ownership and warranty expenditure. In addition, the data insights gained on machine usage in the field contribute to improved future machine design.

The MMC enables the generation of customer centric services allowing AGCO to convey internal expert knowledge to customers and dealers to detect upcoming machine issues early and virtually sending AGCO machine experts to the dealer workshops relieving them from labor- and time-consuming troubleshooting exercises. This approach transforms reactive machine repair activities into a pro-active dealer-customer interaction with fewer, plannable, and highly efficient workshop tasks. The development of these services is closely linked to tool development for AGCO Fleet Monitoring such as technical reports and functional dashboards, enabling machine experts to develop solutions for machine issues using machinery data.

To this end, the MMC acts as the center of collaboration of the key stakeholders in the Technical Service, Engineering, and Quality departments of all AGCO brands as well as key stakeholders in the machine telemetry data department and IT all essential to develop valuable machine monitoring services.

Introduction

The MMC analyses machinery data to generate value for customers, dealers, and AGCO. In this context, machinery data consists of telemetry CAN data, telemetry failure code data, warranty claim data, case management data, product quality data, etc. The MMC services building on machinery data can be conceptionally divided into two major pillars that are highly interconnected.

The first pillar consists of *Individual Machine Monitoring*. This kind of monitoring benefits the customers and dealers by analyzing individual machines regarding maintenance and repair requirements throughout machine operation. From a methodological perspective, *Individual Machine Monitoring* can be subdivided into condition-based maintenance (CbM) and predictive maintenance (PdM).

The MMC's second pillar is *AGCO Fleet Monitoring*. Fleet in this context refers to the AGCO fleet and not the fleet of an individual customer or dealer. *AGCO Fleet Monitoring* can be further divided into two sub-topics: Product Concern Resolution in which a reduction of Time To Identify (TTI) and reduction of Time To Fix (TTF) is achieved through telemetry data analysis. The second sub-topic is an expansion of the data basis for machine design, which allows for an evaluation of machine usage conditions considering regional differences and different application of machines around the globe.

Individual Machine Monitoring

The MMC develops Individual Machine Monitoring use cases for sub-systems or specific modules of machines called *Machine Monitoring Alerts (MMA, Figure 1)*. Through telemetry data analysis, the MMC detects existing or upcoming issues on individual machines triggering an *MMA* and combines these analytical results with expert knowledge as well as with information from other available machinery data such as case management data and warranty data to compose customized *Information Packages*. The MMC provides these *Information Packages* via Technical Service to the dealerships who are then able to proactively engage with their customers and to perform actions required to solve the issue as effective and efficient as possible. The connection between anomalous machine behavior and the compilation of the appropriate *Information Package* is performed by data analytics experts in the MMC and module experts in Engineering and Technical Service and it is tailored to the specific condition of the machine. It consists of information on (i) recommended course of actions to be taken (ii) parts to be replaced, (iii) how to conduct the repair, and (iv) how to check if the repair was successful. *Individual Machine Monitoring* allows AGCO to virtually send its machine experts to the dealer workshops. The *MMA*, thus, enables dealers to convert unplanned reactive machine repairs into fewer and planned repairs, with detailed knowledge on the upcoming repair minimizing labor- and time-consuming troubleshooting. This conversion ensures customers two substantial benefits: increased machine uptime and reduced Total Cost of Ownership. At the same time, *Individual Machine Monitoring* enables dealers not only to pro-actively engage with their customers intensifying their relationship, but also to deploy their workshop labor capacity more efficiently and to plan their part stocks based on actual and upcoming demand.

As a result of this pro-active workflow, AGCO experiences a reduction of warranty costs in that the MMC (i) prevents severe machine failures, (ii) reduces time for troubleshooting, which in turn reduces labor cost at the workshop, and (iii) prevents excessive swapnostics (i.e., unnecessary change of parts).

AGCO Fleet Monitoring

To ensure high quality of AGCO machines both machine design and product concern resolutions (PCR) are of utmost importance. Successfulness of PCR is often measured by the total time the issue affected the market. Consequently, a reduction of TTI and TTF is highly desirable for an efficient PCR.

Today, the likelihood of product concerns that need to be addressed is quantified by analyzing warranty claims, case management data, and parts consumption data. TTI, therefore, is prolonged because warranty cases are only submitted weeks after the failure and repair of the machine. To overcome the time-lag of currently used data sources, the MMC analyzes telemetry machine CAN data and failure codes from all connected machines. Failure codes and CAN-parameter data anomalies can immediately be linked to individual warranty cases to understand failure code patterns underlying the warranty claim. Such data patterns can then be systematically monitored in the telemetry machine data stream and thus can give rise to the extent of the concern in the fleet long before the arrival of many warranty claims.

Once a product concern issue has been identified, the process of fixing the problem is initiated. Finding a fix can take considerable time because the root cause of improper functionality, of performance issues, or of part failure needs to be understood to provide a feasible and fast problem resolution. The MMC assists this process by detailed analysis of the affected fleet by identifying machine parameters and failure codes for situations in which the issue arises in the fleet. This analysis, performed in close collaboration between module experts and data analytics experts, provides insights to constrain the root cause of issues.

Through the systematic analysis of machine usage patterns, e.g., in the form of load collectives, AGCO machine design, as developed in Engineering departments, can rely on a wide data base of machine usage and application conditions. This is especially beneficial for a global approach of machine distribution considering that a global distribution of the field-testing fleet for a new product is very costly. Monitoring a sufficiently large fleet of machines allows for a fast identification of critical and relevant machine usage patterns and conditions with a robust statistical coverage. After identification, critical usage patterns and conditions can be closely examined and considered in the early phases of next generation machine design.

Data analysis environment

Besides providing the so called rules engine derived from the failure code and CAN parameter data to detect machines that trigger *MMAs*, the MMC develops technical dashboards as tools enabling different user groups such as Technical Service, Engineering, Quality, etc. to easily access and consume machinery data and to be able to efficiently gain insight from the data to a variety of questions. These technical dashboards are constantly improved in close communication between the MMC and the respective users. Additionally, the MMC is in close communication with divisions inside AGCO working on related data analytics topics to make effective use of the data available and to ensure efficient tool development. The technical dashboards require the telemetry data that is flowing into AGCO's telemetry data platform to be pre-processed and cleansed, for which the respective algorithms have also been developed in the MMC.

All infrastructure tools and proceedings described above are being developed to be usable in a AGCO-wide context to avoid duplication of effort, to set quality standards, and to foster interaction and intercommunication between the different product expert teams based at the product development and engineering sites (Figure 2).

The MMC takes full advantage of the unique and in-depth expert knowledge of products within AGCO. Making the potential accessible that lies within machinery data requires a seamless interlocking of the following stakeholders:

- Application Expert: someone with a deep understanding of how the products are being used in the field
- Machine hardware expert: engineer intimately familiar with the subsystem, its components parts, and its expected failure modes
- Machine software expert: engineer that designed the machine software and knows how the telemetry/sensor data and error codes are generated on the machine and what data is sent via the telemetry device and what data could be send additionally
- Telematics expert: someone knowledgeable in data collection from the busses on the machine, data compression, and data transfer

Analytics and visualization expert: someone able to analyze and to visualize the data to answer questions posed by the application expert

Examples

The transmission is the first module the MMC has focused on. One symptomatic failure code that indicates a potential issue with the transmission is the clogging of the transmission oil filter. If the filter is clogged a bypass valve opens, leading to unfiltered oil flowing into the transmission. This can lead to increased wear of the transmission's components and potentially to transmission breakdown. Clogging of the transmission oil filter can have multiple root causes. Together with the module experts from Engineering and Technical Service, the MMC developed and installed several *MMAs* that identify potentially dangerous conditions of the transmission module along with their most likely root causes and compiled the corresponding *Information Packages*. In addition, the required workflows to convey the *Information Packages* to the dealers and the required tools for the case and feedback management have been implemented.

The first technical dashboards that have been developed are concerning the visualization of failure code occurrences in different machine series and machine models and regions as well as on the overall status of the fleet in terms of connectivity and the operated vehicle hours to assess the urgency of a potential issue and its statistical significance. The challenge in developing these dashboards is posed in finding the right balance between functionality/versatility and performance. To ensure performance of the dashboards the underlying data needs to be highly aggregated which limits versatility. Therefore, the dashboards' development is closely aligned with their respective users.

Summary and Outlook

Insights generated from machinery data constitute a wide range of opportunities and benefit for customers, dealers, and OEMs. The AGCO Machine Monitoring Center provides services that can be grouped into *Individual Machine Monitoring* services, that provide insights on potential machine issues and the corresponding *Information Package* to solving it, as well as *AGCO Fleet Monitoring* services enabling internal stakeholders to independently investigate machine-related topics with functional dashboards and technical reports. For both, close interaction and alignment between the product experts – application, hardware, software, telemetry - and the data analytics and visualization experts represent the precondition to developing valuable use cases. In the near future, we will integrate different sources for machinery data into a common platform as well as we will expand the users of our Machine Monitoring services to more product modules as well as other departments within the AGCO organization.

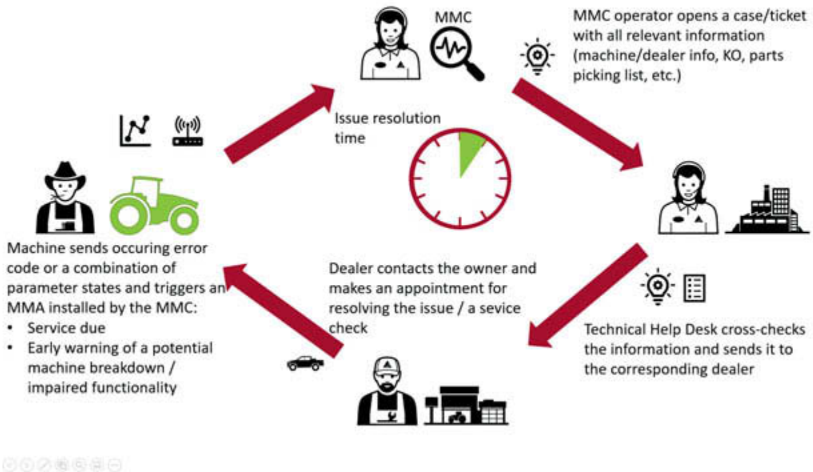

Fig. 1: Schematic of the Machine Monitoring Alert (MMA) workflow (KO – Knowledge Object, internal source of information for the dealer)

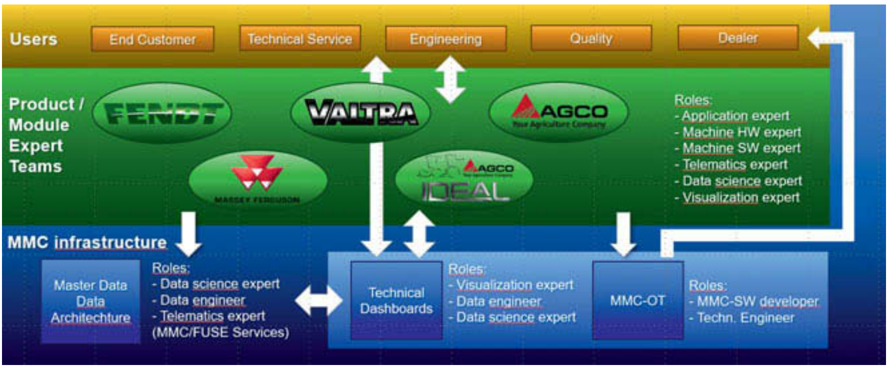

Fig. 2: Schematic of the Machine Monitoring Center Organization (MMC-OT - Machine Monitoring Center Operational Tool, FUSE - AGCO's smart farming organization, HW - hardware, SW - software)

Seed Spacing in Cereals

Using Artificial Intelligence to define a quality value of precision seed placement

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Abstract

Volumetric seed metering is state of the art for seeding small grain seeds and in particular cereals. This kind of seed distribution typically results in random spacing including doubles and skips within the trench. Hence, the question is: Does single grain seed singulation improve the potential growing area of single plants and thus, increase crop yield? Here value would be created that could be monetized through higher yield expectations and less seed costs. Picture recognition and Artificial Intelligence can be used to validate seeding quality. Research activity has been started to evaluate the quality of different seeding techniques to compare different methods of evaluating the single plant spacing accuracy and area use efficiency. To improve the validation and verification of plant spacing accuracy, a comparison of the potential growth area per plant through Voronoi Polygons is an accepted method. Based on research activities in winter wheat, the area-based analysis delivers value to describe the quality of germination and plant distribution in the field, independent of seed rate and row width. In addition, this method can be used to describe crop and yield formation that is also an important driver for yield prediction models.

Seed distribution influencing crop growth potentials

Funded by the BMBF*, the project HyServ** sets the focus on developing innovative service concepts and user interfaces for the usage of smart contracts in farming processes between farmers and contractors. One aim of this project is to investigate methods used to measure and evaluate the quality aspects of production system steps. Monetizing the quality of seeding is one key aspect of HyServ.

Volumetric seed metering is state of the art when seeding cereals, oilseed rape and other small grains/seeds. The resulting random distribution leads to heterogenous spacing including skips and doubles within the trench. To ensure an equal crop stand within the trench, farmers are commonly using higher seed rates to reduce the risk of plant losses due to frost damages and/or pathogens. Nevertheless, research activities have shown that improved plant spacing delivers the opportunity to reduce the seed rates while maintaining or increasing the yield production per area [6, 8]. When planting corn and sugar beets, precision seed placement plays a key role to ensure the maximum yield production, as those kinds of crops have a low potential to compensate skips with additional tiller and ear production, compared to cereals. For wheat it is known that a single plant, growing without competition, can produce more than 50 tillers per plant but with inefficient area yield production. On the other side, to high plant densities carry the risk of lower yields in addition, as the ratio between biomass and grain yield is shifted into an inefficient ratio [1, 2, 3]. To ensure the maximum yield potential of wheat the balance between area use efficiency, plant competition and the needed accuracy in longitudinal seed/plant distribution need to be defined. These aspects can be used as new input to evaluate the quality of seeding operations and defining further crop growth potentials. To define these values, Voronoi-Polygons can be used.

Validation methods of seed placement accuracy

The Variation Factor (VF) and the Coefficient of Variation (CoV) are commonly used methods when comparing the spacing accuracy of seeding technique. When using the VF (Variance divided by Mean), the number of plants in defined lengths along the trench (e.g. 5 cm) are going to be used for calculation. A lower VF value indicates higher placement accuracy. As alternative, the CoV provides a higher degree of precision. This method is mainly used when evaluating the placement quality of corn or sugar beets. In this system, the plant-to-plant spacing is measured and the Standard Deviation of those values is divided by Mean. Similar to the VF, a lower CoV reflects a higher spacing accuracy within the trench. VF and CoV can indicate the relative spacing accuracy, but do not deliver specific insights of how the plants are distributed in particular. In addition, the single plant CoV becomes increasingly imprecise when the mean value (theoretical distance between seeds)

Table 1: Theoretical seed distances & influence on CoV

Corn (75 cm row spacing)			**Wheat (16.7 cm row spacing)**		
Seed rate [Seeds/m²]	Mean distance between seeds [cm]	**CoV** (if 20 percent of values deviate 1 cm of target)	Seed rate [Seeds/m²]	Mean distance between seeds [cm]	**CoV** (if 20 percent of values deviate 1 cm of target)
6	21,1	3,4 %	80	7,5	9,4 %
8	15,8	4,5 %	160	3,7	18,9 %
10	12,7	5,6 %	240	2,5	28,4 %
12	10,6	6,7%	320	1,9	37,8 %

approaches zero, which mathematically happens when seed rates are increased, or row widths get wider while maintaining the same seed rate (Table 1). For example, if 20% of the plant distances deviate 1 cm from the target, this causes a change in CoV by approximately 7% in corn with 12 seeds/m², compared to a 38% change in CoV in wheat with 320 seeds/m². Therefore, based on the reduced reliability of CoV when increasing seed rates, this statistic is less relevant when comparing seed placement of small grains.

An improved evaluation for seed spacing accuracy may be achieved by analyzing single plant area with Voronoi Polygons (Fig. 1). If the in-field plant distribution is digitized as a co-ordinate system, the process of Voronoi Triangulation can be used to define the individual growing area per plant. First, the algorithm analyzes the distance of the nearest neighbors as a reference which is described as Delaunay Triangulation, then defines boundaries around the points (single plants) using the half distance between the kernels as reference, describing and calculating the potential growing area per plant [7]. A similar approach has been examined already, focusing on the seed distribution and yield effects in oilseed rape [4, 5]. This research has proven already that an individual plant space analysis with Voronoi Polygons have the opportunity to evaluate the spacing quality of seed distribution, independent of row spacing and seed rate with the additional usage for simulation models [4, 5].

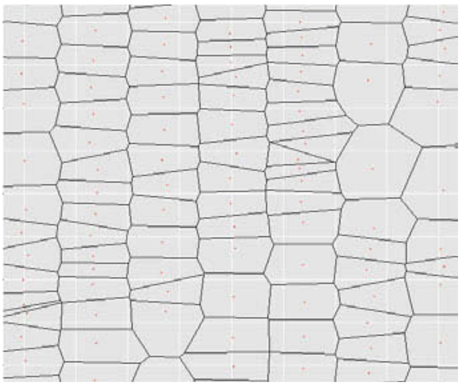

Fig. 1: Visualization of Voronoi Areas

Using Voronoi polygons to describe spacing quality and potential yield

For data generation, field tests of volumetric seeded and planted winter wheat have been used to evaluate seed distribution with Voronoi Polygons. After early field emergence, pictures of ~1 m² have been captured with an RGB-Camera to visualize the plant distribution. Subsequently, the single plants have been tagged manually into a point layer, using the Geo-Software QGIS. In the next step, the point layer can be used as baseline to process and calculate the Voronoi Areas (Fig. 2). The values and size distribution of Voronoi Areas can be used to calculate a CoV, similar to the CoV when comparing the plant distances, indicating the relative spacing accuracy of the plants to each other. When calculating the

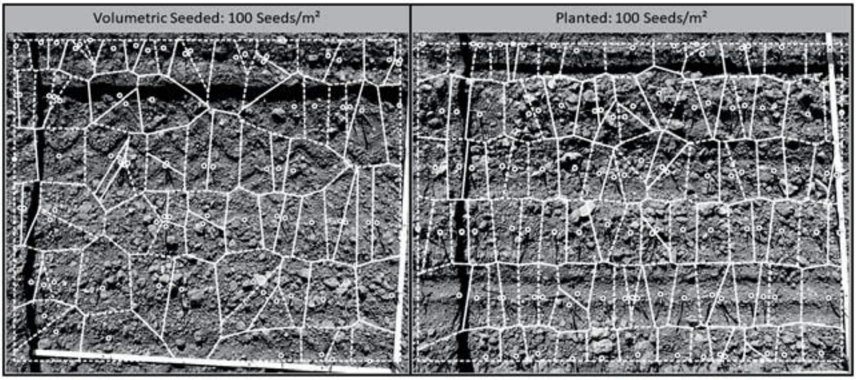

Fig. 2: Voronoi Areas of RGB-Image samples, comparing volumetric and planted seeding

CoV of plant distances at a seed rate of 100 Seeds/m², a CoV of 65 % through planting is indicating the improved plant spacing compared to a CoV of 87 % with volumetric seeding. Calculating the CoV of plant distances at a seed density with 340 Seeds/m², planting delivers small advantage with a CoV of 76 % compared to volumetric seeding with a CoV of 83 %. Here, a visualization of distribution and ratio of the Voronoi-Areas delivers more precise insights of how the plants and their individual growing space is distributed in field (Fig. 3). The example reflects the distribution based on a winter wheat field trial in Germany, comparing the single plant Voronoi Area of planter and volumetric air drill at a seed rate of 340 Seeds/m². A higher peak in ratio of distribution of the Voronoi Areas with the planter compared to the volumetric drill reflects the reduction of skips and doubles.

In addition, the Voronoi Areas deliver the opportunity to predict yield potential, if knowledge exists for the single plant yield production per unit area. Those values can be estimated based on yield curves created from field trials which analyzed yield response to wide ranges of seed rates (Fig. 3). Combining the known distribution of Voronoi Area with a yield curve delivers the opportunity to calculate the theoretical yield potential based on the evaluated growth space per plant. The grey regression line, reflecting yield potential based on seed density & plant growth area, shows the yield optimum at a seed density between 130-160 seeds/m². If the distribution of individual plant space is known, then the total plant yield can be estimated prior to harvest. Separating the ratio of Voronoi Areas of the example with 340 Seeds/m² into three yield zones, planting reacts with 8,3 % more values within a higher yield potential zone compared to volumetric seeding (Table 2). To increase the accuracy of yield estimation, it is essential to know the yield response curve to population density of a given

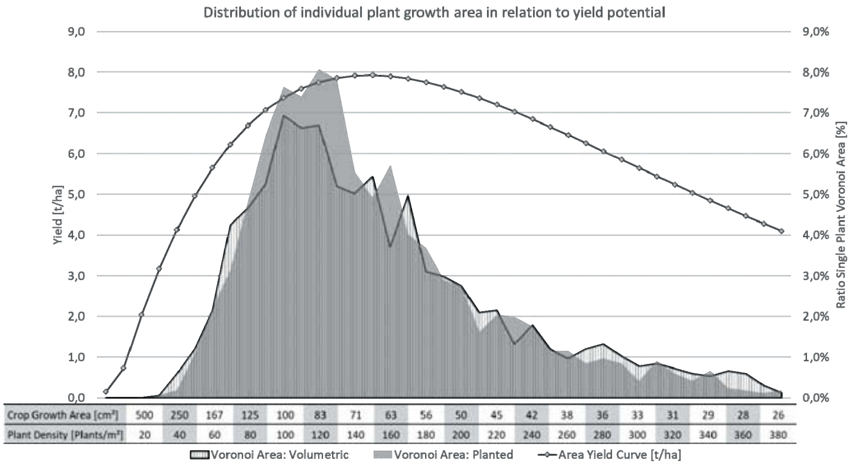

Fig. 3: Winter wheat yield curve and Voronoi plant distribution of volumetric and planted seeding at 340 Seeds/m²

variety, since each variety respond differently to changing growing conditions, such as environmental factors and row spacings. Considering this, the analysis of Voronoi Polygons can provide important definition for the optimum seed rate and placement accuracy for specific varieties and/or crops.

Table 2: Ratio of plant distances in different yield potential areas

	Range of Individual Plant Space:	140 - 500 cm²	50 - 140 cm²	26 - 50 cm²	**CoV (Baseline: Plant Distances)**
	Yield Zone:	2,6 – 6,4 t/ha	6,5 - 7,9 t/ha	4 - 7,5 t/ha	
Ratio Voronoi Area	**Volumetric:**	8,2 %	63,4 %	28,4 %	83 %
	Planted:	6,6 %	71,7 %	21,7 %	76 %

Conclusion

Plant area based values generated by Voronoi Polygons are independent of seed rate and row spacing. Thus, the analysis of individual plant space delivers a precise description of not only plant spacing but also the specific plant agronomic potential via improved spacing to exploit soil resources and sun. An RGB-Image based, manual crop tagging delivered the opportunity to validate the plant density and spacing data of picture samples in the office. The manual crop tagging process is time consuming, an automated crop tagging process could deliver the opportunity to enhance the speed for identification of individual plant space analysis and evaluation of spacing quality. In addition, the number of data sets can be increased massively for improved analysis of the plant emergence and distribution in field. This can be on the one side an important tool to monetize the value of seeding operations and therefor input for payments if seeding operations have been done by contractors. In Addition, the knowledge of plant distribution and plant density can be used to identify the crop growth and yield potentials. These insights can be an essential input for upcoming crop management strategies (fertilization, plant protection, timing of application) to ensure the maximum yield potential after considering actual environmental conditions. Finally, this provides the opportunity to define the technical needed range of seed placement accuracy to generate maximum yield production while reducing the number of seeds to an agronomic optimal density.

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** HyServ (Hybride Dienstleistungen in digitalisierten Kooperationen)

Multipurpose soil tillage with smart machinery
Electric-driven, sensor-controlled soil tillage

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Abstract

Using electric-driven, sensor-controlled agriculutural machinery has high potential for smart and variable processes. The example shows how such a system could look like for a precise, site specific soil tillage operation. Instead of replacing drive trains in existing machinery, the whole machinery concept was designed to use the full potential of electric drives and embedded sensor technology for a sustainable agriculture.

The developed technology will be part of an upcoming Start-Up at the University of Technology Dresden.

Soil tillage is, beside of the harvest process, the most important step for plant production. Starting with the treatment of the residuals of the previous crops, continuing with seed bet preparation for the next crop and taking care of the crop with weed control, farmers need to use multiple machines for different tasks. During the last 20 years the development of chemicals, especially for weed control, made it easier for farmers to reduce their number of machines to a minimum. However, with the upcoming stricter regulation regarding the use of chemical treatments and the overall goal to reduce emissions like CO2 or nitrate, the world of soil tillage gets more and more complex.

To support farmers with soil tillage machinery that meets their specific requirements new approaches need to be considered. One solution was developed at the University of Technology Dresden. The, so-called Kronos system, an electric-driven, sensor-controlled tool system, consists of three modules: a PTO generator (Valkyrie), a soil tillage machinery (Rotapull Evo) and the soil sensor (Ackerscanner).

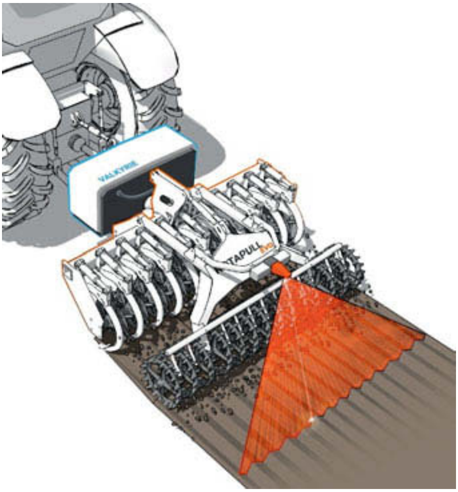

Fig. 1: Overview of the Kronos system

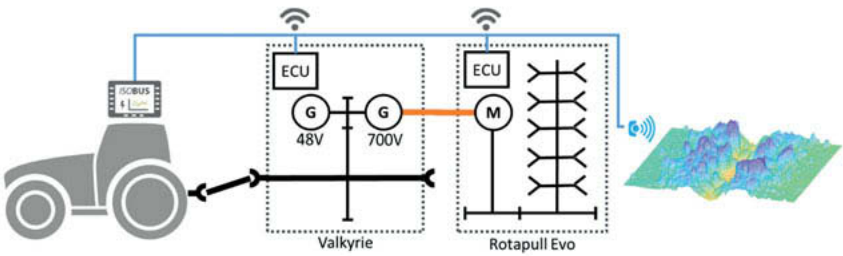

Fig. 2: Schematic representation of the Kronos system

The core component is the soil tillage module Rotapull Evo, it consist of a patented combination of active driven and passive pulled tools. This combination allows Rotapull Evo to adjust the soil tillage process to the specific operating conditions (soil moisture, operating speed, soil type) and to the farmers desired tillage result (e.g. seed bed preparation, weed control, etc.).

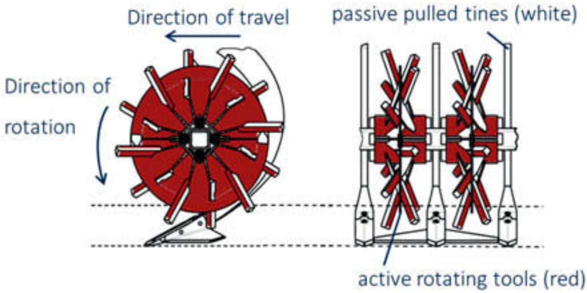

Fig. 3: Working principle of Rotapull Evo

The key for this adjustable usage of Rotapull Evo is the variable, electrical drive system of the active rotating tools. This allows the operator to adjust the machine right to his specific needs. To help the operator evaluating and controlling the tillage process the soil sensor Ackerscanner continuously scans the soil after the treatment for the generated roughness and the mixing of plant material. With this information, the control unit of Rotapull Evo self-adjust his process intensity right to the farmers given desired value. With the help of the variable electric driven tools and the evaluation of the process result, the Kronos system can self-adjust disruption during the tillage process, e.g. change of speed of the tractor, different soil and moisture content on the field etc.

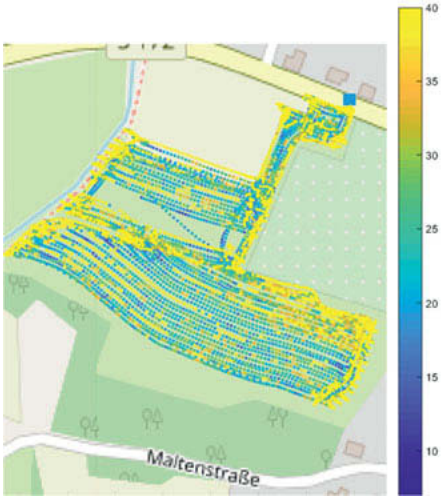

Fig. 4: Example of soil roughness distribution

Fig. 5: Rotapull prototype during field test

To provide the required electrical power, the tractor mounted PTO generator Valkyrie is part of the Kronos system. Valkyrie is connected to the tractor with the three-point-hitch and can be used with any other 700V DC or 48V DC electric driven implement. Rotapull Evo can be used without Valkyrie with every tractor that provides 700V DC electrical power.

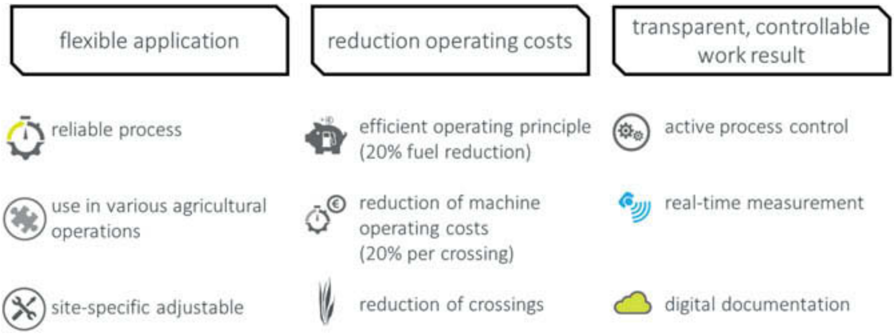

Fig. 6: Overview of the Kronos system advantages

Tool management, controlling and condition detection for highly automated/autonomous soil cultivation

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Abstract

Highly automated and autonomous agricultural machines have the potential to perform field work with a minimum of energy and manpower. For the application case of tillage, sowing and weed control, important tool-specific challenges are the precise and variable depth control of the tools, the identification of the tool conditions in the field and, in the application case of an automated tool change, systems for identifying the tools and the working equipment. To meet all these requirements, the machines need a smart tool control systems.

These functionalities are integrated into the highly flexible and modular machine concept - Feldschwarm[1]. The depth control is able to guide the tool at a defined working depth, thus guaranteeing the desired results and requiring a minimum of fuel consumption. The tool recognition works without contact. The tools have a memory device with a special set of parameters, for example the identification of the tool, the range of optimal working depth and, in case of an active tool, the nominal speed range. A camera system is used to identify the tool conditions. It detects wear, misalignment and loss of tools. The wear values are used to adjust the depth control and stored on the tool memory device.

Keywords: Feldschwarm, agricultural robots, automation, tool management, wear detection

Why is a tool management system necessary?

Over the last few years, numerous concept studies and some market launches of highly automated or autonomous machines for agricultural processes mainly with crop care objectives have been published [1,2]. Most of them are characterised by low weight and energy consumption, site-specific field work and "24/7" operation, which has so far not been typical for agriculture [3]. For this high degree of automation, the entire process requires perception and control

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[1] Feldschwarm is a registered word mark (DPMA registration number 302013018880) oft the Fraunhofer Gesellschaft

systems that simulate human cognitive abilities and actions and support the operator/ administrator. Apart from obstacle detection, control of the travel path and entire machine, this applies in particular to the control and the monitoring of the working tools. The main challenges in this sub-area are to identify the tools and transfer the parameter set to the tool control system, to guide the working tools at a defined and site-specific working depth and to determine the tool conditions in the field. Until now, these tasks have only been carried out by the operator, and in the future this will have to be done by a tool management system.

Tool Management - Current Situation / State of the Art

Systems for automatic identification or parameter setting are not yet known for agricultural equipment without ISOBUS functionality such as a cultivator or disc harrow. Typically, the operator couples the respective tool and sets the required parameters on the tool or tractor. For field work, the process parameters such as the working depth are typically adjusted once. Common systems are guided by support wheels or the attached roller, there are no possibilities to adjust the working depth during operation. The operator have to change the machine setting manually when the machine is stopped.

In related fields of agriculture systems for identification of tools and equipment are well known. An example is construction machinery. For the hard and rough working conditions, similar to those in agriculture, only robust technologies can be used. For this application radio frequency identification (RFID) technology has proven to be useful [4]. For example hydraulic excavators - most of these machines are used for different tasks. Therefore they have to change tools frequently. An identification system and parameter setting are state-of-the-art for these machines. The coupling module of the excavator is equipped with an RFID system. The sensor is located on the excavator and the tag on the bucket. Tool-specific information is stored on the tag and is read by the sensor. The data is used to obtain general information about the bucket, such as the ID and type, or to set tool-specific information to control the excavator. The latter can be used, for example, to achieve exact trench depths or to prevent accidents by restricting movement [5,6].

Tillage systems generally operate with a constant working depth setting. It is determined by the tractor, the support wheels and/or the mounted roller [7] and typically cannot be changed during operation, e.g. to adjust the working intensity or to compensate for wear. In the past there have been studies on the variable adjustment of the working depth during operation [8]. A significant market penetration of implementation in the equipment, e.g. for the cultivator, has not yet taken place. When using cultivators and disc harrows, investigations in practice have shown that the tools work often too deep. This has a negative impact on fuel consumption, ground cover and yield [9].

Wear, misalignment and loss of tools have not yet been detected by any technical system of tillage equipment. Recognition of these parameters is the responsibility of the operator. Also in other related fields, e.g. construction or mining machines, such systems are not known. In this field there are many patents dealing with the recording and evaluation of the condition of rigid and rotating tools, examples are [10–14]. The recognition mechanisms are mostly similar. They often work with optical methods and use a camera system. In this way, the sensor system can detect marks on the wearing parts and thus determine the condition of the tool [14]. Another possibility is the identification of a contour line e.g. of a rotating roller body. In this case, wear, misalignment and loss of single tools are detected by the deviations of the real contour line to the ideal course [13].

Machine Concept Feldschwarm

The modular and scalable system Feldschwarm is presented in [15]. In addition to the high degree of automation, it is characterized by its modularity and the various installation spaces (Fig. 1).

Fig. 1: Feldschwarm-unit (design concept) - various installation spaces

The tools for the main working process are located at the bottom of the carrier between the front axle and the roller in the back (Fig. 1 - blue section). The individual tools in this area are designed as process or tool modules. They are connected to the tool carrier by a proprietary

interface and can be changed according to the work task. The area in the rear part (Fig. 1 - orange section) is used for the second point of the two-point support. For tillage it is usually designed as a roller, for other applications it can be combined with elements for a secondary working process or designed as a chassis with two single wheels. The third installation space is located at the top of the carrier (Fig. 1 – red section). This area is intended for the storage of products of the respective work process, e.g. plant protection products or seeds.
The high flexibility of the system is achieved by changing the working modules. The machine system can be individually and automatically adapted to the respective work task. In highly autonomous operation it is necessary that the tool modules are clearly identified, the condition of the individual tools is known and that continuous monitoring of the tools during operation is carried out.

Concept Development

At the beginning there is the question which tool-specific parameters and properties are set or which tool-specific information is observed by the operator. For some of the common tillage tools, this is the identification of the tools, the setting of the working depth and the condition of the working tools.

Identification:

There are two basic concepts for tool identification and automatic parameter setting - the offline and the online method. For the offline version, the module-ID and all necessary data is stored on a tool module specific storage device. The machine system reads the information and adjusts the parameters. If data has changed during the work process, for example the condition of the tools, this data can be written to the tool module. A data connection to an external memory is not required. This solution therefore enables self-sufficient operation. For the online method, the machine system requires a connection to a tool data base (part of the farm management system or the data base of a service provider, in case of rental devices) on which each individual module is stored. Communication between the machine and the data base is necessary for reading or writing the parameters when changing the tool module. This type also requires a way to identify the tool module.
The concept uses a standard RFID system consisting of a sensor with CAN interface and an RFID tag with a defined memory structure. The storage device for the online process contains only the ID of the tool module. A special storage layout is designed for the offline version. It essentially consists of two delimited areas. The first one (Fig. 1, Section A) contains data and parameters of the whole tool module (ID, tool type, working parameters). The second part (Fig.

2, Section B) contains information about the individual tools (position, condition, wear). The amount of data stored in section B depends on the number of individual tools.

Section A	0	1	2	3	4	5	6	7	Data tool module
	Module-ID		Time of use		Working hours		Module-offset		
	8	9	10	11	12	13	14	15	
	Drive	Speed		Nominal speed	Working depth	Number of tools			
	16	17	18	19	20	21	22	23	
	24	25	26	27	28	29	30	31	
Section B 01	0	1	2	3	4	5	6	7	Data tool - 01
	Tool-ID (01)	Wear limit (abs)	Wear limit (rel)	Current wear	Displacement	Misalignment			
	8	9	10	11	12	13	14	15	
	X-Position		Y-Position		Z-Position				
	16	17	18	19	20	21	22	23	Data tool - 02
	Tool-ID (02)	Wear limit (abs)	Wear limit (rel)	Current wear	Displacement	Misalignment			
	24	25	26	27	28	29	30	31	
	X-Position		Y-Position		Z-Position				

Fig. 2: Storage layout for a tool module in offline use

Working position:

Reasons for the need to automatically adjust the working position of the tools are tool change, wear compensation for an exact working depth or site-specific requirements for work quality with minimum fuel consumption.

To realize this, the actual and the nominal value of the tool position must be known. The nominal value can be specified by the operator or site-specific by the farm management information system (FMIS). The actual value is determined by the theoretical position and the wear condition of the tools. The theoretical position of the tools is composed of fixed values, for example the machine dimensions, and variable values, for example the position of the actuators and the distance to the ground. They can be determined on the one hand by the geometrical conditions of the machine system and on the other hand by the position of individual components. In conjunction with the current wear condition of the tools, the actual tool position can be determined using an inverse kinematics model.

Condition detection:

The condition of the tools influences both the depth and quality of work. For highly automated machine systems it is therefore important to know the condition of the tools and to be able to respond to deviations.

On the headland, when the module is lifted, the single tools, for example shares of a cultivator, or groups of tools, for example several discs of a disc harrow, are recorded by a moveable camera system (see Fig. 3). A special software isolates the tools from the surrounding area so that the current condition can be recognised and processed.

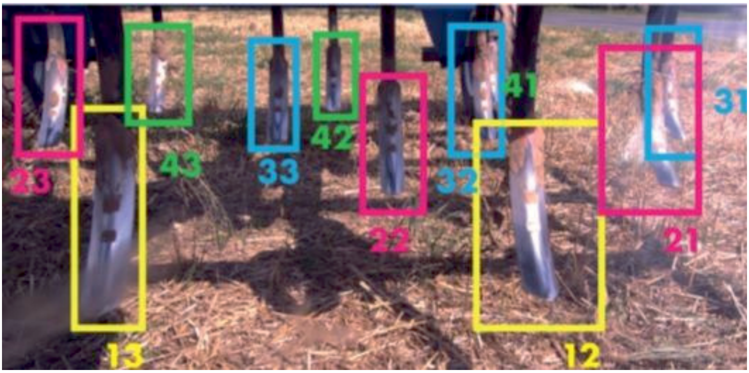

Fig. 3: Condition detection on a cultivator - camera view on headland with the marked single tools

To determine the wear, from a certain number of individual measurements the current wear on each individual tool is ascertained. Based on these values, a virtual model of the tool module with the respective wear condition is created. If the wear of the virtual model exceeds a specified limit, the corresponding information is sent to the tool control system, which adjusts the working position of the tool module. In case of misalignment or deformation of the tools, the defective position is evaluated and a recommendation for the control system is given. If the loss of one or more tools is detected by a measuring cycle on the headland, the work process is stopped and the information is sent to the administrator and the control system.

Integration into a Feldschwarm-Unit

The machine system Feldschwarm is able to carry different tools/types and to execute the corresponding work with them. The current stage of development focuses on the use in tillage. Typical implements are cultivators (with different share shapes) and disc harrows (both passive) or rotary tillers (active). These tools are designed as modules (see Fig. 1/ Fig. 4) and are kept in special boxes for storage or transportation. Each tool module has an RFID tag for identification. The Feldschwarm-system can use both types, the online and offline versions. For initial tests and validation of the control system, the offline method is used, which eliminates the need for a data connection. This increases flexibility for testing and reduces the need for additional subsystems.

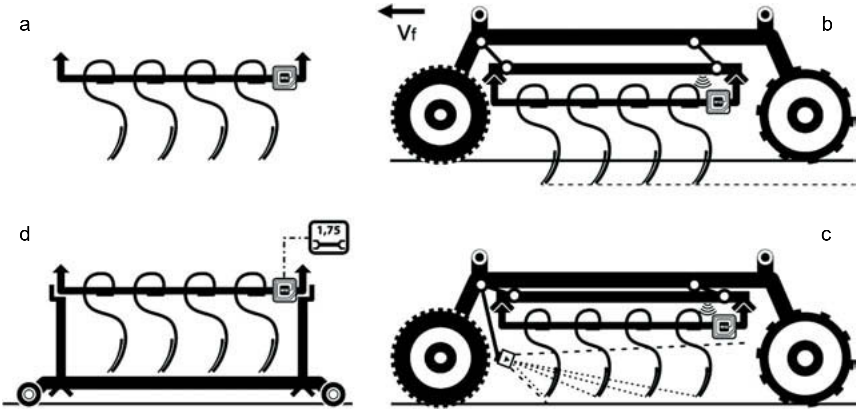

Fig. 4: Use of tool modules (schematic diagram); a: tool module ready to use; b: swarm unit with tool module in use; c: condition detection on headlands; d: tool module in storage/transport box

The tool module storage device contains the data necessary for identifying the individual module (Fig. 4 a), for setting the working process and for initialising the condition detection of the tools. After installation in the tool carrier (Fig. 4 b), the information is read in by the control system and the corresponding default values (working depth, speed / rotational speed) are transferred to the administrator or the process control system, this enables a process- or site-specific adjustment of the parameters. If no other values are available, the tool is set according to the specifications of the tool module storage device. During the working process, the tool is guided exactly at a corresponding working depth. Deviations due to changing ground contours or wearing tools (Fig. 4 c) are compensated. When the work process is finished or the tools are worn out, the tool module can be disconnected and another one inserted if necessary. In this case, key work data (for example working hours) and the current wear values of the single tools are stored on the RFID tag and/ or in the tool data base (farm management system). This allows the data to be accessed when the tool module is reused or maintenance/ repair is carried out. In the second case, the memory can be read by the operator or a workshop employee using a mobile RFID device (Fig. 4 d), so that the current status of the tools can be captured directly. After repair or maintenance, the tool parameters on the RFID-tag are set to the current status and the tool module can be used again (Fig. 4 a).
In order to test and evaluate the different subsystems, a tractor-bound test carrier with a working width of 3 m was built. Laboratory/field tests of the subsystems are currently taking place.

The machine system Feldschwarm with the functionalities of tool management is not only suitable for soil cultivation, but also for other areas of agricultural field work. Mechanical crop care and sowing, with their high demands on variability and precision, are proving to be promising additional fields of application. Furthermore, the areas of green and grain harvesting, field transport and grassland care offer additional potential for the use of the Feldschwarm technology.

Summary

With highly automated machine systems such as the Feldschwarm, the operator or administrator cannot monitor all processes in real time, so the machine system requires a management system. The developed concept focuses on the identification, control and condition detection of the individual tools or tool modules. The use of state-of-the-art RFID technology enables efficient and reliable identification of the tool modules. The variable and adjustable control of the working position of the tool ensures the optimum working depth and compensates for deviations due to ground conditions or tool wear. The latter is detected by a camera system with a special evaluation. The functionality and robustness of the subsystems is currently being tested in laboratory and field.

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Soil protection and energy savings through efficient energy supply to machines for primary and secondary soil tillage

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Abstract

Large-scale primary and secondary soil tillage, even if carried out in accordance with the recommendations given in the VDI guideline 6101, today still requires heavy tractors with high powers. On the one hand, this can cause severe damage of the soil due to compaction, which becomes apparent not at least in dry summers. On the other hand, this type of primary and secondary soil tillage is not really energy efficient. With regard to the stronger need for soil protection and reduction of greenhouse gas emissions and pollutants, the weaknesses of the state of the art soil tillage are highlighted. In addition, a potential future development path with significantly lower soil compaction and a much higher energy efficiency is presented. Following this path, one out of many possible solutions is introduced. This solution makes use of the interaction of two multipurpose, remote controlled and navigable mobile machines, which enable a low emission and very sufficient energy supply to machines for primary and secondary soil tillage. Furthermore, this solution also enables low emission and efficient energy supply to tractors in cases where they are still needed. Another advantage is the high level of automation which can be achieved.

Introduction and state of the art

The state of the art for machine operation with regard to the drive-on capability of agricultural soils is defined in the VDI guideline 6101 from 2014. According to this standard, the available drive energy of standard tractors is converted into the translational energy that is required by the attached implements through the wheel-soil interaction of all driven wheels (sometimes also half and full tracks). For this purpose, high weight forces are required under the contact conditions that usually prevail. The high weight forces can cause severe damage of the soil due to compaction. In addition, there are significant energy losses.

Methodological approach to improvement

From the application of the design methodology according to the VDI guideline 2221 from 1993 (not the one from 2019) for the development and design of energy-efficient agricultural machinery, which was presented in 2016, a scheme of the development and design process with five very promising search areas is known [1]. In 2016, however, only examples were shown for the four search areas “Variation of semis and work schedules”, “Variation of design elements”, “Variation of modules” and “Variation of solution principles”. This time it is about the search area “Variation of function structure”.

Analysis of function structure

For the intended improvement, the analysis of the function structure of the most common solution is helpful. Its result for the load case “Heavy traction work”, which is typical for primary tillage operations, is shown in **figure 1**. This figure visualises the numerous sub-functions of conversions and changes in magnitude and direction that must be realised between the sub-functions “Conversion into drive energy” (realised by the solution principle “Internal combustion” of diesel fuel) and “Conversion into traction energy” (realised by the solution principle “Wheel-soil interaction”) for the provision of the traction energy on the tow hook (or the couplers of the three point linkage) of a standard tractor. In addition, the individual sub-functions are assigned typical energy efficiencies that the solution principles usually have, which are commonly used for their implementation. Apart from the two energy conversions that take place on the input side in the internal combustion engine and on the output side in the wheel-soil contacts of the driven wheels, all other individual efficiencies are so high that the overall efficiency of the so-called drivetrain is $\eta_{DT} \approx 0.8$ (or higher). From a design-methodological point of view, the sustainable reduction of soil impacts and emissions as well as the increase in energy efficiency require either the substitution of the previous solution principles “Internal combustion” and “Wheel-soil interaction” for the sub-functions realised with them, or a variation of the function structure to avoid these sub-functions.

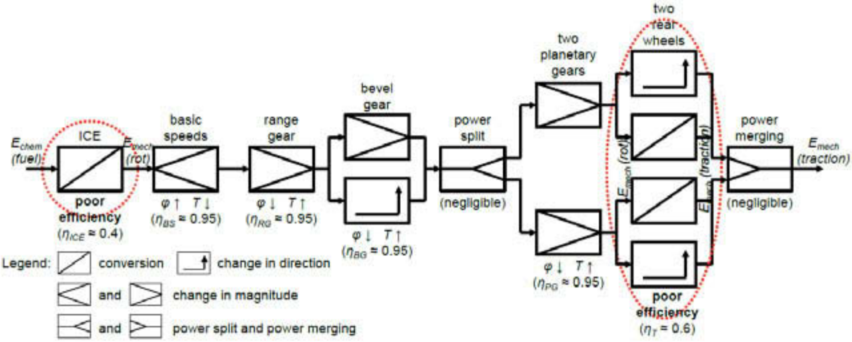

Fig. 1: (Specified) Function structure of a (2WD-) standard tractor for the load case "Heavy traction work"

Variation of the function structure at the input

It is well known that the efficiencies of the internal combustion engines of even modern standard tractors only achieve values of $\eta_{ICE} \approx 0.4$. In addition, these efficiencies need to be divided by the primary energy factor of diesel fuel of $f_P = 1.3$ for standardised comparisons. Since the input-side energy conversion has been the focus not only in agricultural machinery, but also for a long time in numerous other and quantitatively more important applications, various alternative solution principles for the realisation of the corresponding sub-function are known. Some of them are listed in the corresponding article "Energy analyses of different advanced drive systems for agricultural machinery". Accordingly, a significant improvement on the input side can best be achieved by converting electricity (if possible even renewable) into mechanical drive energy with the help of power electronics and the electromotive principle. Then, efficiencies in the range of $\eta_E \geq 0.9$ can be achieved, which have to be divided by the primary energy factor for the German electricity mix, which is $f_P = 2.0$ (or $f_P = 1.1$ for renewable electricity) for standardised comparisons. An efficient energy supply, however, is a prerequisite for the utilisation of this significantly higher input-side efficiency.

Variation of the function structure at the output

In contrast to the input side, the solution principle, which is assigned to the output-side sub-function of energy conversion, is a predominantly agricultural machinery-specific principle. In detail, the relevant sub-function is realised in standard tractors by the conversion of (mechanical) rotary drive energy in the wheel-soil contact of the driven wheels under the impact of the weight forces and the contact conditions into translational traction energy. During this conversion, the weight forces in particular can cause considerable soil compactions. Any improvements should therefore not only be aimed at increasing efficiency, but should also avoid such soil compactions if possible. There are various studies and calculation methods for determining the traction efficiency that can be achieved in wheel-soil contact [2, 3 and 4]. On the one hand, the current soil condition, which can vary widely and is also different when working on-land or in the furrow on the same field, has a significant influence. On the other hand, the respective values for the slip, the traction coefficient, the mass distribution on the individual wheels and the rolling resistance are of considerable significance. The last four values mentioned can in turn be strongly influenced by the inflation pressure, the shape and the type of tyres. Typical traction efficiencies of standard tractors achieve often values of $\eta_T \geq 0.65$ under favourable conditions. Under tricky conditions, however, they can also quickly drop to values of $\eta_T \leq 0.6$. An alternative solution principle known from the past and still obvious, which enables significant improvements in terms of both goals, is the principle "Pull over pulley". The application of this solution principle requires extensive changes to the function structure. But it enables to relocate the forces, which act when converting drive energy into translational traction energy, on ways along the edges of the arable land to be cultivated. As a consequence, only the much lower weight forces of the implements can impact the soil. In addition, both from the history of agricultural tillage and from the use of roughly comparable cable pull systems for numerous other technical purposes, their good energy efficiency in the transmission of traction energy is known. According to various sources, the efficiencies of cable systems when bridging distances of up to a few hundred meters usually reach values of $\eta_T \geq 0.9$ [5 and 6].

Description of the improved function structure

Assuming the availability of electricity as a secondary energy carrier, its conversion into translational traction energy has a very simple (core) function structure. Apart from a number of parallel auxiliary functions, only a few sub-functions are required, which can be realised quite easily by assigning suitable solution principles. These are the sub-functions "Conversion of electrical energy" (using power electronics), "Conversion into rotary (traction) energy" (using an electric motor), "Reduction of magnitude (of the angle of rotation)" (e.g. by using a planetary gear) and "Conversion into translational (traction) energy" with the parallel sub-function "Storage and de-storage (of the rope)" (using a winch).

System design

One possible system that was designed in 2018 on the basis of the improved function structure (and that has been upgraded with some additional features) is sketched in **figure 2**. This system is called “Cable Farming-system” (or CF-system for short). With this system, two multipurpose mobile machines move forward step by step and synchronously on paths along the edges of the field. Such machines can be, for example, further developed forestry caterpillars, which can also be equipped with one or more cable winches, devices for additional support of the cable forces (e.g. disc coulters or furrow press rings), remote control and DGPS-based steering systems for precise tracking. The largely automated operation can be controlled and monitored from a central computer that communicates with the on-board computers of the individual machines and implements using a standardised protocol, e.g. data distribution service (DDS). Each machine (or implement) is an independent one that runs its own operating and navigation system. The orchestration of the farming processes is done by the central computer which can be run on one of the machines (or implements) for example. The energy supply to the multipurpose machines can be provided (as shown) via catenaries or bus bars as well as (insulated) power cables, which can be unrolled and rolled up, for example via cable reels (similar to the automatic hose reels of irrigation systems) on the multipurpose machines themselves or separately from the field edges. Firmly anchored bus bars can also be used for cross support and (with sufficiently large conductor cross-sections) also for an energy supply with a voltage of U_{DC} ≤ 75 VDC (e.g. for power demands of P_{MPM} ≤ 75 kW), so that no special protection against accidental contact is required. Particularly when systems such as wind turbines or (agro-) photovoltaic plants including feed (and possibly also storage) stations are operated near a CF-system, a close to optimum low-emission and efficient energy supply can be realised.

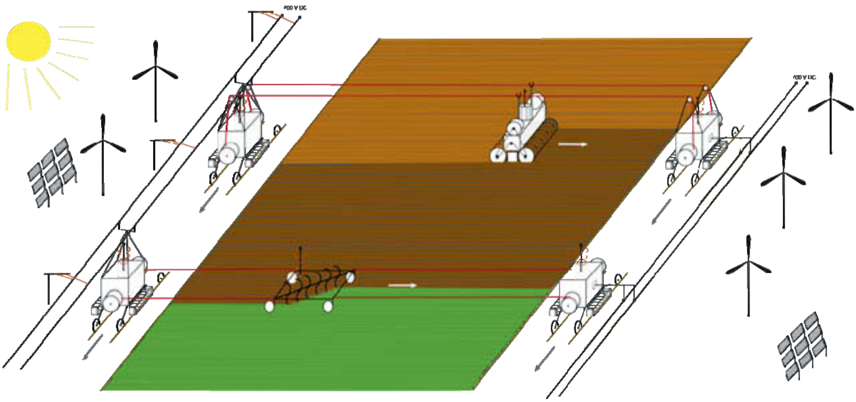

Fig. 2: Sketch of the Cable Farming-system

Typical operation modes

With a CF-system configured in this way, large shares of the primary and secondary tillage tasks that arise on many areas of arable land can be carried out with low emissions, energy-efficiently and largely automatically. In addition to the necessary transport, set-up and monitoring activities, the operator only needs to carry out residual work (for example in a conventional manner). For the main work, the shown CF-system enables several typical operation modes. If pulling ropes are used, then non-driven implements for primary and secondary tillage can be pulled over the soil to be worked very precisely and with only low soil pressure. Nevertheless, these implements can also be equipped with on-board functional drive systems as well as DGPS-based position reporting or fine steering systems if required. Alternatively, if equipped with suitable add-ons and if metal ropes are used, the multipurpose machines can stretch local catenaries that are then moved synchronously to the work progress over the arable land to be cultivated. In this way, energy can be supplied with low emissions and efficiently both to powered tillage machines [7 and 8] as well as (electrical) tractors if these are still needed. It is also possible to use an (insulated) power cable on one (and a rope from the second) multipurpose machine or to use two (insulated) power cables. In addition, the CF-system also enables the low-emission and efficient energy supply to a number of other machines, that can be used on the arable land to be cultivated.

Some additional features of the sketched multipurpose machines and implements

In detail, the machines of the CF-system according to figure 2 can be equipped with the following advantageous features, for example:

Multipurpose machines:

Rope linkage(s) below the longitudinal axis through the centre of gravity and counterweights to avoid tipping; longitudinal profiling of the caterpillar chains or wheels as well as lifts for handling the devices for cross support (which instead of vertical ones only cause less harmful horizontal pressure bulbs); tackle and block rope systems to reduce the torque(s) of the winch drive(s); docking devices for the power supply of implements at the headlands

Plough car:

Chassis with four tail wheels, of which the three on-land rolling wheels are always the carrying ones; (reversible) plough frame suspended in a central swivel and pivot bearing in the chassis, if necessary with additional guidance via pivot pins in sliding blocks on the two end faces of the chassis; attachment of the plough body pairs to the frame with their individual bodies pointing in the opposite direction; on-board hydraulics with directly driven hydraulic pump or on-board electrics with generator or with energy storage when docking to the multipurpose machines (and discharge during operation), especially for setting the working depth and for swivelling and rotating the plough frame

Self-propelled power harrow:

Two (partly or fully driven) packer rolls and two levelling bars for bidirectional use; lifts for seed drills with single seed bars for each direction; energy supply by cable or catenary; electric drives; steering e.g. by independently driven packer roll segments or track markers

Other implements:

Other implements which are well suited for operation by the CF-system are, for example, cultivators, disc harrows, seedbed-combinations, rotary tillers, mowers and grain strippers

Rough cost estimate

Because of the highly uncertain future developments in energy prices, the addition of (CO_2-) taxes, the decreasing CO_2-factor for the (German) electricity mix, interest rates, inflation and market prices for fully functional agricultural machinery as well as in the wide range of farm-specific conditions (e.g. mean traction efficiencies), only rough cost estimates are possible for an investment in a CF-system and its operation. For this purpose, various, very likely investment and operating scenarios were defined and analysed. As a result, net present and terminal values in the order of magnitude of the necessary additional investments and payoff times could be clearly determined within the project duration for almost all scenarios. If the scenarios are extrapolated to the conditions applicable in Germany (i.e. ploughing a replacement area of 91,450 km² per year), the potential savings with the greatest possible use of CF-systems for primary tillage (i.e. without the other possible applications) are already in the order of 500,000 t/a CO2 emissions and 2 TWh/a primary energy (with a primary energy factor f_P = 2). The sensitivity of these results to major changes in the underlying scenarios, however, must be emphasised again.

Conclusion

With the CF-system described, a promising implementation option for the development goal specified in the article "Energy analyses of different advanced drive systems for agricultural machinery" is shown. Compared to John Deere's GridCon2 system [9], which is already quite good in this regard, with the CF-system, the efficiency of typical primary and secondary tillage operations can be further increased, the soil pressure can be sustainably reduced, and the energy can also be supplied with low emissions, but less effort. However, it is by no means ruled out that there are not even more suitable solutions than the CF-system. In addition, emissions and energy requirements for primary and secondary tillage can also be reduced through more no-till or the cultivation of perennial crops. This article should therefore not only guide the methodical search for even better solutions, but also expressly motivate them.

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Legal Risks and Chances of Automation in Agriculture

Is EU regulation stifling or promoting innovation?

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Abstract

Legal frameworks may form enablers of, or barriers to, adoption of new automation technologies in agriculture. This paper examines regulatory structures, or rather lack of them, for new automation technologies in the EU – as a small case study illustrating selected issues for manufacturers and component suppliers. It also examines how the law may provide elements of an answer to these legal issues and how solutions can be developed to enable smooth operations of new degrees of automation in agriculture.

1. Introduction

New automation technologies, driven by data and incorporating emerging techniques – such as Internet of Things (IoT) and Artificial Intelligence (AI) – are setting the grounds for the future of agriculture [1]. By fostering a healthy environment, economic profitability, and social and economic equity, new degrees of automation have the potential to transform and empower the agricultural sector [2]. Simultaneously, automation presents unprecedented challenges from a technical, but also from an EU legal standpoint. Relevant stakeholders in agriculture will likely only embrace new automation technologies, corresponding processes will only be efficient and investments will only be protected, if legal risks are addressed, thus ensuring mutual benefit. Public regulatory bodies in the EU expect compliance in particular from manufacturers and component suppliers of new agricultural automation systems. Concurrently, the legal implications surrounding new degrees of agricultural automation (such as civil product liability or product safety obligations) are partly unclear and raise complex legal questions; namely because of the diversity of potentially applicable or missing regulatory regimes, sparse case law and in parts no substantial, in depth, academic or practitioner analysis on the requirements associated with the regulation of new automation technologies in agriculture.

In view of the foregoing, this paper focuses on selected legal issues of new agricultural automation systems that arise in the EU regulatory context, with emphasis on product liability in general and, more specifically, regarding AI-enabled autonomous systems. Thereby the focus lies on implications for manufacturers and component suppliers. It also examines how the law may provide elements of an answer to these legal issues and how solutions can be developed to enable smooth operations of new degrees of automation in agriculture. In the broader context of new agricultural automation systems, there are, in addition, numerous other legal issues arising from different laws – governing data privacy and ownership, anti-trust or infrastructure security – which require analysis beyond this paper.

2. Product Liability

Rapid changes in agricultural automation technologies and the ways in which food is produced open potential for new product defects – with serious consequences. Particularly IoT-based automation in agriculture may integrate multiple cross-domain data streams (e.g. meteorological data, soil condition data etc.) providing a complete semantic processing pipeline for data-driven automation in agriculture [3]. The seamless interoperability among sensors, services, processes, operations, farmers and other relevant parties, including online information sources and linked open datasets and streams may lead to a growing potential for product defects. Agricultural automation also increasingly depends on networked systems. Reliance on networked systems has brought the security of software systems under considerable scrutiny. Built on an extended notion of a “defect”, security and reliability have become important attributes of complex software systems – especially in the context of cyberattacks. Defective products not only pose a serious safety risk to the public but can also cause significant financial damage to the companies responsible. Even a short-duration interruption by a cyber-intrusion of a highly time-sensitive task such as harvest could cause significant economic losses [4]. All of the above issues are only compounded with an ever increasing degree of automation in agriculture.

It is therefore crucial for manufacturers and component suppliers to identify risks associated with civil product liability laws that may arise from potential product defects, such as cybersecurity vulnerabilities. As concisely noted by security expert Bruce Schneier, “liability changes everything” [5]. Since developing and maintaining robust automation systems in agriculture entails high costs, civil legal liability intends to create incentives in order to motivate the industry to work towards a higher level of safety and security [6] – at least from a policy standpoint. But manufacturers and component suppliers currently face a great deal of uncertainty when assessing the risk of civil product liability that may arise from unintended defects. This issue is compounded by an evolving and fragmented as well as absent and unclear legal landscape.

The civil product liability regime in the EU primarily builds on the Product Liability Directive 85/374/EEC – adopted in 1985 – which has been transposed into national law by Member States. With regard to B2C, the Directive imposes strict tort liability on producers of defective products. Alongside this, general principles of product tort (and contract law) may apply in each Member State on a B2C and B2B level. At its core, the Directive still only intends to regulate the defective implementation of “analog” technologies [7]. Therefore, difficulties arise in respect of the application of the Directive in certain technological contexts.

Taking for instance complex control algorithms deployed with the embedded software of new agricultural automation systems: It would be difficult to assess the civil product liability exposure of the responsible manufacturer or component supplier for claims for personal injury and property damage caused to third parties due to product defects. Under the Directive software is also not considered a product – only if it is stored on a physical storage medium (e.g. hard drives) [8]. Furthermore, it is particularly unclear how the term “product defect” will be interpreted with respect to new automation technologies in agriculture. Under Article 6 of the Directive, a product is defective “when it does not provide the safety which a person is entitled to expect, taking all circumstances into account, […]”. IoT devices (e.g. sensors) that support higher degrees of automation can be notoriously problematic with regard to defects. Thus, the complex question arises what level of safety one is generally “entitled to expect” from new automation technologies in agriculture. Such expectations of safety may also further vary depending on the specific market. According to German courts, prevention of possible “misuses of a product” – most notably cyber-intrusions – are generally not to be expected [9]. To this end it appears that respective manufacturers and component suppliers of new automation technologies are effectively insulated from liability for product defects where such liability arises in a situation that falls outside the scope of the Product Liability Directive.

Nevertheless, manufacturers and component suppliers may be subjected to national tort regimes in other respects. At least in Germany, manufacturers and component suppliers have to principally meet a duty of care after their product has been placed on the market. “Producers” – including software developers – are obligated to monitor their products for previously undetected security vulnerabilities as well as other defects and, if necessary, take measures to avert emanating risks [10]. However, in this respect, difficult legal questions arise from new agricultural automation technologies in Germany. First, it is unclear, if under this duty of care monitoring measures have to be technically integrated into the product, as product-integrated monitoring solutions may be available on the market [11]. In case of monitored defects, it is also unclear if settled German case law applies. The question arises, if manufacturers and component suppliers are obligated to update/patch their systems by available remote access. Often development methodologies (rightly) do not focus on the quality or security of a product but rather on functionality and time-to-market [12]. According to the Federal Court of Justice (*Bundesgerichtshof*) [13] manufacturers and component suppliers are – at least for the moment – only required to warn operators about any defects detected if this is sufficient to avert risks. Be it as it may, unlike in the available case law, where product updates required cost-intensive product recalls, remote updating processes are principally more cost-efficient; it is often only a matter of a mouse-click to update software accordingly. Another issue to be considered is the standard of care which ought to apply to new agricultural automation systems in the future. Standards may evolve with changes and developments in the degrees of automation. This raises the issue of software updates and patches in agricultural automation in a much more general way. Contrary to a (potential) duty of care, software updates/patches may not always be available. Agricultural automation systems may be designed without the ability to accommodate firmware or software updates, thus creating factual constraints.

To that end the Regulation on Software Updates and Software Update Management Systems by the UNECE's World Forum for Harmonization of Vehicle Regulations (WP.29) – which will be implemented into EU law before 2021 – is relevant. The UN Regulation applies to agricultural vehicles permitting software updates (categories R, S, T). Unfortunately, at this moment, it is unclear how the framework will affect the civil product liability regime in the EU. The new regime will require the agricultural vehicle sector to put in place software updating processes, such as for identifying vehicle targets and verifying their compatibility with an update or assessing if a software update affects the type approval.

It is also frequently forgotten that EU product safety rules and regulations set forth very specific and strict technical standards in relation to new automation systems – especially in agriculture. These standards apply not only to OEMs and system integrators, but also to component suppliers and finishers who see a high market potential for new technologies, such as embedded software systems, IoT networking or driver-assistance systems. Violations of EU product safety rules and regulations may lead, among other consequences, to civil product liability, product recalls and fines. EU rules on product safety for new agricultural automation systems are generally defined in the General Product Safety Directive 2001/95/EC. In addition, there are a series of regulations that are particularly relevant to new automation technologies in agriculture. The safety requirements for machines are specifically regulated in Directive 2006/42/EC. Lex specialis is the Regulation 167/2012/EU on the approval and market surveillance of agricultural and forestry vehicles. Furthermore, the Radio Equipment Directive 2014/53/EU, Low Voltage Directive 2014/35/EU or the Electromagnetic

Compatibility Directive 2014/30/EU may apply. Concerning agricultural automation systems, the related norm EN ISO 18497:2018 on principles for design of agricultural machinery and tractors regarding safety of highly automated agricultural machines is of considerable importance. It is to be noted that the rules and regulations listed above do not yet, contain any AI-specific requirements.

Finally, it is worth noting that EU product safety law is about to enter a new era of enforcement. Principally, as of 16 July 2021, the new EU Market Surveillance Regulation 2019/1020/EU will apply. The Regulation strengthens controls on harmonized products sold in the EU by introducing a number of key changes, such as significant expansion of market surveillance powers (including access to software embedded in products, details of the supply chain/distribution channel and quantities of products on the market, unannounced on-site inspections as well as reverse engineering and access rights).

In addition, Member States such as Germany are considering expanding (cyber-) security oversight of IT systems that are also relevant to automation technologies in agriculture. The Federal Ministry of the Interior is proposing extensive and far reaching changes to the Act on the Federal Office for Information Security [14]. Among other regulations, the bill authorizes the competent authority (BSI) to audit all available IT products on the German market for compliance with (cyber-) security standards – even without a particular reason. This includes products "intended for provision", i.e. products still in development. The proposed amendment to the Act could see fines of up to EUR 20 million, or in the case of an undertaking, up to 4 % of the total worldwide annual turnover of the preceding financial year, whichever is higher – at present, the Act stipulates a maximum penalty of merely EUR 100,000 [15]. Respectively, manufacturers and component suppliers should consider monitoring how legislatures shape new product security provisions applicable to their product.

In light of the above, product-related risk is one of the biggest perils facing manufacturers and component suppliers of complex automation systems, with recall exposures having increased significantly over the past decade. As such, manufacturers of new automation technologies in agriculture and their component suppliers should consider relevant adjustments to their quality control systems to manage product liability risks. This may include suitable quality assurance agreements with contractual partners, determination of appropriate criteria for the delimitation of risk areas or the allocation of specific interests in a shared production environment. In some cases, simply updating or developing new quality management manuals, liability guidelines, product descriptions and instructions for use will suffice to manage risk exposure. In addition, proactively implementing monitoring technology in new automation systems to prevent and drive future recall risks (e.g. by remote maintenance and updating functions) can be considered as part of a product life cycle management (PLM) framework – if they are not mandatory. In limited cases, where adjustments to quality control systems do not minimize product liability risks, an insurance for new automation technologies or adjustments to a product recall management system may mitigate liability. Understanding the root cause of the technical problem is essential in the event of a product recall. Complex automation systems in agriculture may consist of numerous different components of software and hardware – from different suppliers or joint manufacturers. Therefore, to identify product defects in a timely and cost efficient manner, technical documentation and the traceability of components (e.g. by way of product-embedded monitoring systems) should increase in relation to the complexity of the automation system. This may also include storage of accident data in order to comprehensively reconstruct an accident. Such proactive approaches may prevent product recalls from the outset.

In light of civil product liability and other repercussions, rightfully hardening any system, i.e. securing it by reducing its surface of vulnerability (e.g. by encryption) may lead to unintended and paradox consequences in the supply chain. New automation technologies in agriculture may cross national borders. With regard to hardened systems, this may entail export licensing requirements under relevant export control regulations. Products that are, for example, designed or modified to use certain cryptographic functions are governed by encryption export controls (especially in the US and the EU) [16]. That is because most countries, to varying degrees, regulate encryption as a so-called dual-use item, having both civilian and military applications. Such elements should be taken into account at the development stage of the product life cycle by manufacturers and component suppliers as they may negatively impact the marketability of new automation technology in agriculture.

3. Focus: AI-enabled Autonomous Agricultural Systems

Further to the above, many other legal issues surrounding civil product liability arise within the context of automated agricultural systems, especially with respect to highly or fully autonomous systems. This is most notably the case when “intelligent” technologies are leveraged, such as AI (e.g. Machine Learning, Computer Vision or Context-Aware Computing). Intelligent and autonomous systems (e.g. AI-enabled harvesting and crop sprayer robots) are able to maximize yield and at the same time safeguard and make more efficient use of natural resources [17]. But as things currently stand, such benefits cannot be realized fully by European agricultural market participants. This is, to a significant extent, due to an absent, fragmented and unclear regulatory framework, which fails to address and resolve issues in relation to potential risks emerging as a consequence of the use of autonomous technologies. The existing regulatory frameworks in the EU – especially the civil product liability regime – seem particular incapable of managing the risks associated with AI-enabled autonomous systems in agriculture. Current ex ante regulation is unsuited, because AI solutions – not just in agriculture – tend to be discrete (components of an AI system may operate without conscious coordination), diffuse (allocation of responsibilities between different parties for autonomous decisions is unclear) and not transparent (AI algorithms may be “black boxes” to outside observers but even also to their creators) [18]. Legal doctrine is also generally focused on specific human conduct and not autonomous decision making. Moreover, regulation at any stage is complicated by the difficulty in defining what, exactly, “artificial intelligence” means.

In the absence of a clear picture on tort liability, current product law is especially not able to meet the demands of deploying autonomous farming systems. AI is an emerging technology that is prone to failures. With its actions AI may cause damages for one reason or another; and thus issues of compensation will have to be addressed. One of the main problems regarding tort liability for AI technology in agriculture is that EU product law is not able to allocate liability in the context of diffuse AI systems. Without a legal framework, it is inherently unclear who “controls” an intelligent and autonomous system and thus who should be held liable in tort: The person primarily deciding on and benefitting from the use of the system (operator) or the person continuously defining the features of the technology and providing backend support (e.g. manufacturer/component supplier)? Similarly, the issues associated with foreseeability and causation are outside of the scope of EU product law. If, for example, very complex AI algorithms use multiple data streams from several data providers/sources and a defective data set and/or a defective algorithm causes damage, it may be very hard to prove (to the contrary) the existence of an element of liability beyond what can be reasonably expected [19]. In view of this, the modification of the premises of fault-based liability (especially the distribution of the burden of proving fault) or establishing liability that is independent of fault (usually called strict liability or risk-based liability) are being discussed as possible legal solutions [20] – if the European regulator does not address these issues.

In February 2020, the European Commission published its report on the safety and liability implications of Artificial Intelligence, the Internet of Things and robotics [21]. Alongside this report, a white paper on a European approach to artificial intelligence was published [22]. The Commission proposes updating the existing product law framework to ensure, among other things, that compensation is always available for damage caused by products that are defective because of software. The EU Commission is also considering whether it should alter the burdens of proof on plaintiffs – which are currently required by Member State liability rules for AI systems. In addition, the Commission also acknowledges that the complexity of IoT/AI products contributes to difficulties in establishing what components caused a malfunction, which may make it difficult to prove liability in cases involving such products. In light of possible changes, manufacturers and component suppliers should consider participating with industry groups and government agencies to develop ethical guidelines and industry standards that reflect the benefits, risks, and limitations of agricultural automation systems with AI.

To harness the opportunities of autonomous technology in agriculture and to intelligently manage the potential risks emanating from this new future, relevant parties should consider the often unappreciated legal protections that are available, such as contractual warranties and indemnities. However, there are no legal blueprints. Only a multifaceted, case-by-case legal approach may help to bridge the current gap in the regulatory framework. An adequate legal risk management framework may include, for example, contractual limitations of liability, adequate operating instructions or establishing policies for handling liability risk in the development stage of the product lifecycle (e.g. accountability, explanation, data governance, audibility, validation and testing of AI technology). The latter may especially be important in the context of regulatory compliance and as a defense of civil liability before a court of law.

4. Conclusion

The EU product regulatory regime which applies to manufacturing and development of new automation technologies in agriculture appears to be complicated, fragmented and partly outdated. However, an essential aspect of this regime is that parties have different rights and obligations under different laws which may make it possible to allocate liabilities. The law also allows defenses in certain cases which are particularly specific and relevant for promoting developments in technology. Even more compellingly, where permitted by law, parties may re-allocate legal liabilities specific to new automation technologies in agriculture.

In case of outstanding issues such as the legal status of autonomous agricultural systems tangible legal solutions may be developed in certain cases. In the corresponding process, it is essential to take a holistic and case-by-case view of legal risks by integrating the operational concerns of an agricultural automation venture with legal concepts, such as dynamic contractual arrangements or risk-based analysis. Where legal barriers cannot be overcome, legislative action may be warranted to address and distribute legal risks adequately. The agricultural automation sector would be ill advised to go along with such a change without drawing attention to legitimate concerns, such as technical neutrality of the regulatory system, i.e. the freedom of individuals and organizations to choose the most appropriate and suitable technology for their needs [23]. Lastly, there are numerous other legal issues arising in the broader context of new agricultural automation systems (e.g. from data governance and data privacy law) which require analysis beyond this paper.

[1] Cf. European Parliament, *Precision agriculture and the future of farming in Europe - Scientific Foresight Study* (2016).

[2] See footnote 1.

[3] E.g. Kamilaris, Andreas & Gao, Feng & Prenafeta Boldú, Francesc & Ali, Muhammad Intizar, ‘Agri-IoT: A Semantic Framework for Internet of Things-enabled Smart Farming Applications’ [2016] in 2016 IEEE 3rd World Forum on Internet of Things (WF-IoT).

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[5] Bruce Schneier, ‘Liability changes everything’ (heiseSecurity, 20 November 2013) <https://www.heise.de/security/artikel/Liability-changes-everything-270356.html accessed 2 October 2020>.

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[7] Charlotte de Meeus, ‘The Product Liability Directive at the Age of the Digital Industrial Revolution: Fit for Innovation?’ [2019] EuCML 149, 150.

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[9] BGH, Urteil v. 07.07.1981 – VI ZR 62/80.

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[11] Cf. Alexander Schmid, ‘Pflicht zur „integrierten Produktbeobachtung“ für automatisierte und vernetzte Systeme ‘ [2019] CR 141.

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[16] Cf. e.g. Annex I, Category 5 Telecommunications and “Information Security” dual-use Regulation 428/2009/EC.

[17] Tanya M. Anandan, ‘Cultivating Robotics and AI for Sustainable Agriculture’ (ROBOT-ICS ONLINE, 22 July 2019) <https://www.robotics.org/content-detail.cfm/Industrial-Robotics-Industry-Insights/Cultivating-Robotics-and-AI-for-Sustainable-Agriculture/content_id/8195 accessed 2 October 2020>.

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[19] See footnote 18.

[20] See footnote 18.

[21] COM(2020) 64 final.

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[23] Since 2011, technology neutrality has been recognized as a key principle for internet policy (OECD, 2011).

ROS2 for Autonomous Agriculture Applications

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The state of the industry for autonomous machines for agricultural applications is in the process of transitioning from what has been mostly concept machines and research projects to real production solutions in a wide variety of applications. This is happening with growing momentum that is moving at a fast pace driven by the market needs for increased agricultural production and efficiencies and evolving technologies that make these solutions possible. The market needs are driven from a combination of factors that include skilled labour shortages, limits of machine size growth trends, sustainable farming methods, all under the pressures of higher food production needs globally. Applications where the business cases make the most sense with the current technology are emerging across a wide diversity of areas with specific machine functions, and these will continue to expand as the technology matures and lowers the barrier to autonomy in new applications. Autonomous machines in agriculture has been enabled by broader advances in robotics technology that spans multiple technologies (e.g. vision systems, controls, navigation and guidance). Integrating these technologies requires systems that can manage the complexity of integration with architecture and tools that allow for development efforts to be focused on the application-specific areas. ROS (Robot Operating System) has emerged as the de facto standard platform for autonomous applications in agriculture (as well as many other industries). Its wide adoption is a result of its flexibility and capability of supporting wide varieties of systems, its accessibility through the open source community, and the tool set that facilitates rapid development of complex systems. Just as the autonomous agricultural machine industry is undergoing this transition from research systems to production system, ROS has evolved to make this leap from a research platform to a production platform, and ROS2 is the major initiative in this step change. This paper provides high-level overview and benefits of ROS in general, the new key features of ROS2 that enable scalable autonomous systems, the implications for autonomous agricultural machines, and how JCA has integrated and applied these technologies within the JCA Autonomous Framework (AFW).

1 Background: Integration of ROS with Agricultural Mobile Machine Controls

1.1 ROS Overview

ROS (Robot Operating System) is a set of software libraries and tools that can be used to build robotics applications. It had evolved out of robotics efforts from Stanford University in the mid-2000 and originally took shape in 2007 in the robotics incubator, Willow Garage (ROS History, 2020). The developers of ROS found that they had spent much of their time in working through technology integration and infrastructure problems with each new robot they worked on, which limited the time available to work on the core robotics problem unique to the specific robot. ROS was developed with the goal of minimizing the effort on infrastructure and integration, allowing for rapid development of new robots through reuse of core software libraries, and a defined communication architecture. This approach has become widely successful as ROS has been deployed across a wide variety of different robotic applications. The primary strengths of ROS that have facilitated its adoption are:

- **Open-Source with commercially friendly licensing** – ROS software libraries are open-source, which has resulted in a large community contributing to the development and progress of the platform. Additionally, the licensing is friendly to be used in commercial and closed-source products, which allows commercial-focused organizations to build their unique offerings on a ROS platform, while maintaining a competitive edge in their unique offerings.
- **Robot Geometry Library** – The ROS robot geometry library provides a framework for combining sensors and actuators in a common frame of reference that represents a 3-dimensional world. The ROS geometry library performs the transfer function math in the background that allows sensors to be described by a physical location on the robot/machine and the data produced by the sensors/actuators to be associated with a physical location relative to the 3D model that makes up the complete system. This drastically simplifies integrating multiple sensor systems that are mounted in different physical locations into a common model.
- **Distributed/Modular Architecture** – ROS provides a communication infrastructure that allows ROS applications to span multiple processing modules with the concept of ROS node and a pub/sub message passing system. This allows data from sensors, actuators, and communication interfaces to be interfaced to different processing modules within a system and the information to be shared throughout the system in a simple way. This facilitates edge computing and multi-processing systems with a common machine application.

- **ROS Packages** – ROS has a large number of packages that consist of commonly used functions and features needed in robotics, such as localization, pose estimation, mapping, navigation, and perception system processing.
- **Integration with other libraries** – ROS integrates well with third-party libraries that are also commonly used in advanced automation applications, such as OpenCV (OpenCV, 2020) used for vision system processing, Gazebo (Gazebo, 2020) used for simulation, and Point Cloud Library (Point Cloud Library (PCL), 2020) use for image and point cloud processing.
- **ROS Tools** – Several highly capable tools have been developed as part of the ROS ecosystem that have proven to be extremely useful in development of complex robotics systems. These include tools such as Rviz, a visualization tool that can be used to visualize multiple sensors in the ROS frames of reference, and ROS Bag, a logging tool for logging and playback of data collected across the entire system.

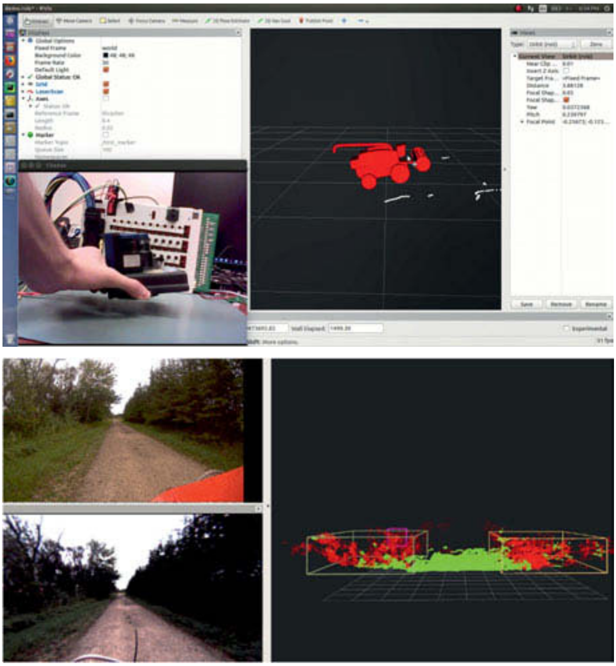

Fig. 1: Example output from ROS Rviz Tools

These key features provided a strength in development of complex systems need for advanced automation and robotics systems that had not been prevalent in simpler mobile machine control systems.

While ROS provides strong benefits to adapting to the technologies and complexity needed for robots and autonomous machines, it was originally developed for very different use cases than what is needed in agricultural mobile machines. The use cases that guided the original development of ROS (Gerkey, 2020) were:

- A single robot
- Workstation-class computational resources on board
- No real-time requirements (or, any real-time requirements would be met in a special-purpose manner)
- Excellent network connectivity (either wired or close-proximity high-bandwidth wireless)
- Applications in research, mostly academia

These use cases allowed for focused development of ROS to meet its goals of developing infrastructure that facilitates rapid development of complex robotic systems, without being handcuffed by ensuring the systems were scalable for production-intent systems. This has been very useful in the development of concept and prototype machines, but has some barriers when the goal is scalable robotics systems. It is useful to contrast this with the evolution of agricultural machine controls systems, which has been driven from a need to meet practical and business needs for agricultural machines on a large scale.

1.2 Agricultural Mobile Machine Controls

Agricultural mobile machine controls have developed over several decades on a very different path than the robotics world from which ROS emerged. Through the 1980s and 1990s machine controllers for agricultural systems developed on a path towards ruggedized and reliable ECUs that had heavy overlap in technology to that of the automotive electronics market (Stone, Benneweis, & Van Bergeijk, 2008). The division of separate machines between the powertrain (the tractor) and the machine application (the implement) is more common agriculture than in other off-highway industries (such as mining, construction, and forestry), which has resulted in the need for standard methods of communicating between the tractor and the implement controls. This drove the development of the ISOBUS standard (ISO11783, 2017) with its Universal Terminal (UT) concept that could be used in the tractor as an interface to variety of different implement ECUs. This has developed an approach of standardization and collaboration within agriculture that sets it apart for many other similar industries.

Another core technology that has heavily influenced the evolution of agricultural mobile machine technology is GNSS/GPS satellite systems, which has been in the catalyst to what is known as precision ag systems, and has been applied heavily in planting, seeding, spraying, and harvesting applications. These systems have all evolved in parallel with connectivity and mobile device technology fueled the evolution of farm management information systems (FMIS) that integrate with machine controls. Each of these key technologies and innovations have resulted in complex tapestry of offerings that have caused continual integration challenges for agricultural systems. To combat these integration challenges, the industry has pushed towards standardization efforts, driven by organization such as AEF (AEF ISOBUS, 2020), with the goals of providing defined functions and interfaces that allow multiple parties to integrate systems together. This has been supported with initiatives such as Plugfests (AEF ISOBUS, 2020) used to facilitate collaboration and conformance to these standards.

This progression of mobile machine controls technology in agriculture has resulted in real-time control systems, rugged and robust electronics, and structured, defined, and standardized module interfaces built around CAN-based communication networks.

While this model has worked well for robust, reliable, and scalable systems it does not adapt well to the complexity needed for advanced autonomous machines. Autonomous machines have an order of magnitude complexity compared to traditional machine controls, as there are many more functions and subsystems required. This is where the strengths of managing complexity offered by ROS world need to combine with the robustness and reliability of the agricultural machine controls world to result in effective and scalable agricultural autonomous systems.

1.3 Early Adoption of ROS in Agricultural Machines

The initial use of ROS in agricultural machine applications has come through research and concept machine development, largely for autonomous machines. The technology and systems available through traditional agricultural machine systems could not handle the complex systems needs for advanced perception systems, simulation, guidance and navigation needed for autonomous machines. ROS has been used in the development of many different autonomous agricultural machines, but most often on hardware platforms that are of a prototype nature, and with glue-technology that works for a one-off demonstration, but would not be sustainable in a production environment. This has been in alignment with the original use cases of ROS (i.e. research systems), but as the technology and industry for autonomous agricultural machines matures, it is no longer sufficient to produce machines that cannot be extended to production systems.

2 ROS2 – Expansion to Scalable Robotic Platforms

As ROS has gained in momentum, and robotics technology in general has matured, there has been a need to expand beyond the original use cases for ROS, which is ultimately driven from the need for robotics systems to emerge from research and academic environments towards scaled production systems. ROS2 has been developed with a focus on new use cases that enable scale robotic systems, which are defined (Gerkey, 2020) as:

- **Teams of multiple robots** – Expansion from the single robot use case to a system that considers multiple robots.
- **Small-embedded platforms** – Consideration of microcontroller-based processing platforms integrating into the ROS ecosystem.
- **Real-time systems** – Support of real-time systems considering inter-process and inter-machine communication.
- **Non-ideal networks** – Robust operation in networks that may suffer from intermittent and poor-quality communication.
- **Production environments** – Use of ROS beyond lab and prototype environments, to be expanded to real-world production applications.

These use cases are very exciting in the context of scaled autonomous agricultural systems, as they address many of the concerns with ROS related to its suitability beyond prototype and research systems.

The following sections describe, at a high-level, some of the key changes implemented in ROS2 that help to achieve the targeted use cases. This is not an exhaustive or in-depth description of ROS2, but rather a highlighting of some of the key components that are significant in the consideration of autonomous agricultural machines.

2.1 ROS2 Architecture

In order to address the targeted use cases effectively, it was determined that breaking changes to ROS were needed, which prompted the development of ROS2 (as opposed to further development of ROS1 to achieve these goals). Some of these changes are realized in the underlying architecture of ROS2. **Fig. 2** shows key components of the ROS2 architecture as compared to ROS1.

Some of these key differences are:

- **OS Support** - ROS1 is supported mainly by the Linux operating system, where ROS2 has more operating system support including Linux, Windows, Mac, and can be expanding to other real-time operating systems in the future. This enables the ability to expand the processing platforms for ROS, with potential to expand to real-time OS, supporting the embedded and real-time use cases for ROS2.
- **Use of DDS** – DDS (Data Distribution Service) is a communication transport middleware that supports a publish-subscribe transport for messaging (Woodall, 2020) that was introduced in ROS2. DDS is a based on a defined standard and has a strong technical credibility as it been implemented in mission critical applications, such as space and flight systems, locomotive systems, financial systems, and has multiple implementations that are supported from different vendors. The change to DDS maintains the publish-subscribe messaging model that was used in ROS1, but also provides additional reliability, quality of service, security, and modularity that allows ROS2 to be effective with non-ideal communication networks and in production environments (two of the key ROS2 use cases).
- **No ROS Master** - ROS1 was developed with a concept of a ROS master that acts as a server for multiple nodes within the system. Communication between ROS nodes is routed through the ROS master. This is a centralized communication system, so while distribution of ROS nodes can be across multiple processing systems (and even multiple machines), one processing module (or one machine) has to run the ROS master, and as a result acts as the master for the system. This means that the ROS master must always be present in the system for other ROS nodes to communicate with each other, which drives the need for a master or hub in multi-machine systems. This architecture change drastically improves the potential to support the teams of robots use case.

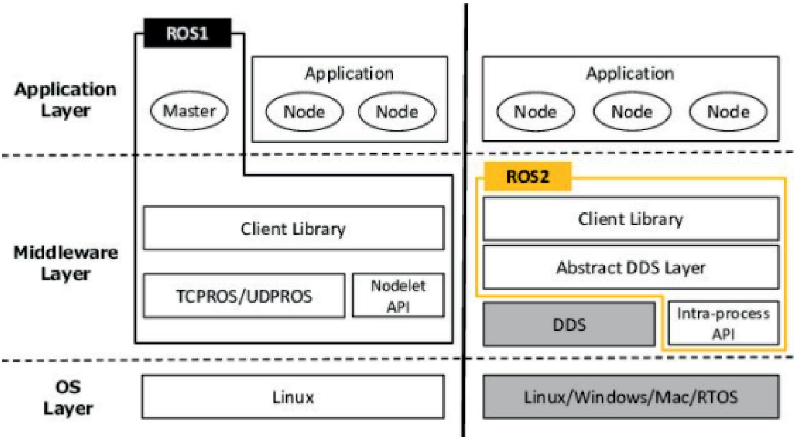

Fig. 2: Comparison of ROS/ROS2 Architectures (Maruyama, Kato, & Azumi, 2016)

2.2 ROS2 Communication

The ROS1 communication model is based on topics and services. Topics allows ROS nodes to communicate to each other in a publish/subscribe method, where one ROS node publishes a topic, and other ROS nodes may subscribe to that topic if they wish to receive information associated with that topic. Services are an alternative method of communication to topics, where instead of the publish/subscribe method, a service is defined by a pair of request-respond messages between ROS nodes. This method is more appropriate when specific information is to be exchanged between ROS nodes. In general, the ROS1 communication model is dependent on the ROS master within the architecture to route messages between nodes, which limits the use in multi-machine systems, as well as is more susceptible to network communication reliability issues.

In contrast, the ROS2 communication architecture adopts a DDS-based communication model that enables a dynamic, distributed, and robust data transport. This introduces the concept of “domains” in which ROS nodes belong to and can communicate within this domain. Independent domains may exist within the same processing module, and domains can extend across multiple machines as well. The communication model applied within ROS2 consists of (Maruyama, Kato, & Azumi, 2016):

- **Domain Participants:** The domain participants are ROS nodes that can publish and or subscribe to a global data space within a defined domain.
- **Publisher:** The publisher is responsible for data issuance and manages one or more data writers that send data to topics within the domain.
- **Subscriber:** The subscriber is responsible for receiving data and making the data available, acting on behalf of one or more data readers.
- **Data Writer:** The data writer publishes data of a specific type through a publisher.
- **Data Reader:** The data reader reads data of a given type associated with a subscriber.
- **Topic:** Similar in concept to ROS1, a topic identifies a data-object between a data writer and a data reader. A topic has a specific name and data type.
- **Quality-of-Service (QoS) Policy:** All entities have a QoS policy that defines the data transport behavior. It specifies communication parameters that define reliability, continuity, and message timing deadlines for each participant. This is an important addition to ROS2 that has a major impact in reliability of communication in networks that have less than ideal connection reliability.

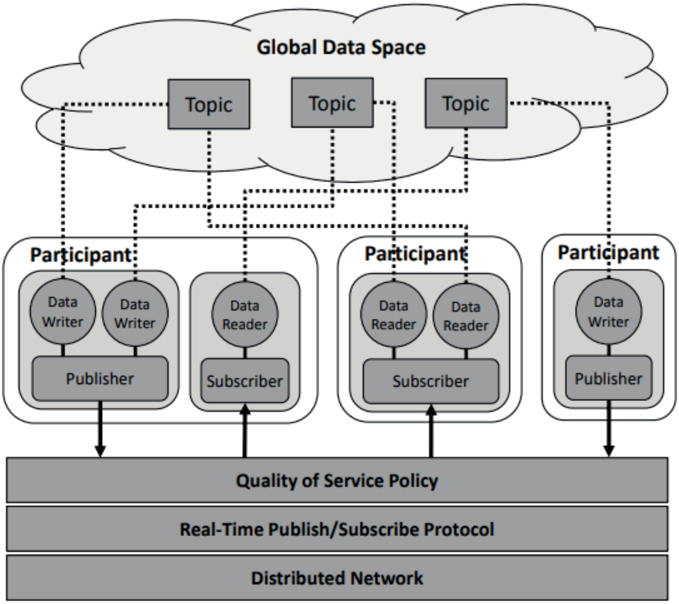

Fig. 3: ROS2 Communication Architecture from (Maruyama, Kato, & Azumi, 2016)

2.3 ROS2 Security

A key reason for the adoption of DDS as communication transport middleware in ROS2 is to take advantage of the security benefits possible with DDS. The DDS Security Specification (Object Management Group, 2018) is an expansion to the DDS specification that defines a Service Plugin Interface (SPI) for a specific set of security functions. There are five SPIs defined (Fazzari, 2020), which are:

- **Authentication** – Verifies the identify of each domain participant
- **Access Control** – Enforces restrictions on the DDS-related operations that can be performed by an authenticated domain participant
- **Cryptographic** – Handles all encryption, signing, and hashing operations
- **Logging** – This is an optional SPI that provides the ability to audit DDS security related events

- **Data Tagging** – This is also an optional SPI that provides the ability to add tags to data samples

An architecture diagram of how these security SPIs fit together is shown in **Fig. 4**.

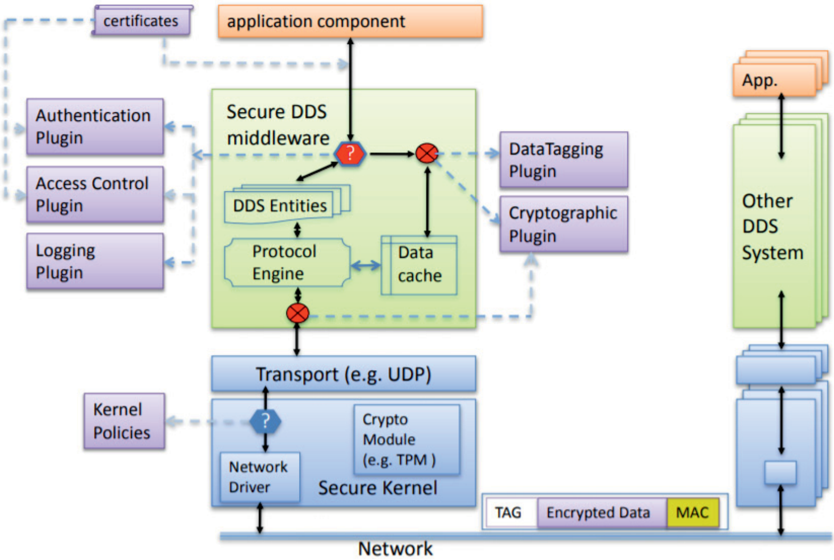

Fig. 4: DDS-Security Architecture from (Object Management Group, 2018)

The details of implementation of the security components are beyond the scope of this paper, but the important takeaway in understanding enhancements offered by ROS2 is that secure communications have been a focus, these have been implemented through the DDS standards, which are proven and mature technologies. This is a critical component of expanding ROS2 based systems to production environments, especially in safety-critical applications like autonomous agricultural machines.

3 Scalable Autonomous Agricultural Machines

Autonomy in agricultural applications are a subset of the wider applications where ROS can be applied, and similar to maturation of the robotics industry as a whole is going through, the next step in autonomous machines in agricultural systems is to make the leap from concept and prototype systems to scalable deployed machines. The approach taken by the ROS community in defining the relevant use cases that are necessary for achieving scalable autonomous systems. Use cases that apply to autonomous agricultural machines extend beyond the specific technologies needed to achieve these use cases, but rather define some of the core characteristics that are needed to be achieved in broad terms for truly scalable autonomous systems in agriculture. We have defined these use cases based on JCA's experience across a wide variety of applications to be:

1. **Multi-machine missions** – Mirroring the ROS2 "teams of robots" use case, scalable autonomy for ag machines requires the heterogeneous machine types from working together in a common mission. This may include a mixture of autonomous machines and operator-driven machines.
2. **Real-time controls** – Closed-loop real-time machine controls is a key part of agricultural machines. These are applied in drivetrain functions (steering and propulsion), as well in a wide variety of implement control applications (typically hydraulic and/or electric systems). Robust controls are a critical element of scalable agricultural autonomous machines.
3. **Integration with existing vehicle networks technology (CAN / J1939 / ISOBUS)** – CAN-based machine communication networks are standard in most agricultural machines, and this long history of use has proven this to be an effective and robust method of communication for a wide variety of machine messaging. Limits to this technology are reached as higher data rates are needed for more advanced systems and new wired communication systems (primarily Ethernet networks) have been evolving to meet these needs. However, these higher data rates will not replace CAN networks, but rather augment them. The depth of technologies that have developed in the mobile machine industry around CAN bus technologies means that autonomous agricultural systems need to be CAN compatible.
4. **Environmentally ruggedized processing platforms** – Agricultural machines operate in harsh outdoor environments, the "workstation-class computational resources" required by ROS are typically not available in processing platforms that are made to survive high vibration, wide temperature, dusty and wet, and electrically noisy environments, which is where agricultural machines are used. Any system that depends on processing platforms that do not meet this need will not be scalable in agricultural applications.
5. **Operation in areas without Internet connectivity** – Agricultural machines are often used in areas where there is not dependable Internet connectivity. Agricultural

machines that can be scaled need to be able to operate effectively in these areas. While certainly there are major efforts underway to expand connectivity to remote areas, reliable Internet connectivity in remote areas will not be a given still for many years to come, so developing autonomous agricultural machines that depend on this connectivity may not work for many use cases.

6. **Connected machines over wide work areas** – There is the need for machines to communicate with each other over a wide working area, which can be especially challenging in areas without Internet connectivity. Machines that are working on a common mission over areas that are more than a few kilometers away are common in agricultural applications, so the ability to exchange key information related to a common mission over these areas are needed for scalable autonomous agricultural machines.
7. **Integration of tasks to mission management** – Agricultural machines exist for the purpose of execution of a task, whether this is spraying, seeding, harvesting, transporting, baling, mowing, or any number of different agricultural machine tasks. The management of these tasks includes planning, deploying, executing, monitoring, and analyzing the task results. Autonomous missions include management of both the task, as well as management of the path that the machine will drive to execute this path. The concept of the task is not new to agricultural systems, and has a long history of development towards standard methods of managing and communicating these tasks, much of this defined by the ISOBUS Task Controller of the ISO 11783 specification (ISO11783, 2015). There has been a large ecosystem of technology developed around these standards, and these will not be displaced suddenly by any one new autonomous machine, so integrating task control that is compatible with existing systems and standards is an important part of scalable agricultural autonomous machines.
8. **Integration with Farm Management Information Systems (FMIS)** – As an extension to the task management, there has been a rapid development of farm management software systems that interact with machines that are executing farming tasks. These FMIS enable analytics that agronomic and operational efficiencies, and integration with the ag machines are a key component. These FMIS are an industry unto themselves, and common interfaces are developing to allow for farmers to have independent choices across FMIS and machines that best fit their needs. Integration with wide variety of FMIS are a key component of scalable autonomous agricultural machines.
9. **Secure platforms** – The connectivity that is needed to enable much of the multi-machine, mission management, and FMIS connectivity comes with potential of security concerns that could open up machines to have unauthorized use, interfere with

authorized use, or expose application data. Scalable agricultural autonomous machine systems need to apply robust and proven security systems to prevent any of these potential security breaches.

10. **Functionally safe systems** – Functional safety has developed significantly in the mobile machine industries over the last few decades. Several standards have been developed to define levels of functional safety, and provide guidelines for the development of functionally safe machines. Autonomous machines bring new challenges with safety systems, in particular, this brings challenges in applying existing standards to more complex and advanced systems that are needed for perception systems that are capable of object detection and recognition. Safety is a key concern, and considerations and solutions to address safety for autonomous machines are needed for scalable systems.

Even with a cursory examination of these use cases, it is clear that ROS2 alone does not address the needs of platforms for autonomous agricultural machines, however it can play a significant role in meeting many of these needs. The JCA AFW is a platform of technologies aimed at addressing all of these use cases, the role of ROS2 within the AFW provides an indication of how ROS2 is applied for autonomous agricultural machines.

4 JCA Autonomous Framework (AFW) Overview

The JCA Autonomous Framework (AFW) (Cook, 2020) is a set of technologies that serves as technology building blocks that enable the rapid development of autonomous agricultural machines. These technology building blocks consists of hardware and software systems that span all core subsystems of autonomous machines, including perception systems, power and drivetrain, localization and mapping, mission management, human-machine interfacing (HMI), communication and data management, and safety systems.

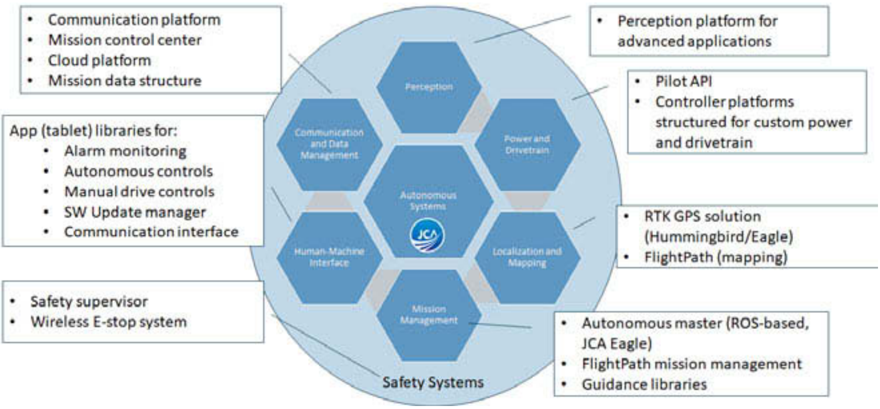

Fig. 5: JCA Autonomous Framework (AFW)

Similar to the philosophy that spurred the development of ROS, the JCA AFW has been inspired by the idea of reducing the development effort of the underlying infrastructure needed for autonomous agricultural machines to allow effort to be spent on the areas that make each machine unique in its application. This is achieved through providing these building block technologies that can be adapted and used for customized autonomous machines. The development of the JCA AFW has been guided by meeting the needs of the use cases defined in the previous section towards a platform that is suitable for scalable autonomous agricultural systems. Key components of the JCA AFW are:

- **Advanced processing platforms** – Ruggedized computing platforms made for execution of autonomous master, perception, guidance and localization, and mission management
- **ROS-node controllers for real-time machine controls** – Controllers capable of real-time closed-loop machine controls, interfaced to ROS-based processing systems
- **Mission management system** – Mission planning, deployment, monitoring, execution, and analysis of multi-machine autonomous missions
- **Perception platform** – Object detection, object recognition, and advanced sensor interfacing software systems
- **Multi-machine communication** – Communication system for coordinated multi-machine autonomous systems with a common mission

- **Flightpath cloud platform** – Task management software, including map management, task progress, and data management across multiple machines. Interfacing with FMIS and task controller compatibility.
- **Guidance and localization software** – Autonomous machine guidance, navigation, and localization software
- **Safety module and alarm management** – Safety monitoring, watchdog, and alarm management
- **Simulation systems** – System-level simulation for verification

The complete scope of the JCA AFW is beyond the scope of this paper, however highlights of key components of the JCA AFW that specifically relate to the use of ROS2 are highlighted in the next sections.

4.1 Advanced Processing Platforms

The JCA Eagle (JCA Eagle Feature Sheet, 2020) serves as processing platform for autonomous agricultural machine systems. It has been designed specifically for surviving the harsh environmental conditions encountered in agricultural applications (wide temperature, high vibration, sealed for dust and water ingress, electrical mobile machine conditions). It features the NVIDIA Jetson Xavier SOM for processing power that provides advanced edge-computing capabilities, dual RTK-GPS for orientation and localization, multiple high-speed (Gigabit ethernet), wireless communication interfaces, cell modem capabilities, up to 8 camera interfaces, 4 CAN/J1939 interfaces, and inputs/outputs made for machine control applications.

Fig. 6: JCA Eagle - Ruggedized Advanced Processing Platform for Autonomous Systems

This platform can run both ROS/ROS2 (simultaneously) on a Linux-based software platform. It provides a key hardware component that addresses several of the ag autonomous use cases, most significantly the environmentally ruggedized processing platforms capable of ROS2 execution.

JCA also has other linux platforms, such as the JCA Hummingbird controller that are suitable for simpler applications that don’t require some of the sophisticated equipment needed for autonomous machines but would still benefit from the use of ROS/ROS2.

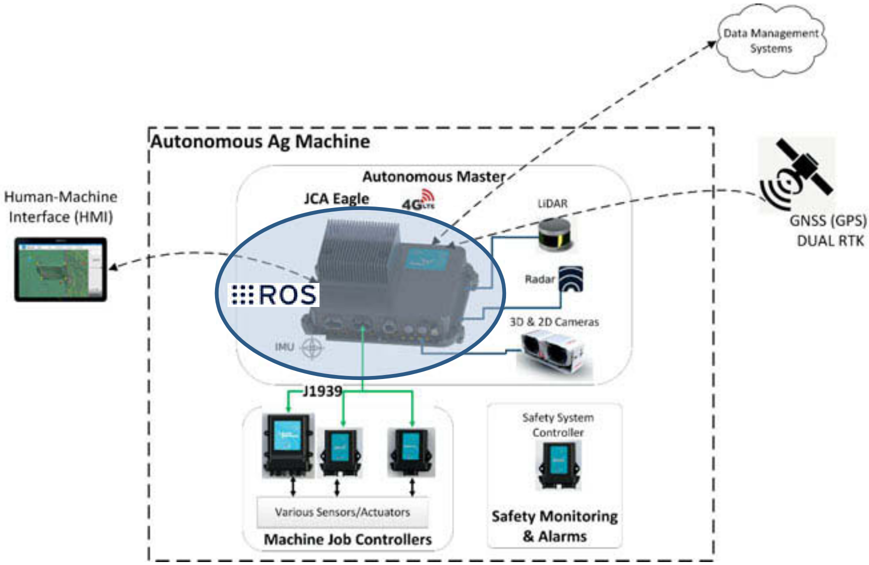

Fig. 7: JCA Eagle Running ROS in an Example Application

4.2 ROS-Node Controllers – Real-Time Machine Control

The JCA ROS node controllers includes a family of machine controllers that are capable of real-time closed-loop controls needed for machine controls through configuration and commanding from a ROS system (JCA ROS Node Controllers, 2020). This is enabled through the combination of ROS nodes that provide an interfacing to commanding over a J1939 bus of controllers that have a defined API that allow for I/O control, PID control loops, and variety of other functions. The application function of the real-time controllers are defined in the ROS application, eliminating the need for custom application software on the real-time controllers, and direct interfacing through a ROS application.

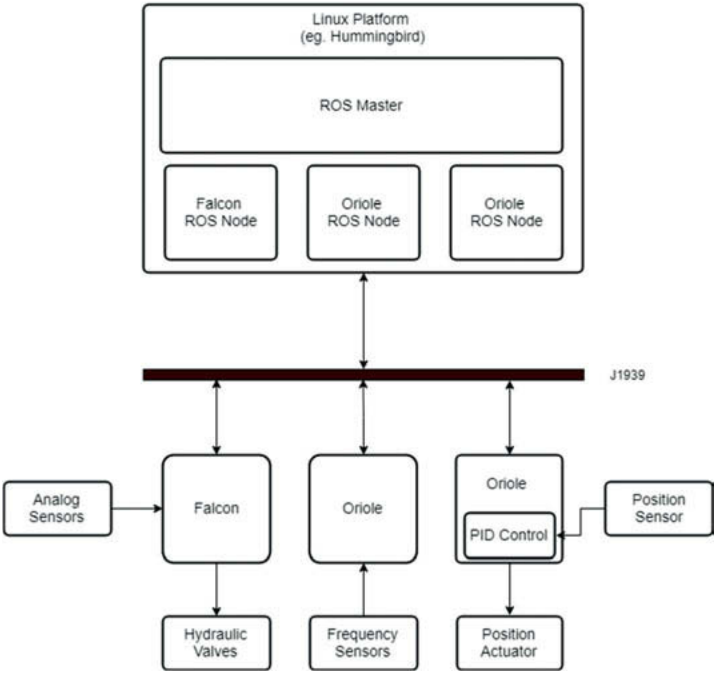

Fig. 8: ROS Node Controller Diagram (ROS1 Architecture)

This JCA AFW technology addresses the real-time controls and integration with existing vehicle networks use cases for scalable ag autonomous machines.

4.3 JCA AFW Multi-Machine Communication System

JCA has also developed a communication system that addresses several of the defined ag autonomous use cases, specifically the multi-machine missions, operating in work areas without reliable Internet connectivity, connected machines over wide work areas, and secure platforms.

To address the challenges of needing both high bandwidth communication, and long-distance communication, multiple frequency bands are included in the communication system, with definition of messaging types that include:

- **Persistent** – Persistent communication is used to send mission critical information between all machines in the system. This communication is over a long range, and has a lower data rate that proximity communication. Persistent messages include critical health and status messages, RTK corrections, and low-resolution mission progress updates. This is implemented over a physical layer that operates in 868-900 MHz range.
- **Proximity** – Proximity communication is used to transmit high-data rate information to machines that are in close proximity to each other. This communication has shorter range, but with a high data rate. Proximity messages includes mission deployment, detailed mission progress and task information, video feedback, manual machine controls, and machine-to-machine coordination. This is implemented over a physical layer that operates in 2.5 GHz and 5GHz ranges.

The JCA AFW architecture supports a multi-machine system that includes a mission control center that coordinates missions across multiple machines in a given work area, multiple machines, and multiple users with HMIs as an interface to the systems.

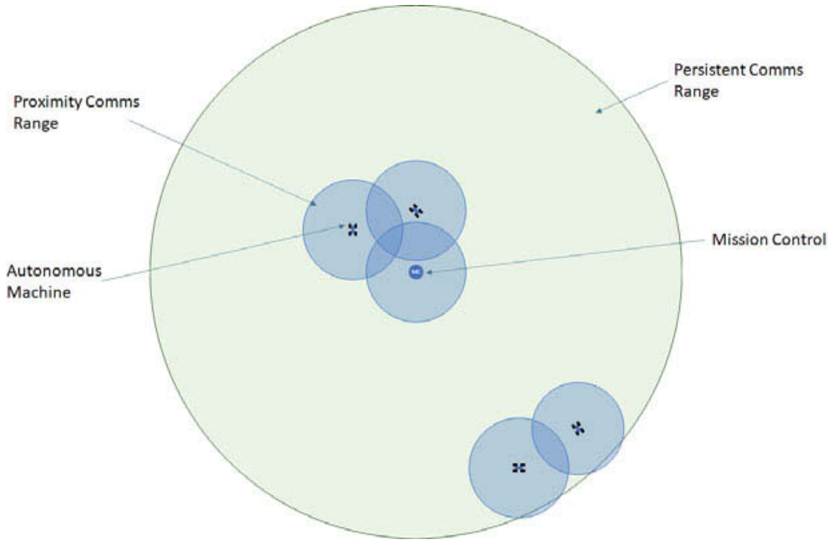

Fig. 9: AFW Multi-Machine Communication

Each of the machines within the system, as well as the mission control center run ROS, so this communication system allows for broad multi-machine communication using ROS infrastructure. The key features of ROS2 communication that consider security and non-ideal networks allow for this communication system to expand ROS-based multi-machine systems reliably for agricultural autonomous machines. Specifically, secure communications and quality-of-service attributes implemented with ROS2 provide a solid base in which to build the communication systems that address the specific needs for agricultural systems.

The mission control center in the multi-machine system has capability for Internet connection when available (through cell connections), that allow for cloud system connections for integration with mission control functions that include remote planning, monitoring, and analysis.

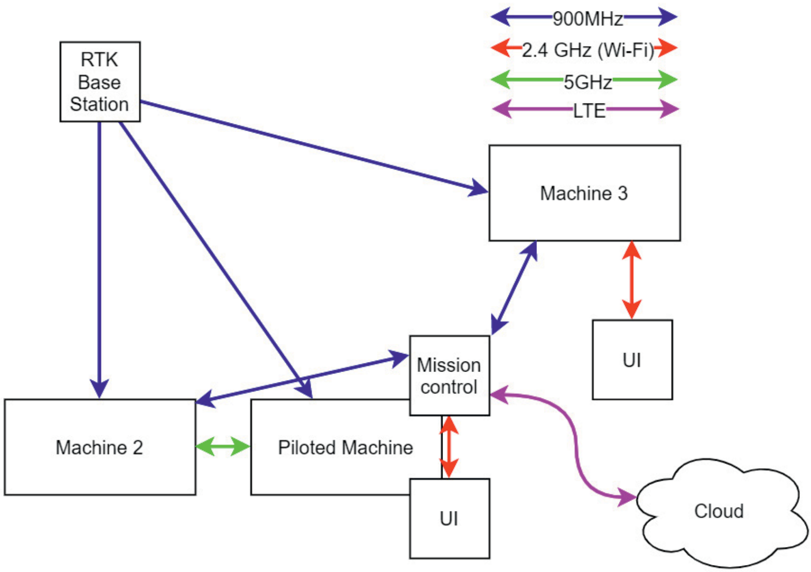

Fig. 10: Diagram Showing Communication of Systems within a Work Area

5 Summary of ROS2 Applicability to Autonomous Agricultural Applications

ROS2 provides a key step towards scalable autonomous agricultural machines. The table below summarizes the applicability of both ROS2 and the JCA AFW components have in addressing the key use cases or scalable autonomous agricultural systems. It can be seen from this that while ROS2 does not address all areas needed for these machines, it provides a core technology component that takes a meaningful step on the direction of increasing the reliability, robustness, and scalability of autonomous agricultural machines. The JCA AFW builds on ROS2 as a core technology, and further bridges the gaps between robotics and agricultural machine controls, providing a platform that can be used to develop customized agricultural autonomous controls.

Table 1: Summary of ROS2 and JCA Components Relative to Autonomous Agricultural Machine Use Cases

Autonomous Agriculture Machine Use Case	**ROS2 Applicability**	**JCA AFW Components**
Multi-machine missions	Direct applicability – Expansion to “teams of robots”	AFW Mission management, communication system, FlightPath cloud
Real-time controls	Indirect applicability – ROS2 is moving towards supporting embedded MCU platforms (with limited functionality), a more complete set of real-time features is available if used in conjunction with JCA ROS node controllers	ROS node controllers provide the bridge between ROS systems and real-time controls
Integration with existing vehicle networks technology (CAN / J1939 / ISOBUS)	Not addressed	JCA Eagle and Hummingbird platforms provide this capability of ROS-based systems with CAN interfaces
Environmentally ruggedized processing platforms	Not addressed	JCA Eagle and Hummingbird platforms provide rugged hardware platforms for ROS systems
Operation in areas without Internet connectivity	ROS2 adoption of DDS transport provides reliable expansion of communication that can be used for this.	JCA multi-machine communication system designed specifically for this use case, enabled with ROS2 communication
Connected machines over wide work areas	ROS2 adoption of DDS transport provides reliable expansion of communication that can be used for this.	JCA multi-machine communication system designed specifically for this use case, enabled with ROS2 communication
Integration of tasks to mission management	Not addressed	JCA FlightPath Cloud system integrates mission management and task management compatible with ISO11783 Task Controller
Integration with Farm Management Information Systems (FMIS)	Not addressed	JCA FlightPath Cloud system integrates provides APIs for connection with farm management systems

Secure platforms	ROS2 provides security build on DDS-security. This provides secure communications within local work area communication	JCA multi-machine communication system designed specifically for this use case, enabled with ROS2 communication. JCA FlightPath Cloud systems also provide security (unrelated to ROS) for cloud systems.
Functionally safe systems	Not addressed directly, but reliable and deterministic communication provides strong base to build on for functionally safe systems.	JCA safety module and alarm management systems provide safety systems tailored to the needs of autonomous machine systems

6 The Road Ahead

ROS2 has significant improvements that have built on the success of ROS systems, and grown through the adoption within the open-source community. There is still more evolution of this technology to come. Groups such as ROS Agriculture (ROS Agriculture, 2020) as well as many universities, OEMs, and technology companies continue to push the boundaries of the technology with new use cases and applications, which are collectively driving improvements in all areas. It is clear that any organizations that are serious about autonomy in agriculture are beginning to adopt ROS in a big way, and concerns of a lack of suitability of ROS to production systems are becoming outdated. There is no single organization that will be able to develop similar core technologies at the pace the ROS continues to develop. It is also clear that ROS alone will never meet the complex needs of autonomous agricultural machines, as this is not its intended scope. The JCA Autonomous Framework provides this bridge between the available technologies, such as ROS, that facilitate autonomous machine development, and the specific needs of the agricultural machine industry, with a platform that can be adaptable to needs of any unique machine application.

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Test as a way to implement robots in agriculture

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Robotics is a safe and proved technology which has been successfully implemented in many business areas such as manufacturing, packaging, transport, medical and more. Agricultural mobile robots, on the other hand, are a relatively new technology. It is uncommon to see them driving around in the fields, but sales of these machines are increasing, and they will become more and more common in the near future.

The current lack of specific regulations at European level, is one of the major aspects that negatively impact sales since end-users might be reluctant to invest in a product which has not been built and tested according to dedicated laws. Manufacturer of agricultural robots are aware of this barrier and are working alongside national and international institution to remedy to this issue and to speed up the process. However, it is likely that it will take a few years before Standards and guidelines will be made available. In the light of the facts, it is our belief that third-party testing could make up for the lack of regulation and promote both sales and implementation of robots in agriculture.

As an example of how testing could improve a product, the Danish Technological Institute is currently working on a National project alongside Agro Intelligence ApS, Aarhus University, Technical University of Denmark and Business Region MidtVest to develop and demonstrate a collaborative fleet technology for an autonomous agricultural robot. Our role is to test and validate the robot swarm according to the stress testing principles, where aspects such as safety, communication as well as route planning are put under pressure, in order to be able to deliver a safe and commercial-ready product on the market, which will increase farmers possibilities to operate in the field and manage crops. At the same time, Agro Intelligence ApS will likely to be the first agricultural robot manufacturer to deliver such a product, gaining a potential large share of the market.

A further test project involves the other Danish robot manufacturer, Farm Droid ApS. The objective is to evaluate the robot's weeding and driving accuracy, as well as to demonstrate the robot's abilities to farmers and agricultural professionals. This particular test is based on camera-vision analysis, since the weeding implement is located under the robot canopy and therefore it would have been difficult to perform the assessment using any kind of receiver such as, for example, a GPS antenna. As an alternative to this technical solution, if the robot design would have been different, it would have been possible to use the iGPS system, to increase the accuracy to a sub-millimeter level. The added value for the end-users from such a test, is to have the proof that the robot is accurate enough to perform a task in the field not damaging the crop.

Other parameters which would be useful for potential customers to know, are communication stability, agricultural performances as well as user friendliness.

For what regards the communication point of view, a test has been run on an autonomous mower produced by Agro Intelligence ApS. As greenkeeping activities are frequently located next to buildings, which represent a barrier for communication between the autonomous vehicle and the GPS or Cloud, it is important to determine what are the limits of the connection devices in operative situations. This test has provided useful knowledge for the development of the autonomous mower as well as autonomous vehicle in general. The practical outcome is that manufacturers can supply information regarding operational constrains, so that the end-user is aware of the limits of the machine.

Further important advantage that could be provided by testing autonomous agricultural mobile robots is an evaluation of the user friendliness. This test has a direct outcome for the robot's producer, as they can receive feedbacks on the system interface as well as the level of complexity to prepare the robot to perform a specific task. However, also end-users can take advantage from the tests, by being provided well-structured user manuals or by being delivered a product easier to operate.

Last, but not least, agricultural performances are a fundamental indicator of the usefulness of the robot. These evaluations can cover many aspects that would increase crop productivity, such as soil compaction, sowing and fertilization accuracy and more others. This information represents a strong marketing tool for the promotion of a product, as well as a proof of how the robot could improve farmers income.

To resume, testing can give added values to the product independently from its development stage. In early Technology Readiness Levels (TRL) it can help to find early and "basic" issues, which lead to address resources in a more efficient manner and improve the reliability of the whole project. In later TRL scale, testing is helpful for improve the implementation of new components and functionalities, which will result in a higher market appeal for the robot and therefore a higher sales potential. At last, third-party testing has also a “social” outcome. In fact, validating and certifying product performances increase the end-user’s confidence in such a new technology and therefore boost the implementation of agricultural robots in real life. This is the crucial and final purpose of testing and for this reason it is important to include new generations in the process, so that they can drive us towards their view of agriculture.

Parameter identification for Discrete-Element-Method (DEM) particles of a self-propelled forage harvester (SPFH) chopping sample

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Abstract

Crop-flow processes in forage harvesters are influenced by a variety of parameters where machine settings are actively used to control process results and compensate disturbances. Thus, there is potential for optimization by adjusting process parameters to accomplish the desired chopping results. However, to achieve an optimized state, the behavior of crop-flow processes needs to be better understood. Current knowledge of the crop-flow is typically achieved through empirical testing but limited by the applicability of commercial measurement techniques. To achieve more in-depth knowledge, in addition to empirical tests in lab and field, numerical simulation methods, like Discrete-Element-Method (DEM) and Computational-Fluid-Dynamics (CFD) are used. This paper discusses an approach to obtain currently unavailable data about biogenic particle properties as a basis for numerical simulations of the SPFH crop-flow, specifically considering the complex transfer functions between simulation parameters and physical crop-flow characteristics.

Keywords: Discrete-Element-Method (DEM), crop-flow processes, parameter identification

1. Motivation and introduction

Sufficiently defined particle models are a prerequisite for using the DEM. Most of the necessary particle parameter values of chopping samples are not known. In addition, most parameter values are not constant and change e.g. with moisture or chopping length. Therefore, characterizing the biogenic particles is the first step and main objective of this study. Thus, this work introduces a concept to analyze parameter values for DEM models of SPFH chopping samples, which provide the basis for further numerical crop-flow investigations. These investigations lead to assessing simulation feasibility at an early stage and emphasize a meaningful benefit in the product development process.

2. Current state and background

Classifying the complex morphology of nature presents a quite challenging part for utilizing biogenic particles in numerical simulations. Besides the topology of the characterized particles, material parameters like density, Poisson's ratio, Young's modulus as well as contact describing parameters like coefficient of rolling friction, restitution, and static friction have to be known. Shape and material parameter like mass and volume can be directly determined through conventional measurement technics. All other parameters listed above can mostly not be determined through direct measurements. Friction or coefficient of restitution values of biogenic material can be found in the literature, but they are very rare and mostly limited to a very specific particle type, condition, and application as mentioned by WIENEKE [1], NEUMANN [2], AFZALINIA [3], CHEVANAN [4], MENZIES [5] or KAJTÁR [6]. Fig. 1 shows a schematic diagram of the complex transfer function between operating and physical parameters in the environment of the SPFH crop-flow. All highlighted values in Fig. 1 are necessary as input values to simulate the SPFH crop-flow.

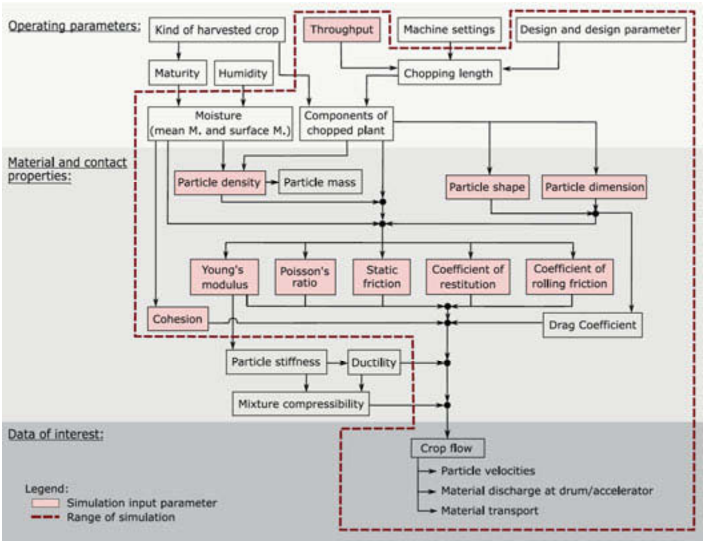

Fig. 1: Relationships between operating and physical parameters in a SPFH crop-flow

3. Objectives, challenges and requirements

The aim of this paper is to determine all parameter values highlighted in Fig. 1. Obtaining parameter values through direct measurements or experimental tests is only possible for a few parameter values like particle shape, dimensions, density, or friction values by using static or dynamic angle of repose tests or inclined plane tests. Other standard calibration experiments are e.g. compression tests, shear cell tests, rheometer tests, or cone penetration test. All these tests eliminate individual effects and provide values for one specific parameter but they do not characterise dependencies and interactions between parameters. Thus, to consider all dependencies and interactions, a validation test is necessary to collectively identify the interaction-parameter values, like coefficient of rolling friction, restitution, and static friction in between the particles themselves and the particles and the wall. To achieve these micro-mechanical parameter values for a reliable macro-mechanical response in the targeted industrial scale application, it is important that the calibration test involves dominant processes of the final application scenario. For the SPFH crop-flow dominant processes are visualized in Fig. 2. This study considers the derived process range of transport, acceleration, and discharge. Particles in particular for cutting and compression processes are not part of this paper.

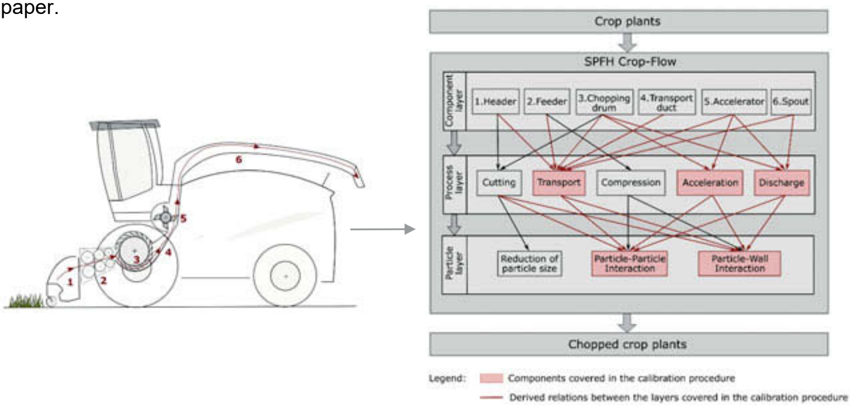

Fig. 2: Derived process range for aimed DEM particles, exemplified for grass-harvest

4. Approach, methods and test procedure

A tailored calibration procedure introduced in this study allows to determine required parameter values to simulate the SPFH crop-flow. The derived calibration cycle for SPFH chopping samples is shown in Fig. 3 for a grass sample. In the 1st step, the topology of the sample is fundamentally investigated, as exemplified in the sub-steps, to determine shape, dimension, mass, and their distributions. In the 2nd step, single contact parameter values are achieved through simple ex-situ standard calibration experiments, such as static angle of repose tests for mainly particle-particle friction or inclined plane tests for mainly particle-wall friction. These values provide an initial input for an in-situ test in the 3rd step. The developed in-situ calibration test stand represents a downsized SPFH accelerator model, which ensures close parameter identification to the targeted SPFH crop-flow. In addition, the in-situ calibration test entails the particle behaviour for the targeted process range at the drum and accelerator: transportation -

acceleration - discharge. Thus, the experiment considers the complex transfer function between all required parameter values at the same time. In the in-situ test rig the stationary rear wall in the SPFH crop-flow is abstracted into a container filled up to 50 mm with the chopping sample and a translation motion towards the rotor with 150 mm/s, as shown in Fig.4.

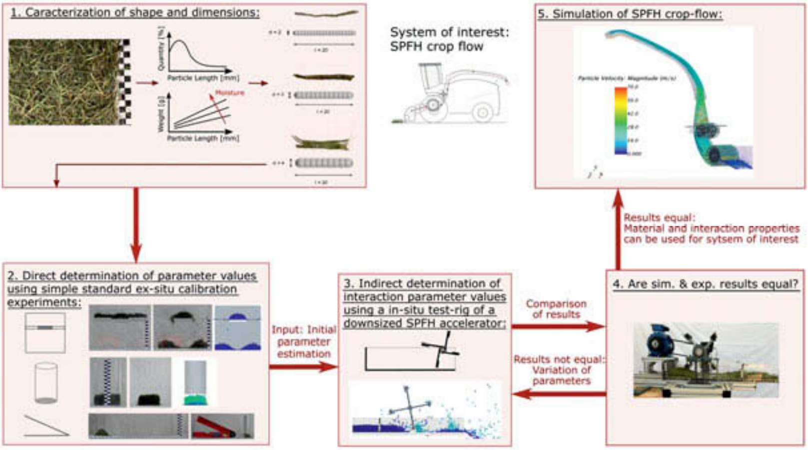

Fig. 3: Calibration cycle of a SPFH chopping samples

The rotation speed of the rotor used was in a range between 200 rpm and 500 rpm. This model abstraction with scaled down dimensions also allows a reduction of particles in the domain, which concurrently reduces computational time. A translation motion of the container and a lower rotation rate of the rotor than in the real application, causes a deviation of the relative speed to the chopping sample compared to the process in the SPFH crop-flow. This abstraction of the calibration experiment enables a simplification of the various feeding processes of the rotor and emphasizes the focused processes transport, acceleration and discharge.

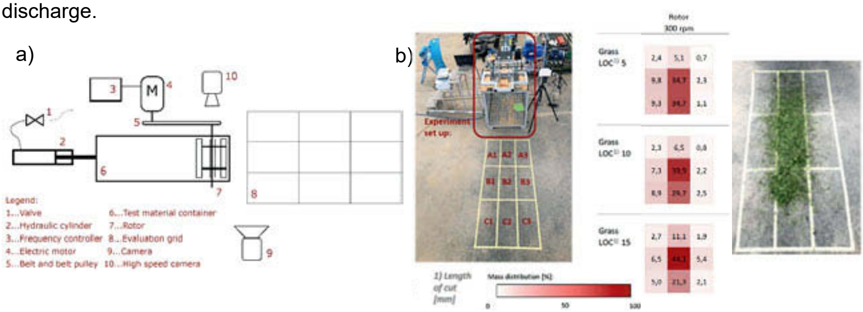

Fig. 4: a) Schematic of in-situ test rig, b) Raster on the ground to measure distribution patterns

The results achieved through the validation between the 3rd and 4th step build the basis for the crop-flow simulation in the 5th step. As validation criteria between the 3rd and 4th step, a raster on the ground is used to compare distribution patterns (Fig 4b), camera recordings are used to capture the particle behaviour from the distance, the immersion of the rotor-paddles, and remaining particles in the container. The numerical approach in the 2nd, 3rd and 5th step is a two-way coupled CFD-DEM simulation carried out using *STAR-CCM+* from *Siemens Industry Software GmbH.* The calibration cycle was carried out for grass chopping samples with three different chopping lengths: 5mm, 10mm and 15mm and for different moisture contents. In addition, all highlighted parameter values of Fig. 1 were varied in order to analyse their sensitivity to the process.

5. Results

The results are pointed out for a brief excerpt of comparatively experimental and numerical tests obtained so far, as displayed in Fig. 5. The graphs indicate a dominant effect of the particle length, particle diameter as well as the coefficient of restitution to the maximum throwing distance and height.

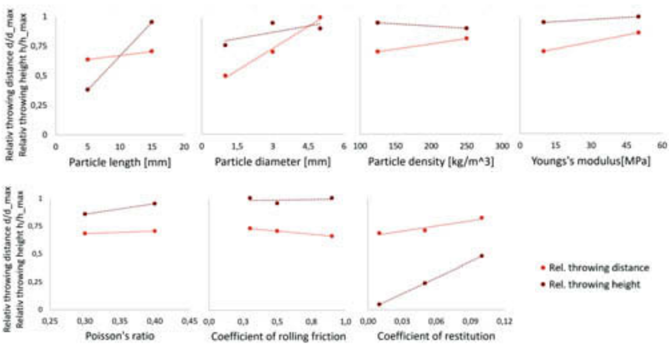

Fig. 5: Excerpt of numerical sensitivity studies

By increasing the moisture, the particles start to accumulate and form lumps (Fig. 6). Due to the fact that biogenic particles absorb water, there is a variability in the surface moisture and this influences most physical values, particularly the friction.

Fig. 6: Snapshots of trajectory characteristics for different moisture contents

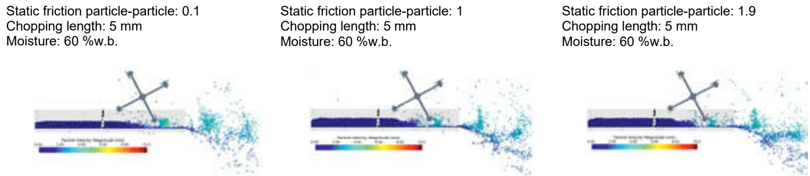

Fig. 7: Snapshots of trajectory characteristics for varied static friction between particles

By increasing the friction value between particles, a higher accumulation effect of particles can be seen in the numerical results in Fig. 7 but this effect cannot fully be attained just by increasing the friction. This indicates the presence of a cohesion force. The numerical results in Fig. 8 confirm the influence of a cohesion force to lump formation in moist chopping samples.

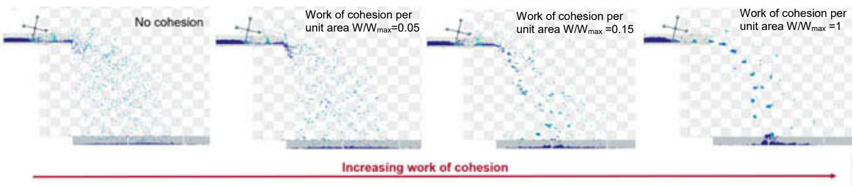

Fig. 8: Impact of cohesion force

In this study, the cohesion force is modelled through the linear correlation in the following equation [7]:

$$F_{Cohesion} = R_{min} \cdot W \cdot \pi \cdot F$$

Where R_{min} is the minimum radius of surfaces in contact, W the work of cohesion and F a model based factor after the Johnson-Kendall-Roberts (JKR) model [8] with a value of 1.5.

6. Conclusion and outlook

The parameter values and their interactions of particularly grass chopping samples achieved through the introduced calibration strategy can provide the basis for numerical crop-flow investigations. The influence of further parameter values will be investigated more in depth using the introduced calibration cycle to improve the DEM particle models e.g. the right work of cohesion value for different moistures.

The first numerical results of the real scale SPFH crop-flow model, using the grass DEM-particles, are plausible and reflect practical experience, which will be validated more in-depth by experimental data. Furthermore, the same calibration strategy can be applied to other chopping samples like maize chopping samples.

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A Season in Data: Efficiency of a Forage Mower

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Abstract

Harvested grass with a significant moisture content can be preserved as wrapped bale silage to feed housed animals during the winter months. The implements employed for silage harvesting require tractors which consume significant amount of fuel during operation and transport. In this study a rear hitch-mounted mower implement was monitored over several months using an array of electronic sensing equipment. From these measurements, the data is filtered and automatically segmented into field sites, cutting and baling operation and road transport. For each scenario, the machinery fuel and time efficiency are presented. Results highlight the datapoints that dictate fuel and time efficiency for the measurements herein. The paper highlights the inefficiency of machinery transport when compared to the in-field and in-work scenarios.

Introduction

Over 150,000 machinery contractors perform out-sourced heavy machinery operations on European farmlands [1]. Irish machinery contractors produce over five million bales of silage annually, spending an 40% of their turnover on vehicle amortisation and a further 20% on employment and fuel costs [1]. Budgeting these outlays is a significant challenge in a business model that involves intermittent periods of intense workload which are constrained by weather conditions.

The operating information of the machinery can be recorded and analysed to quantify performance and efficiency [2,3,4]. Webster *et al.* [2] monitored a single pass combine harvester and baler for the entirety of a corn harvesting season. Sensor data were recorded from the CAN and serial bus networks. Despite drawing conclusions regarding the efficiency of the machinery operation within the field, no GPS location and fuel consumption measurements were recorded.

Buckmaster *et al.* [3] developed a model to determine the number of transporters required to minimise the idle time for a forage harvester. The model was verified using observed filling rate data at the farm silo.

A study of the efficiency of a rice paddock compact harvester over six seasons in Vietnam is documented in [4]. Efficiency was evaluated based on the rice yields obtained, fuel consumed and hectares harvested per day. The results highlight that combine efficiency peaked with a rice field area between 2000-3000m^2. The study did not include temporal and fuel losses due to transport between field operations.

This study presents an overview of the efficiency of an Irish harvest machinery contractor based on machinery measurements acquired throughout the 2019 season. The measurements were obtained from an array of electronic sensors fitted to a rear hitch mounted mower. The paper highlights the operator efficiency in terms of the periods of machine operation and idle time within a field. Transport losses between sites are illustrated and the relationship between salient features and the implement fuel consumption are modelled. Data acquisition is outlined in Section 2, results are illustrated and discussed in Section 3 and, finally, the conclusions presented in Section 4.

Methodology

Machinery and Measurements

An array of electronic sensors were fitted to a McHale Proglide R3100 rear hitch mounted mower. The machinery was owned and operated by a machinery contractor based in Galway, Ireland. The array of sensors included rotary sensors, hydraulic pressure gauges, inclinometers, ultrasonic range transducers, a GNSS positioning chip. A custom electronic Control Unit was programmed to connect to the digital and analog sensors and relay that information across a J1939/CAN network. Fuel and displacement measurements were obtained from a Duetz Fahr Agrotron 6180, through the tractor J1939 interface [5]. All sensor and tractor J1939 packets were received, parsed and stored locally in a document based NoSQL database operating on an 8th generation Intel Nuc (Intel i3 processor and 4 GB of RAM) running Ubuntu 16.

Pre-processing

All recorded data was segmented per field using an automated algorithm. These job timings were separated again into machinery idle and working times, to isolate when the machinery was no just active but harvesting crop. For the mower, the mower bed location, hydraulic pressure and Power-Take-Off (PTO) speed were filtered. Crop intake was monitored using an ultrasonic ranging sensor alongside the PTO speed.

Results

Transport Efficiency

Measurements from the mower were recorded over 22 days between May and September 2019. One to six fields (mean 2.5) were mowed each day with an average area of 3.67 Hectares. The tractor and mower were in transport for a total of 232 km with an average 2.86 km of transport required per hectare of grass mowed. Table 1 details the fuel, distance and time spent during mowing and transport over the season, while the box plot in Figure 1 highlights the fuel and time proportions spent during each scenario. Figure 1 highlights how the temporal losses are significantly greater than fuel inefficiencies during the transport of the mower. If the cost of agricultural diesel is priced at €0.7 per litre [6] and the minimum wage of an operator taken at €10.10 [7], then the total cost of fuel and labour within the field is approximately €711 while the transport outlay is €229, 24% of the total cost.

Table 1: Table describing the total fuel and time used mowing and in transport.

Hectares Mowed	80.76
Distance travelled in transport	231.329km
Distance travelled in field	202.617km
Distance in transport per hectare	2.86km
Fuel used in field	644.88L
Fuel used on road	141.96L
Litres burned per hectare (in field)	7.98L
Litres burned per hectare (on road)	1.76L
Time in field	25 hrs,46 Minutes
Time on road	12 hrs,47 Minutes
Time used per hectare (in field)	19.14 Minutes
Time used per hectare (on road)	9.5 Minutes

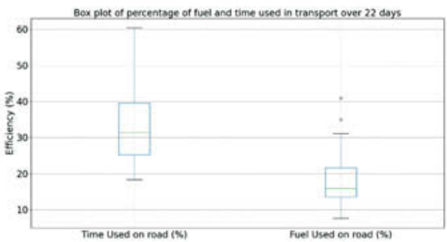

Fig.1: Time and fuel usage of the mower tractor setup for 22 days from May to September 2019 in transport and in the field

Mowing Efficiency

A total of 80.76 Hectares of mowing was recorded during the season with a mean field area of 1.5 hectares. The average time taken to mow a hectare was 19 minutes and 14 seconds as shown in Figure 2(a). An average of 7.98L of fuel was consumed per Hectare at a mean rate of 25.04L/Hr and an average of 11.94L consumed per field as shown in Figure 2(b).

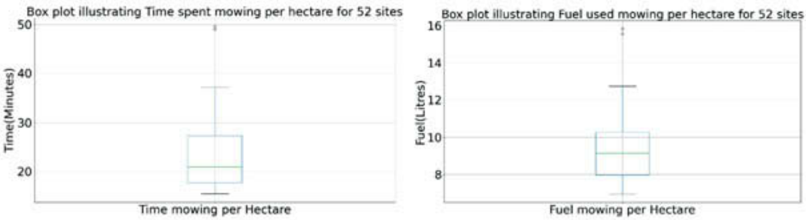

Fig. 2: Box plot illustrating time (a) and fuel (b) used mowing per hectare for data gathered from 52 sites gathered during mowing from May to September 2019.

Fuel and time efficiency within the field is illustrated in Figure 3, where the implement idle and operating times are compared. In Figure 3(a) the mower was operating for an average of 76% of the total period spent in a field. Figure 3(b) illustrates that 21% of total fuel was consumed when the mower was not cutting crop. This waste is a result of driver navigation, where the mowers are raised at each headland while the PTO are running at full revs.

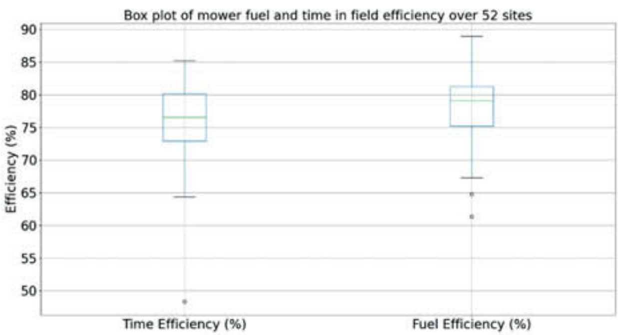

Fig. 3: Box plot illustrating average percentage of time and fuel used in the field while the machine was actively mowing grass throughout the 52 sites where mowing was monitored.

In Figure 4, the area of each field site was compared to the time and fuel elapsed. A significant correlation is shown in Figure 4(a) between field area and the mowing time with a coefficient of determination (R^2) of 0.93. Figure 4(b) denotes the relationship between fuel consumption and area, with a significant ordinary least squares fit ($R^2 = 0.97$).

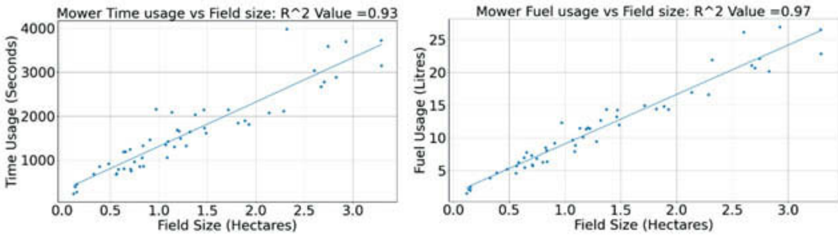

Fig. 4: Mowing Time (a) and Fuel Usage (b) of the mower tractor setup compared with field area (Hectares).

Crop Yield and Efficiency

Once the crop was mowed a wilting period was observed over a period of 24-48 hours. Prior to baling, the mowed crop was merged using a 6m central delivery rake. The mower operation is compared with the crop yield in Figure 5. Yield is quantified by the number of bales produced per hectare in each field. There is a no significant correlation between the yield and the time (R^2 = 27% in Figure 5(a)) taken per hectare or fuel (R^2 = 9% in Figure 5(b)) consumed per hectare while mowing a field.

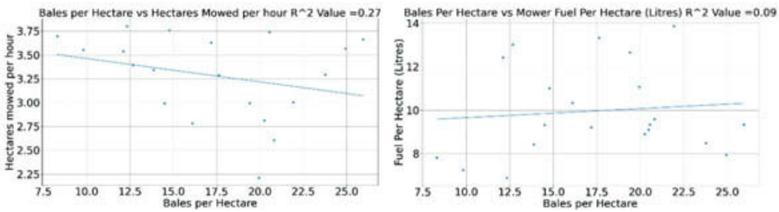

Fig. 5: Average hectares mowed per hour (a) and Fuel usage per Hectare (b) for each field compared with the number of bales per hectare for each field during bale harvesting from May to September 2019.

Conclusion

Sensor measurement data were acquired from a rear hitch-mounted mower machine throughout the 2019 silage harvesting season. The paper highlights the significant proportion of fuel and labour that is consumed while the mower is inactive. A method was derived to quantify the operating time of the mower while cutting crop, allowing for the temporal segmentation of the time-series recordings for mowing activity, inactivity and transport time. The results show that, for this study, over 24% of the contractor costs can be attributed to machinery transport. 71% of fuel, on average, is consumed while mowing crop in the field. Models highlight the significant correlation between field area and contractor expenses. Future work will examine the efficiency of a combi-baler operation and model development to better approximate fuel consumption using implement sensor measurements.

Acknowledgements

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Investigations of a cutter bar operated in resonance mode with an electric direct drive

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Abstract

Bar mowers are generally coupled with gearing mechanisms that convert a rotating power source into an oscillating movement. An alternative approach is to drive the cutter bar directly via a linear motor. In this approach, the kinetic energy of the system can be stored in springs. In order to reach optimal energy efficiency during operation, the system is then excited in natural frequency.

The concept and its characteristic properties are presented in this paper. A prototype has been created, the structure of which is explained. Furthermore, the control strategies designed for the system are briefly presented.

1. Introduction

Although bar mowers play a minor role in grass harvesting today, they have a number of advantages. Compared to rotary mowers they require much less drive power in relation to the working width and are lighter. The exact cut results in less contamination and also promotes the regrowth of the grass. Apart from this, their deployment is interesting for nature conservation purposes, as they are considered to be gentle on insects and micro-organisms due to the lower work intensity [1].

Bar mowers are usually driven by a rotating power source. In a gearing mechanism, the rotational movement is converted into linear oscillation. This conversion is also a source of loss.

An alternative approach to generating the required linear oscillation movement is to couple the cutter bar directly to a linear motor capable of generating an oscillating driving force. As electric motors have become stronger and more compact and the electrification of tractors and mobile machinery has progressed significantly, driving the cutter bar with an electric direct drive has become a viable approach to this function. Another aim of the project is to get to know the limits of the linear electric direct drives possible today.

This approach is being investigated as a partial aspect of a joint project looking into possibilities for the electrification of linear actuators of commercial vehicles. An electric linear motor has been optimized for operation with the bar mower. Above that, control strategies for the operation of such a mower were developed.

Finally, a prototype of the mower was built, which will be presented here.

2. Approach

A schematic representation of the cutter bar under consideration is shown in Figure 1. It is a cutter bar with stationary shear bar. The cutter bar is oscillatory driven with an approximately sinusoidal motion profile. For this purpose, the cutter bar is accelerated out of the end position. At the center of the stroke, the cutter bar reaches maximum speed. Subsequently, the cutter bar is slowed down until it comes to a stop at the opposite end position.

A major challenge with this system is the energy-efficient reversal of direction at the end of the stroke, in which the kinetic energy of the moving masses is temporarily stored during braking and fed back into the process during acceleration. With conventional gear mechanisms, kinetic energy can be stored in the continuously rotating part of the system. This is not possible with a purely oscillating mechanism. There are two possible solutions: the recovery of the braking power into the electrical circuit or the use of mechanical energy storage.

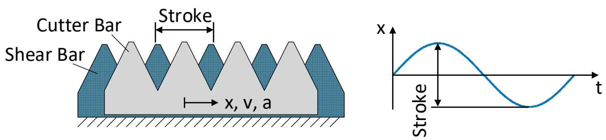

Fig. 1: Cutter bar schematics

In the approach considered here, the oscillating mass is coupled with compression springs. The result is a spring-mass oscillator with a characteristic natural frequency in which the system transmissibility is at a maximum. At this operating point, a required amplitude can be achieved with the lowest energy input.

3. Basic characteristics of the resulting system

The natural frequency of the spring-mass oscillator is determined by the moving mass of the system as well as by the spring stiffness. The damping in the system is also an influencing factor.

As the moving mass and spring stiffness are defined by the design, the natural frequency during operation of the cutter bar is only slightly influenced by the variation of the damping due to bearing and cutting forces. Since a required amplitude can only be achieved with a minimum amount of energy while the system is operated in its natural frequency, the operating frequency of this system is predefined during the development process.

The situation is different for the stroke of the mower. The stroke is necessarily variable, the operating amplitude is only reached when the oscillation builds up. In this system, a target amplitude for operation is specified, taking into account the geometric parameters of the blades and shear bar.

Thus, the considered system differs fundamentally from conventional rotary driven systems, in which the amplitude is geometrically determined by the gearing mechanism and the speed is often adaptively selectable.

4. Implementation

Complementary to its basic functionality, the design of the direct drive cutter bar is to be elaborated. In [2] and [3] experiments are described that laid the basis for the derivation of specifications for the force and power requirements of this mower. Due to their size, linear motors that meet these requirements cannot be placed directly on the cutter bar without significantly affecting the crop flow. Instead, the prototype arrangement shown in figure 2 was developed as a concept for the direct drive mower. The motor is positioned at a sufficient distance from the mower so that the crop can flow between the two components. The outer stator of the tubular linear motor is connected to the support structure of the mower deck. The motor shaft is led out of the stator on both sides. Compression springs, which are supported on both sides of the stator and which are arranged around the extended shaft, act as energy storage. The distance between the motor and the cutter bar is bridged by arms that connect the ends of the extended motor shaft on both sides with the cutter bar.

Fig. 2: Detailed prototype concept for the electric direct drive bar mower

The design of the arms is a compromise between strength and weight. Sufficient strength is required to ensure safe operation of the cutter bar. Aside from this, the mechanical structure of the cutter bar is subject to deformation due to the forces that occur. This elasticity can also influence the system response of the vibrating system.
For the mower unit, a commercially available system with linear guidance of the cutter bar is used. This system was slightly modified to allow coupling to the arms.
The selected mower unit has a 2 inch blade pitch. The system is intended for operation with a stroke slightly higher than the blade pitch. This coincides well with the characteristics of the electric motor, which has advantages in medium strokes and high speeds.

5. Control Strategies

In the case of rotatory driven bar mowers, the speed profile of the knives is determined by the transmission. Speed fluctuations of the drive can overlay this. In the presented directly driven mower, the speed profile can be influenced by the mower control. For the controls designed here a sinusoidal reference profile is specified. However, other speed profiles can also be implemented for an optimized cutting process.
In order to be able to implement this under field conditions with changing friction and cutting force influences, two control approaches were designed for this mower, which were presented in [4].
In the first approach, a position control system was set up with the aim of obtaining accurate control with fast reaction times. The controller is based on a super-twisting algorithm whose control parameters are adjusted via online optimization. Furthermore, the natural frequency of the system is determined by means of recursive least square estimation and the reference value input is adjusted.
In a second approach only the oscillation amplitude is controlled. Since the system responds to an excitation with a sinusoidal oscillation, the excitation amplitude is changed until the mower reaches its full stroke. Here, too, the reference frequency is optimized.
Both approaches showed good compliance with the reference amplitude in tests on a stationary test bench. The first approach is characterized by its fast reaction to deviations from the reference curve. It is expected that the controller will also be able to react quickly to disturbances in the field. The disadvantage is that in order to control the position, acceleration or braking is sometimes unnecessarily strong, which results in higher motor load and losses. This does not occur with the second approach, where a largely uniform sinusoidal excitation takes place. However, since the controller also reacts much more slowly to disturbances, the robustness under field conditions is still to be examined.

6. Field testing setup

The cutter bar is designed for operation on an implement carrier vehicle for municipal applications. The setup is shown in figure 3. The vehicle has an interface with lifting function in the front area, via which the mower is attached to the vehicle. The floating function of this interface also allows the mower to adapt to uneven ground. The power and control electronics for the test operation are located on the roof of the cabin for space and safety reasons. Since the carrier machine has a conventional drive with diesel engine, the electrified mover cannot be powered from the carrier machine in this setup. To provide the electrical energy for the test operation, a generator is attached to the rear of the machine.

Fig. 3: Cutter bar, control and test equipment mounted on implement carrier

7. Outlook

The presented concept will be tested in the field under realistic conditions. Hereby the basic functionality of the system shall be demonstrated. Next to that, the applicability of the developed control approaches under the changing conditions of field operation shall be examined. Special interest is also focused on the energy demand of this electrified implement.

8. Acknowledgements

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AEF Wireless In-Field Communication – Agrarian M2M communication for inter brand cooperative machine applications

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Abstract

Multi brand agricultural machine operation is a daily business for farmers, either in combination of tractor and implement or multi vehicle systems.

AEF is taking care to ensure interoperability of Machine-to-Implement communication. In this area ISOBUS as a standardized and established solution for wired based communication is available and widely used. Looking at real operations with multiple machines working in fleets, **M**achine-to-**M**achine and cloud-to-machine communication will address many needs, but standardized solutions for interoperable operation are not yet available on the market. AEF assigned the task of standardizing machine-to-machine communication to **P**roject **T**eam 11 to work out a guideline for an interoperable solution for **W**ireless **I**n-field **C**ommunication (WIC).

In the next few years WIC is likely to become an important part of an interoperable communication system to ensure safe, secure and private exchange of process and control data between agricultural machines worldwide. Establishing a solution based on existing radio standards and communication protocols from the C-ITS (Cooperative Intelligent Transportation Systems) ecosystem and providing a common middleware for less effort integration of WIC in communication modules will ensure a midterm availability of direct M2M communication for our customers. AEF also will take care to ensure availability of conformance test and diagnostic features as well as necessary infrastructure like Private Key Infrastructure for security measures.

In addition, participation in the C-ITS ecosystem will also enhance road safety by means of communication with other road users to increase the situation awareness.

Our Vision: Big picture and use cases

Communication is one key element to enhance efficiency in agricultural systems of systems. Today's widely used communication tools with human interaction (radio communication, messenger, pen & paper) will be soon complemented by direct M2M communication. Commercial solutions available so far are usually cloud-based, where all data is sent to a central server and then forwarded to the receiver. This works well for many use cases but suffers from limited cellular coverage (esp. in rural areas) and is not suitable for safety-relevant communication with strong requirements on latency.

Looking at a farming business several use cases with communication needs are observable:

PT11 collected several use cases and condensed them based on technical characteristics such as range, latency, data throughput to four main use cases.

	Process data exchange	Cooperative machines Platooning	Camera and remote terminal	Road safety
				
Range	High (2/6 km)	Low (up to 50 m)	Medium	High
Bandwidth	Medium	Low	High	Low
Latency	Average	Low	Low	Low
Relationship	n to m	1 to 1	1 to 1	n to m

Process data exchange

Working groups of cooperative machines have an intrinsic demand to share recorded work progress. This in particular includes communication of coverage data in order to avoid multiple operations on the same area and to consolidate the distributed work state into consistent application maps. A pre-condition for efficient cooperative work in the same field is the synchronization of guidance lines and coverage maps to optimize the field operation while bearing the equipment's working width in mind. For the use cases of this category, the range of the radio standard is the dominant factor. Since distances within a single field might span several kilometers in some regions, a long-range physical layer technology is desirable. A store-and-forward propagation approach for the process data might be required in order to synchronize equipment that is temporarily out of range. In order to allow for quick exchange of the medium-sized data packages, a transfer rate in the range of few Mbps is required. Latencies of a few seconds are tolerable. The network standard of choice should allow for one-to-many and many-to-many topologies. While sharing private data this must be protected against access and manipulation from third parties.

Table 1: Process data exchange characteristic

Range:	High (1 to 2 km)
Bandwidth:	Medium (up to 500 kBit/s)
Latency:	Average (up to seconds)
Relationship:	n to m

Cooperative machines / platooning

Use cases in the real-time control category include assistance systems for unloading grain during a harvesting process or cooperative machines joining pairwise in a leader-follower setup. These scenarios are concluded under the terms virtual drawbar or longitudinal and parallel platooning. Real-time exchange of control data is essential for these applications, which determines strict latency constraints and requires functional safety compliance. A short-range radio standard is required whereas the desired throughput is at least fairly above the data rate of a CAN bus.

Table 2: Cooperative machines characteristic

Range:	Low (up to 100 m)
Bandwidth:	Low (up to 500kBit/s)
Latency:	Low (<50ms)
Relationship:	1 to 1

Camera and remote terminal / high-volume data streaming

Specific use cases are based on the point-to-point transmission of continuous high-volume and low-latency data. This is a main characteristic of real-time video streams as they might be produced by a remote camera or a remote display session. Similarly, high-definition sensor information, which may include camera sources as well as other types of data, can be sent to a remote participant in the WIC working group for data analysis or processing. Ideally, these use cases are possible to be established via a medium-range radio technology.

Table 3: High volume data streaming characteristic

Range:	Medium (few 100 m)
Bandwidth:	High (up to 20Mbit/s)
Latency:	Low (<100ms)
Relationship:	1 to 1

Road Safety

Participation of agricultural equipment in C-ITS based road safety use cases is key to reduce the number of traffic accidents with agricultural machines since slow-moving vehicles increase the risk of sudden traffic jams and collisions. In addition, farm equipment entering or leaving public roads is related to the majority of accidents between agricultural machines and passenger cars.

Technical implementation

Due to the limited number of vehicles sold by the entire agricultural industry in comparison to the automotive domain or consumer electronics, it initially was not considered possible - and from an economical point of view not feasible - to define an agricultural-specific radio standard. Therefore, using an existing standard and if necessary extending it with additional functionalities remains a major objective of PT11 activities.

Based on the set of requirements gathered while analyzing the described use cases and the constraint of using existing technology the focus was directed to radio technology used in the comparable ecosystem of C-ITS. Based on investigations performed inside AEF PT11 IEEE 802.11 a/g/n/ac, IEEE 802.11p and Cellular-V2X (direct communication) could fulfill the majority of the requirements.

The findings of a more detailed examination of these technologies confirmed that Cellular-V2X is not sufficiently mature and available for direct communication besides limited tests. The higher performance announced for this standard remains unproven by now, especially in agricultural use cases.

IEEE 802.11p as a Wi-Fi based radio technology design for C-ITS use cases comes with a major downside as there is a limited bandwidth and regulation on duty cycles. Nevertheless it is a good fit for three of the four use case categories. and software are available from different suppliers and first car manufacturers have integrated the technology into their series production.

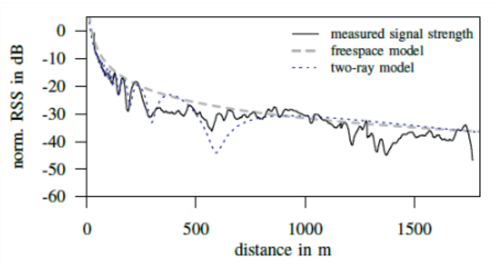
Based on our evaluation IEEE 802.11p is considered the most suitable and promising physical layer technology.

Field Test

To prove the feasibility of IEEE 802.11p based communication for agricultural use cases, the University of Paderborn and the company Autotalks performed a field test in Warendorf at the Deula facilities. Both parties equipped a forage harvester and a tractor with IEEE 802.11p radio equipment.

Range scenario

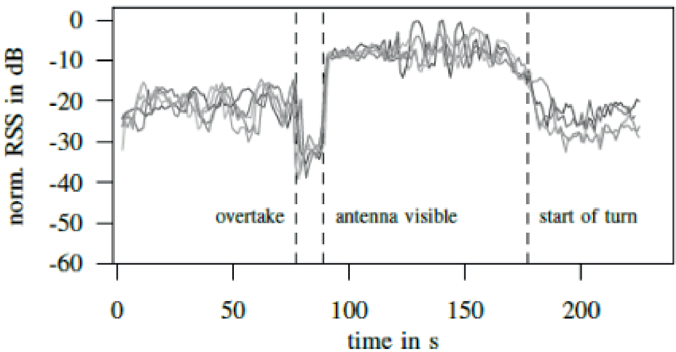
The tractor was placed statically on the road while the forage harvester started to move away continuously sending a test message. Signal strength and possible data throughput was measured at any time.



A range of 1700 m was reached without losing connection. Due to the limited road distance available for the test, it was not possible to determine the maximum communication range. Given the measured signal strength, a line of sight range of 2000 m seems to be feasible. Due to the fact that the test was performed on a narrow road with trees on both sides a longer communication range in a scenario on a large field without obstacles in the line of sight is expected.

Multi vehicle scenario

An unloading simulation from a forage harvester into a trailer was simulated while a second tractor approaches behind the first trailer. In this scenario the first trailer accelerated and the second tractor with trailer moved closer toward the forage harvester. Main goal was to gather information about the loss of signal strength due to the trailer in the line of sight.



As a result, by using IEEE 802.11p it was possible to continuously maintain a valid connection, even with a trailer between sender and receiver. Nevertheless, the loss in signal strength while obstructing the receiver behind the trailer is in the order of magnitude of the maximum allowed transmit power of a consumer Wi-Fi system in Europe.

Field-test results

In summary, IEEE 802.11p is a radio technology which provides a good tradeoff between range, data throughput and robustness. Major benefits are the infrastructure-less peer-to-peer communication topology. Based on these findings, IEEE 802.11p has been chosen the underlying physical layer for WIC.

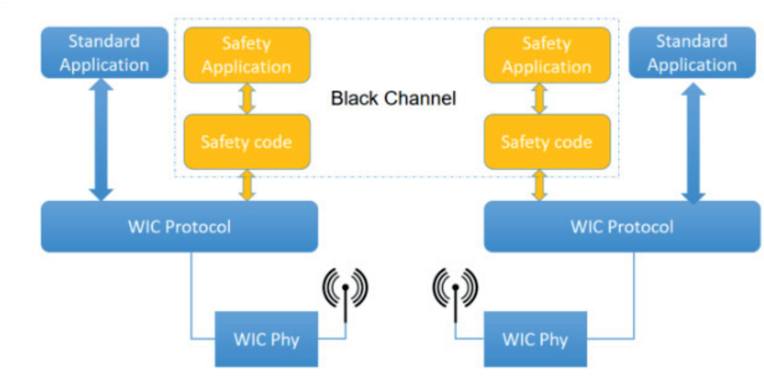
Technical implementation

Protocols

One objective of the project team is to maximize reuse of existing protocols in the C-ITS eco-system. So far it turned out that this standard, initially developed for the automotive realm, needs to be extended (e.g. to enable transport of coverage data) in order to be applied for agricultural use cases. Fundamental concepts of the communication scheme will be reused. The road safety use case even suggests a full adoption of the standard.

Functional Safety

Offering safe communication as a service is a major goal of the AEF activities. In collaboration with project team AEF PT02 Functional Safety, a communication architecture was developed to allow a reliable communication even with non-safety certified hardware.



Based on a black channel approach, safety requirements are primarily relevant for a limited area of the overall WIC system. By adding a heartbeat functionality, checksum and sequence number, safety code ensures that major parts of hard and software will be seen as an element outside the safety context. Finally, safe communication will not ensure overall safety compliance. It remains up to the individual company to ensure general product safety.

Security

PT11 is in collaboration with project team AEF PT13 Security to define a set of state-of-the-art security measures to ensure that no third party can access or manipulate data sent out by WIC.

Common software

In order to lower efforts for system integration, AEF PT11 is looking forward to offering a common middleware providing communication functionality to different applications. Including bespoken security and safety functionalities this common software could be used for individual as well as for brand independent communication.

Conclusions

Main goals of AEF PT11 are to offer a guideline and software for a convenient setup of M2M communication based on C-ITS standards. By including safety and security measures this technology will enable use cases where today's cloud-based approaches are not offering sufficient performance. In addition, road safety based on C-ITS will be in scope and will be beneficial to lower the risk of fatal accidents during road transport.

Industry 4.0 and Agriculture 4.0 – The same or different?

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Introduction

The terms Industry 4.0 and Agriculture 4.0 are currently frequently used in the public debate on the future development of the sectors. However, a closer analysis reveals, that both the content of the individual terms and their possible interrelationships are insufficiently clarified. In many cases, everyone associates their own image and imagination with them. This leads to the fact that although everyone uses the same term, very different ideas are associated with it. This is a very poor basis for a common orientation, which is what the pair of terms is intended to achieve.

A structure is to be created here within the framework of a VDI/VDE guideline committee on the topic of "Status of the use of Industry 4.0 - Technologies in Agricultural Engineering". The discussion covers several stages. It is based on the current understanding of the term Industry 4.0, with its structure and objectives. In the transition from Industry 4.0 to agriculture, the sectoral differences between industry and agriculture must be analysed in order to determine the direction of the degree of mechanisation. Based on this, the current status of structures of Industry 4.0 in agriculture in practice and theory will be presented using various examples from the arable and livestock farming. Altogether it is shown that in many cases a broadly coordinated understanding of the terms of the group concerned is necessary. Therefore, this contribution is also intended as a basis for discussion with the expert public in order to further develop the general understanding on this basis.

History of terms

The term "Industry 4.0" became widely known with the Hannover Fair 2013. It goes back to an initiative of the German Federal Government in 2011. To date there is still no binding definition of the concept Industry 4.0, but a generally accepted understanding is emerging. The term "Agriculture 4.0" has arisen to follow on from this. However, this term is even more difficult to grasp. Up to now, “Agriculture 4.0” is little more than a kind of promotional buzzword, claiming the most modern IT and production concepts and techniques for agriculture. Often, “Agriculture 4.0” is just a new coat, meaning digital techniques in agriculture and precision farming, like in Roland Berger Focus – Farming 4.0 [1]. In order to find a sound definition of “Agriculture 4.0” as a revolutionary stage of agricultural production, generations 1.0 to 3.0 of agriculture must be defined first, and then the revolution that lead to 4.0 must be described as a second step – if there is any revolution at all, justifying a new generation 4.0. Due to the lack of such historic clarification, the term “Agriculture 4.0” will be avoided in this work. Some authors already see an upcoming “Agriculture 5.0” at the horizon [2,3].

Understanding Industry 4.0

Over the last 270 years, industry has developed within the framework of so-called "industrial revolutions". The first industrial revolution began in the second half of the 18th century with the development of the steam engine. The second revolution took place towards the end of the 19th century, with the development of mass production and the use of electrical energy. In the second half of the 20th century, the third industrial revolution began, characterised by the automation of production using electronic and IT approaches.

Every industrial revolution involves a fundamental change in the production paradigm, made possible by the development of one or more technologies that trigger a fundamental change in established ideas and practices. However, their effects are not limited to production; they touch and influence the whole of society.

The current stage, caused by the fourth industrial revolution, is known as Industry 4.0. This differs from the third industrial revolution in that it focuses on the networking of the various automation modules.

Despite the current widespread use of the Industry 4.0 concept, it is difficult to find a clear definition. The term is best described by its components.

From a purely technical point of view, Industry 4.0 approaches can be summarised by the term networking. Instead of managing different machines, sensors, etc. individually as in the past, Industry 4.0 is based on cyber-physical systems (CPS), which can be flexibly connected and used; and on the equally flexible service-oriented architecture (SOA), which enables the use of the necessary software components. [4] This also improves the possibility of simulating processes, right up to the digital twin of the process. However, the networking and service-oriented character of Industry 4.0 goes beyond the boundaries of purely technical aspects and enables the design of new business models [5].

From this, the following implementation options [6] can be derived for the smart products and services to be offered by Industry 4.0:

Digital individualisation: digital media significantly simplify the offer of individualised products and services. This includes the entire production chain from the customer's request to its realisation.

Flexibilisation: Industry 4.0 allows, for example, the possibility to react quickly to fluctuations in demand by making production capacities more easily scalable (e.g. through smarter plants and simplified capacity procurement) and by providing more data about the environment and the company itself.

Demand-orientation/ "X-as a Service": service orientation is transferred to business models, which in turn is facilitated by increasing the amount of data and flexibility. This allows, for example, products and services to be offered and invoiced according to the extent of use.

Sustainability: by allowing better planning and control of production processes through digitisation, it is possible to save resources, for example through cost- and load-optimised production programmes for energy-intensive processes. Additional reductions in the demand for resources are possible through the availability of extended and near-real-time data from production and the supply chain; for example, through the early detection of quality problems.

Consistent process orientation: the networking capabilities enable each value-added stage in the supply chain (internal and external to the company) to call up information about the overall process. This allows for a customer and employee-oriented organisation of work.

Automated knowledge and learning: increasing the amount of data and the level of automation in Industry 4.0 environments prove to be ideal conditions for using self-learning functionalities. The data can come from beyond the company's boundaries, for example, through IoT approaches. In addition, the systems concerned enable extended and simplified knowledge management in companies.

Collaboration competence: in line with end-to-end process optimisation, Industry 4.0 approaches reduce the collaboration effort between value-added partners. For example, it is possible to know the current stock and available capacity of suppliers.

Productivity optimisation: all the above implementation options contribute to an increase in productivity. Optimisation options can be found at various levels, from the strategic orientation of the company to the operational management of production processes.

Although these implementation options have been analysed for the machinery and equipment sector, the benefits identified are also relevant for agriculture. However, the implementation of a highly flexible and distributed architecture is not without challenges. The desired fast connection in the production chain also requires a corresponding data exchange. However, this requires appropriate standardisation or standardised interfaces and data formats between components from different manufacturers.

The processing and storage of data on distributed systems, often outside the company, raises concern about data security. For this purpose, both software-based and methodical approaches are being developed. While the former are based on novel security applications and protocols, the latter focus on topics such as intelligent data control and anonymisation. The analysis of the definition of the term Industry 4.0 shows that this definition is still under development and discussion.

Industry 4.0 approaches in agriculture

When transferring the definition of Industry 4.0 to agriculture, it quickly becomes clear that agriculture is still characterised by additional aspects. Here, the environmental character of agriculture, which includes not only society and government but also nature, the environment, people, farm animals and the weather to a high degree, is particularly striking. The organisation of work is also structured differently in agriculture than in industry. This shows that the socio-economic, technical and ecological systems in agriculture are much more closely interwoven, making it more difficult to define the term Agriculture 4.0 in comparison with industry.

In order to explain the current status of Industry 4.0 approaches in agriculture, therefore, examples from arable and livestock farming are used and a differentiation and possibility of description is created on the basis of technology levels.

Exemplary example from foreign trade: steering systems

Steering systems started in the 2000s as simple local systems, which, for example, steered a forage harvester along the rows of maize using mechanical deflection sensors in row crop. The first tractors were kept on a given track by GNSS.

In recent years, these systems have been developed with great innovative power. Digital customisation is achieved by taking into account a specific implement, so that the working width of the implement is automatically taken into account for the track guidance via ISOBUS and the collaboration between implement and tractor.

Flexibilisation is achieved through standardisation. A steering system can now be mounted from a tractor to a self-propelled-machine or other tractor within minutes.

Demand-orientation is gaining ground through new business models. A "steering system as a service" does not yet exist at present, but the software activations, such as correction signals

(RTK for 2 cm accuracy and long-term repeatability), which are subject to a charge, are only sold and invoiced if required.

Sustainability is the top priority when using a steering system. The working width of the machine is used optimally, double crossings are avoided and fuel and CO2 savings are achieved through optimal driving.

Automated knowledge and learning is currently not applied to the steering system. Only databases with lanes are built up, which can be used for subsequent processes. Automated learning does not take place at present, but is in preparation with teach-in procedures and intelligent lane planning systems. Lane planning systems will in future be supplied with field boundaries and the planned work process and the lane planning system will determine a proposed course of action for working the field in a self-learning manner and on the basis of collected experience values.

Steering systems are increasingly being given collaborative competencies. On the one hand, the correction signals are now often obtained via mobile phone from external service providers. In addition, steering systems are networked with each other, e.g. in order to exchange track lines or, by means of an electronic tiller, e.g. to automate overloading processes.

Productivity optimisation is the main objective when using steering systems. Due to the optimum use of the working width saves machining time and fuel. The crop yield is increased by minimising soil compaction.

This means that modern GNSS and online-based guidance systems fulfil a variety of features that make up Industry 4.0. In the coming years, these systems will be further developed and make an important contribution to the increasing automation requirements of farmers and contractors.

Exemplary example from the livestock farming: automatic milking system

Automatic Milking Systems (AMS) have been in use since the 1990s. Here the individual process steps of milking are automated. These include recognising the cow via a sensor, cleaning the udder, recognising and targeting the cluster to the individual teats of the cow, flow-controlled milking of the cow, removing the cluster and dipping the cow. The basic structure of the processing of individual process steps of AMS is basically comparable to machine tools in the Industry 3.0 sector.

In the field of digital individualisation, the AMS has started to work on both cow and product milk. For example, the alignment of the animals in the AMS is partly based on the stored body measurements. Another possibility here would be quarter-individual milking in terms of milking phase duration and milking vacuum depending on the animal's previous notification. In the case of milk, the approach is to separate the milk individually according to animal and ingredient to enable individual marketing.

Flexibility is difficult to implement in the AMS due to the workload and continuous use. A possible approach here could be the AMS container, which accompanies the cows to the alpine pasture in the case of alpine pastures and returns to the barn in autumn.

In the field of automated knowledge and learning, the AMS offers great potential, as animal-specific data series are continuously generated. However, these data are not yet used consistently in the sense of Industry 4.0. The situation is similar with collaboration competence. Here, networking various automatic systems in the barn would result in many approaches for Industry 4.0. For example, a measured change in the milk quantity could lead to an automatic adjustment of the feed quantity. This intelligent linking of different automated systems also makes it possible to optimise productivity, which at the same time can lead to a change in the farmer's work structure in the system.

Overall, AMS offers great potential for Industry 4.0 approaches. The possibilities are partly considered, but not yet stringently implemented.

Discussion

When analysing Industry 4.0 applications in agriculture, it is striking that although much initially looks like 4.0, on closer analysis decisive aspects such as networking across sectors or individualisation and flexibilisation of production are missing. These technical solutions are therefore more likely to be classified as automated isolated applications of Industry 3.0.

Another aspect that is often shown is the gap between practical implementation and technologically possible realisation. An example of this is TIM for balers and tractors. Here implementation is slow although, with regard to Industry 4.0 approaches, other aspects such as lane transfer from the previous implement, e.g. combine harvester or swather, performance planning based on the power requirements of the combine organs or logistics planning based on yield estimates would be possible. Also in indoor farming, e.g. quarter individual milking based on past milking cycles or route optimisation of column robots according to the current movement data of the cows would correspond to the basic idea of Industry 4.0.

In many cases, these technological developments would only require appropriate adjustments and coordination. However, this requires a manufacturer-independent will, which is often hindered by company-specific interests. It is very clear that without networking across different manufacturers no application of Industry 4.0 in agriculture is possible, only the automation of individual machines.

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New INFO feature under AEF development

Is the potential for a new and independent ISOBUS Functionality given?

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Abstract

ISOBUS, after more than 20 years of history, is synonymous for a functional, CAN-bus based infrastructure that enables cross-manufacturer tractor implement control and is standardized in ISO under project number ISO 11783 in various parts and versions. Known functions include e.g. the Virtual Terminal (VT), the AUX control (AUX), the Task Controller (TC) or the Working Set Master (WSM), which represents the functional remote station on the implement side.

Over 10 years ago, various manufacturers came together and founded the AEF (Agricultural Industry Electronics Foundation) to give the ISOBUS development a boost and to improve the quality of ISOBUS implementations. Since the foundation of the AEF in 2008, the further technical development, as a preliminary stage of the ISO standardization, as well as the improvement of the technical validation in the form of a common conformance test (CT), has been the focus of the development activities. The youngest child of this development is surely the multi-vendor Tractor Implement Management (TIM) in version 1.0, which can be certified by the test laboratories involved in the conformity process since the end of 2019 with the release of the associated CT. However, there is a number of further projects in the AEF. These include e.g. High-Speed-ISOBUS (HSI), the next generation ISOBUS infrastructure based on ethernet or Wireless-Infield-Communication (WIC), for wireless communication between ISOBUS systems. All of the functionalities that have already been introduced, as well as the new AEF projects mentioned, also show that the complexity and networking of the systems will increase significantly in the next few years.

That was also the reason why the AEF Project Team 04 Service & Diagnostics dealt intensively with how these increasing complex systems can be controlled by the various process participants in the future in the field. To the process participants belong the owners or drivers, the service experts of dealers and the machine manufacturer, and not to forget the sales experts

of the dealers and manufacturer. In addition to the AEF quality activities around the CT and the provision of jointly developed training documents and web-based training, it is important for the AEF PT04 experts to provide the various user groups the tools they need to have sufficient transparency about the expected, combined functions of an ISOBUS system, with all its functionalities and options. It is also important to indicate the necessary service information to the respective user as early as possible in the process, to save this if necessary, so that it can be exchanged between the manufacturers involved. The discussion on improving system transparency brought into the AEF by PT04 has now progressed so far that the official project work began at the end of 2019 with the aim of developing an INFO Functionality that meets the mentioned requirements.

This manuscript and the lecture on the INFO Functionality gives an overview of the motivation and introduces the intended functions and their possible application. The lecture ends with the presentation of the project plan including status and the question:

"Is the potential for a new and independent visible ISOBUS functionality given?"

Use-Cases (Motivation)

In the life of an ISOBUS machine, different people come into contact with it again and again and need corresponding information about the concrete characteristics or the current status of the individual device or the entire system network for their respective use case.

Examples are:

Use-Case "Service" (to solve issues: something is not working like expected, …)

- Operator/Customer

  Requires detailed information about the system (on-board)

  - Which ISOBUS functionalities and options are available in a combined system and can be used?
  - Are there any problems? DTCs?
  - …
- Dealer/Manufacturer (Service)

  1) – Contact with the operator/customer by call –

  Requires detailed information about the system (on-board)

- Which ISOBUS functionalities and options are available in a combined system and can be used?
- Are there any problems? DTCs?
- Is the ISOBUS running?
- What are the software versions?
- …

2) – Contact with customer, face to face at the machine –
Requires detailed information about the system (on-/ or off-board)
- Which ISOBUS functionalities and options are available in a combined system and can be used?
- Are there any problems? DTCs?
- Is the ISOBUS running?
- Which manufacturers are involved?
- What are the software versions?
- …

Use-Case “Sales” (change of the system: new or other product, new features, …)

- Operator/Customer
  Requires detailed information about the system (on-board)
  - Which AEF functionalities and options are available in the existing machines and are compatible with a needed/new device?
  - Is it possible to get a functional update (software) or feature activation for the existing system to be able to use all advertised features of the device offered?
  - …
- Dealer/Manufacturer (Sales)
  Requires detailed information about the system (on-board)
  - Which ISOBUS functionalities and options are available in the existing machines and are compatible with the device offered?
  - Is it possible to get a functional update (software) or feature activation for the existing system to be able to use all advertised features of the device offered?
  - …

The INFO Functionality

In order to provide the different users with necessary information about an existing ISOBUS system for their use case, unfortunately, right now there are no uniform, not even standardized, but only manufacturer-specific, proprietary solutions.

The necessary on-board presentation of the information of an ISOBUS system is so far mostly done by visualizing of window and alarm masks on an ISOBUS UT (Universal Terminal), or in the case of the tractor or ISOBUS terminal manufacturers via proprietary software solutions directly on the tractor or ISOBUS terminals (Fig. 1). Most of the larger manufacturers also use off-board PC tools (e.g. in the service), which require a special vehicle communication interface (VCI) to read out the necessary system information from the ISOBUS.

However, all these proprietary manufacturer solutions, as good as they may already be in detail for their own manufacturer use cases, have in common that the visualized information is not uniform and possibly already existing export formats are manufacturer-specific and therefore not or only very limitedly suitable for the necessary system and manufacturer-spanning information exchange.

This topic is not new for the AEF. Some years ago, the topic of system transparency and standardized information exchange has already been addressed. The result was and still is the proven and continuously developed AEF ISOBUS Database, as well as the AEF Check-Tool, which for various reasons has not found the expected distribution.

This is where the current AEF INFO project comes in again. Extensive discussions in the AEF have shown that the following two core requirements must be implemented to enable the various use cases and thus improve system transparency:

Req. 1

In future, it shall be on-board possible to display a standardized basic set of information about a concrete ISOBUS system to the user.

Req. 2

In future, a standardised exchange of ISOBUS system information across machine and tool manufacturer boundaries shall be ensured.

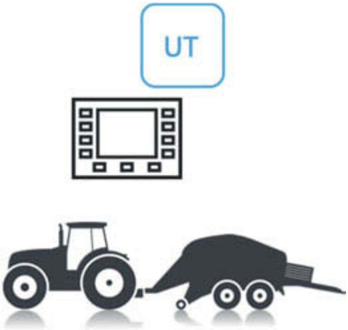

Fig. 1: Terminal with ISOBUS UT

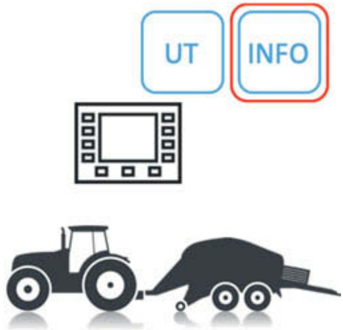

Fig. 2: On-board INFO Functionality

The planned INFO Functionality will provide a technical response to these two basic requirements.

With the INFO Functionality (Server), e.g. as an additional software module on an ISOBUS terminal, parallel to the UT Functionality (Fig. 2), the following shall be possible on-board in the future:

- Presentation of ISOBUS functionalities and options (Req. 1)
- Generation of a digital system description (SYSTEM-XML) (Req. 2)
- Presentation of products, ECUs and CFs with its hard- and software (Req. 1)
- Presentation of AEF certifications (and components without certifications) (Req. 1)
- Presentation of diagnostic trouble codes (DTCs) (Req. 1)
- Presentation of ISOBUS network status (Req. 1)
- …

The generation of a digital system description in the form of an XML file (SYSTEM.XML) certainly represents the core functions of the new INFO Functionality. With this file, in which a system is described as a digital twin with regard to its ISOBUS capabilities, it is then possible, thanks to standardization, to exchange ISOBUS system information across system and manufacturer boundaries and to use it for a variety of known and future applications.

The discussion in the coming weeks and months will show which of the individual functions shall be mandatory and which can be optional in order to obtain the corresponding AEF certification for the "server" side INFO Functionality. In principle, the "client" side already exists today and is described by the "minimum control function” functionality, whose requirements are already met by all units active on the ISOBUS and AEF certified. But here too, future enlargement is entirely conceivable.

But what are the application possibilities of the INFO Functionality in detail? Here is an example.

Example: Tractor-Implement combination (Fig. 3)

Fig. 3: AEF certified ISOBUS system [1]

For the user, the following can be seen from the outside with his eyes:

1. Tractor from CASE
2. Square baler from KRONE (Implement)
3. ISOBUS terminal in the cab from CCI

But what are the combined ISOBUS functionalities and options of each individual device? So far, this is hardly accessible to the user, and certainly not in a reliably available, uniform, manufacturer-spanning form.
With the new INFO Functionality this will change, and the user can rely on the fact that e.g. the ISOBUS functionalities can be displayed if the INFO Functionality is available in the system (Fig. 4).

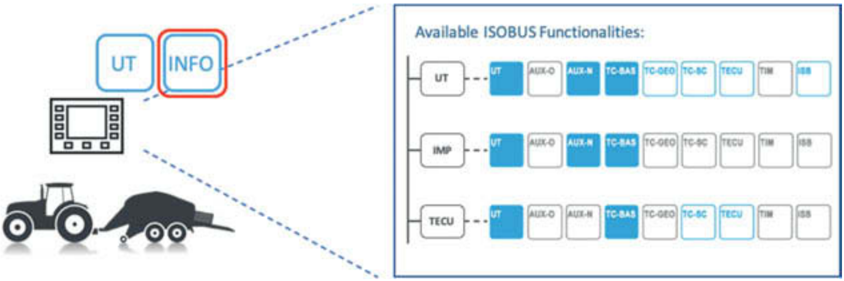

Fig. 4: On-board presentation of ISOBUS Functionalities

The user can now see exactly which different functionalities are available per device, and that in this example the UT, AUX-N and TC-BAS functions can be used in the system. For the other functions the appropriate counterpart, the corresponding client functionality, is missing.

If the customer now makes a service request to his dealer by telephone, the dealer service expert can ask the customer with the knowledge of the standardized information of an INFO Functionality directly for the necessary information about the current system in order to get his own picture of the system.

With the new SYSTEM.XML it is now for the first time also possible to provide the necessary system information directly in digital form, e.g. as an attachment in an e-mail or online service request (Fig. 5).

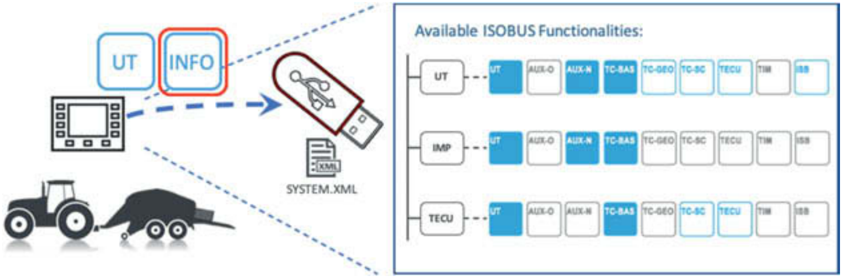

Fig. 5: On-board generation of SYSTEM.XML file

This was previously not possible and usually required a personal visit on site with special tools, which in many cases meant an unnecessary loss of time and money for the customer until the machines could be used again.

Fig. 6: SYSTEM.XML upload to the AEF database [2]

The AEF database is one example/tool for the use of the standardised exchange format for system information across manufacturers. In future, it will be possible to upload the new SYSTEM.XML into this database (Fig. 6) to display further more detailed information of an ISOBUS system, to find out about newly available function updates or, in the case of a planned new purchase, to check the compatibility of the desired device (e.g. implement) with the existing system (e.g. tractor with UT, AUX and TC).
In addition to the INFO on-board solution shown as an example, there will be further possibilities in the future. For example, off-board tools connected to an ISOBUS system via a VCI (Vehicle Communication Interface) can carry the INFO Functionality and could be certified accordingly by AEF (Fig. 7).

Fig. 7: Off-board INFO Functionality

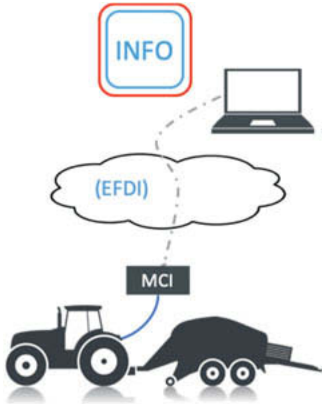

Fig. 8: Remote INFO Functionality

A further development stage will be the INFO Functionality as a remote solution (Fig. 8). In this case the necessary information is collected via an MCI (Mobile Communication Interface) and transferred to the user's application via a cloud-based exchange platform.

Summery and next steps

The presented INFO Functionality offers many new possibilities and should help to create the necessary transparency for a better understanding of the system by the different users in the face of a constantly increasing range of ISOBUS functions and the associated system complexity. Be it for the operator/owner or for the service and sales staff of the dealers and manufacturers.

The AEF Project is the result of numerous expert discussions and was officially released in late 2019. The preparation phase has been completed and the actual project work began in October with the entry in the definition phase. If the development proceeds as planned (Fig. 9), the INFO Functionality can be implemented and certified by the manufacturers by mid 2023 at the latest.

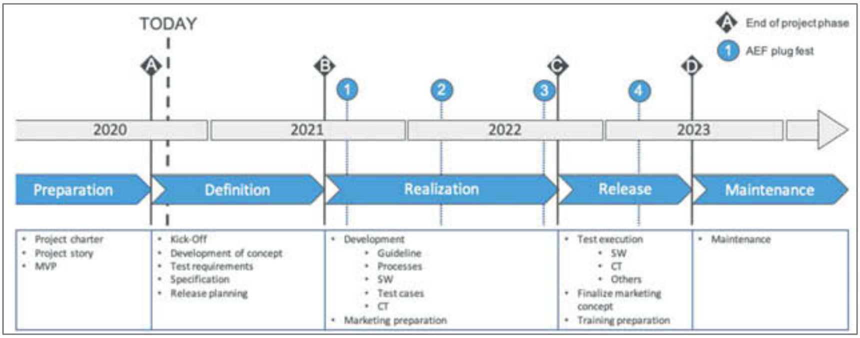

Fig. 9: Current time schedule

But much remains to be done before then. Development content on side of the AEF will be the specification (AEF guideline) of the actual INFO Functionality, the development of the associated conformance test, as well as the adaptation of the AEF database to the new SYSTEM.XML. In addition, the project will also examine whether jointly developed software libraries can support the implementation of the manufacturers.

And now the final question:
Is the potential for a new and independent ISOBUS functionality, with its own visible functionality logo given?

A) YES, the potential is given, and the INFO Functionality should become its own functionality logo.

B) NO, the INFO Functionality should be a hidden feature without its own functionality logo.

We as AEF PT 04 Service & Diagnostics say YES, the potential is given. The functionality should become an official ISOBUS functionality with its own function logo to make the availability visible for all users!

[1] KRONE homepage (www.krone.de)
[2] AEF ISOBUS database (www.aef-isobus-database.org)

Integration of a crop moisture sensor in a combine harvester in order to improve the automatic machine adjustment

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Abstract

In order to improve the automatic straw chopper adjustment of combine harvesters, the moisture of the whole crop, including straw and ear, is a very important factor. Current state of the art is a manual adjustment of the machine parameters according to each change of these surrounding conditions. In practice, this is established as a manual adaption once or twice a day, for example with every change of crop or field. Therefore, a correct setting depends on whether the driver can estimate the crop moisture and the straw condition in every single situation.

The solution presented here shows how an industrially used planar sensor system is adapted for crop moisture detection. The lines of electric flux of a high frequency stray field permeate the material in front of a capacitive sensor. This material takes effect as a moisture dependent dielectric, which directly influences the capacitor. By interpreting the capacitance, the amount of water inside the measuring range can be captured.

For the depicted use case, a sensor has to be customized under several aspects. It has to be resistant and robust against wearout and other ambient conditions. Considering the measuring principle, several calibration models of different crop varieties have to be calculated by regression analysis. For this purpose, plenty of samples with various degrees of moisture have to be examined by gravimetric analysis.

With this sensor, the combine harvester is able to control the counter knifes and the friction bar of the straw chopper automatically by taking the straw load, the straw moisture and the predefined chopping strategy into account. As a result, energy can be saved and the chopping and spreading pattern is significantly improved.

Motivation

The main purpose of a crop moisture sensor inside a combine harvester is to assist the driver to estimate and adjust the machine settings according to the actual crop conditions. The system relieves the driver from looking after varying crop conditions in constant intervals several times during the day. With the crop moisture sensor analysing these changes permanently, a distinct improvement of the automatic chopper adjustment is realized. Positive side effects and slight increase in comfort and reliability for other automatic machine adjustments also come along with it. The most obvious additional benefit of the sensor is the possibility to visualise the crop moisture for the driver permanently on the machine terminal in order to give a better feedback about the surrounding field conditions.

Measuring principle

For measuring the moisture inside a material, different measuring principles can be utilized. A common example is the conductive principle, which is based on measuring the electric current from one electrode to the second one through the analysed material [1]. Another one is the microwave measuring principle that allows to detect the moisture by analysing the offset in wavelength between radiated and received waves, caused by the permeated material [2]. Based on the absorption of specific wavelengths the near infrared spectroscopy allows the detection of the percentage of water in the sample [3].

The capacitive measuring principle utilizes the impact a dielectric medium has on a capacitor. The analysed material contains a certain amount of water that influences the permittivity and with it the capacitance of the capacitor [4].

Considering the cost and benefit of the system, the contactless capacitive measuring principle was chosen for the crop moisture measurement on the combine harvester. Because of the measurement being independent of the density of the material, some other methods would be more precise technically, but also a lot more expensive. For this use case the chosen principle is the best suitable one. It is functional and affordable.

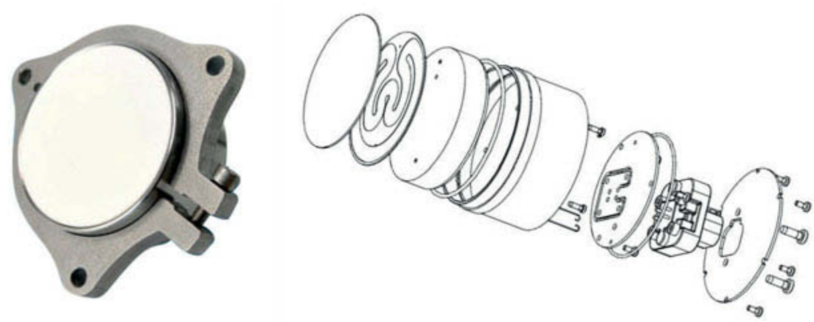

Fig. 1: Design of the sensor hardware

The used sensor hardware and its design is shown in the figure above. A stray field capacitor permeates the measuring range and the material inside with a high frequency field. The field is built up between an inner and an outer annular plate. The electronic processing unit provides information about the sensor state, internal temperatures and the measuring signal in raw and filtered quality.

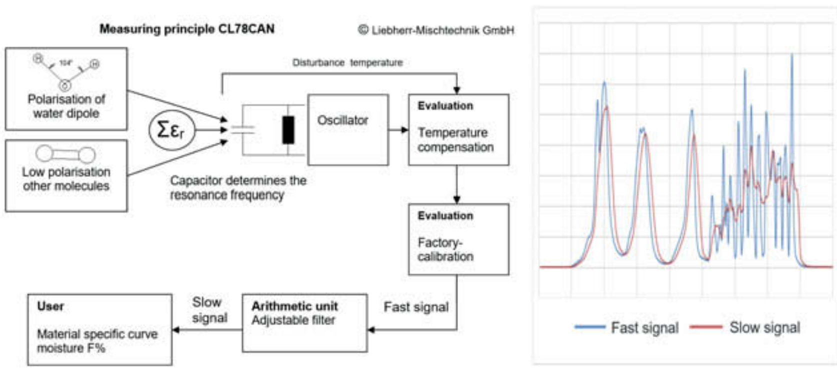

Fig. 2: Signal processing of the capacitive sensor

A basic requirement for a reliable result with this measuring principle is, that the measuring area has to be filled with the material completely. Leaving parts of this area empty would cause disturbances and incorrect measurement values, because the permittivity of air and the one of crop material differs a lot. To avoid such errors, the crop moisture measurement is connected to the existing throughput measurement of the machines. This ensures a minimum layer thickness in front of the capacitive sensor and a fully filled measuring range up to the maximum penetration depth.

Machine integration

For reliable measurement results even with minimum throughput the sensor has to be positioned directly facing into a continuous and steady material flow. The optimal positon which fulfils these requirements, can be found at the front of the machine inside the feeder house. Here the whole cut plants are transported in a smooth layer of material from the header to the threshing aggregates by a chain conveyor. To withstand the permanent direct contact to the material, the sensor is covered by a ceramic plate on the front, which is strongly resistant against wearout.

A second very important impact of this measuring position is that the sensors for the throughput are located in the exact same place. This brings the advantage, that there are no time shifts or delay times, which have to be calculated and have to be considered depending on the individual material speed. Both signals can be related to each other directly.

Fig. 3: Sensor position underneath the feeder house at the front of the machine

Calibration

The output of the sensor consists of a filtered signal corresponding with the moisture of the material in the measuring range in front of the sensor. The signal provides a value from a minimum of 10.000 units with no material and no moisture in front of the sensor up to the maximum of 350.000 units for waterlogged material. By a calibration curve the real actual moisture is calculated out of the sensor signal.

For generating this calibration curve, a large number of material samples of varying moisture has to be collected and analysed. All samples are directly extracted out of the throughput of the machine and a timestamp in the Can Bus signal is generated. Thereby the exact sensor values at that time can be referred to the collected sample.

In order to generate a useable raw signal a few preparations have to be done. A general time shift is integrated, because the measuring position and the sample extraction are not in the same spot of the machine. The duration of the time shift depends on the distance between both spots and on the transport speed of the material inside the combine harvester. Another necessary preparation results out of the fact, that every sample consists of crop material, which is collected during a period of several seconds. Because of that, not the exact sensor value in the moment of triggering a new sample, but the mean value over the time period of sampling is calculated and saved. Every material sample then has to be dried and weighed before and afterwards to find out the effective included amount of water and the real moisture of the analysed material.

This way with every sample a measured value can be assigned to a certain crop moisture. Obvious anomalies or implausible measuring points, which can result out of material losses or other mistakes during the handling of the samples, have to be sorted out, before the calibration is calculated. Another reason for discarding a sample can be extremely varying crop conditions during the time period of its collection.

The exemplary depicted calibration curve is based on samples of the varieties barley, wheat and rape. It is useable for the named crops and other special breeds of these. Also almost similar crops like rye, oats, triticale, canola and spelt work with this calibration model.

Separate calibration models are needed in order to support further crops. One additional model is designated for beans like soy and another one for corn.

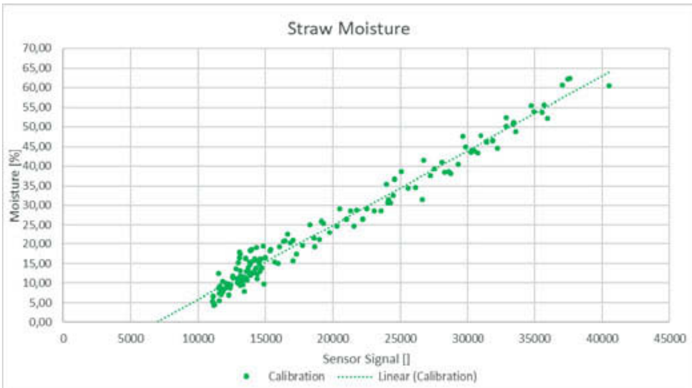

Fig. 4: Exemplary calibration curve for grain and rape breeds

Visualisation and machine automation

It is common to keep the operator of a combine harvester permanently informed about the grain moisture. With the new system additionally the information about the percentage of moisture inside the complete harvested crop is available in the machine silhouette on the touch screen terminal on the first view.

Fig. 5: Visualisation of the straw moisture value on the machine control terminal

On top of that the information of the crop moisture is used to adjust the straw chopper automatically. To achieve a constantly high and steady chopping quality, the counter knives and the friction bar can be controlled by this automation. Therefore the measured moisture is classified in the states dry, normal or wet. Changes in the actual crop moisture class or the current straw load make specific reactions of the mechanical settings of the chopper necessary. The automatic chopping adjustment actuates these adaptions. In order to incorporate individual requirements e. g. based on the special harvesting conditions, the driver can predefine a chopping strategy, which also affects the settings of the chopper. With the chopping strategy a higher valuation can be put either on the chopping accuracy or on the optimisation of the fuel consumption of the machine.

Taking into account the complete Claas Electronic Machine Optimisation System, the crop moisture sensor is an important component with a wide impact on the whole process inside the machine. This can contribute to the improvement of the fine tuning adjustment and the ease of use of several automation systems used on a combine harvester.

Summary

In conclusion the crop moisture sensor provides a permanent support for the machine operator. By this relieve the focus can be laid on other observation or adjusting tasks while driving a combine harvester. By choosing a chopping strategy the machine controls all necessary settings automatically in order to realise the optimal processing of the crop residuals, depending on weather a high chopping accuracy or a high machine efficiency is preferred. Further the continuous information about the crop moisture can be used for the settings on other aggregates working inside a combine harvester and on top of that to inform the machine operator about the actual surrounding conditions.

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Determination of grain losses and broken grains

Comparison of measuring methods and methods of result representation of lossthroughput- characteristics and broken grains at combine harvester benchmark tests

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Abstract

The performance of a combine harvester is determined internationally by the loss-throughput behaviour. A conflict within measuring methods and methods of result representation of loss-throughput-characteristics and broken grains exists in the ratio of result to effort. Within a benchmark-test, carried out by the German Agricultural Society (DLG), the DLG-rethreshing-system and pan method for total grain loss determination were compared. The results show the suitability of the pan method for total grain loss determination. Results of both methods correlate strongly with 93.8 % (R^2=0.853). On average, the DLG rethreshing-system increases total grain loss by 0.3 % compared to the pan method. The results of the pan method are lower since the pan method did not include the measuring of the threshing losses. If threshing losses are taken into account, both methods correlate very strongly, significantly with 94.5 % (R^2=0.868) and differ on average by 0.1 % in the total grain loss determination. If only total grain losses are relevant, the use of the pan method is recommended – less cost and time-intensive. However, to take account of threshing losses, loss samples by the pan method should be rethreshed. A representation of confidence intervals increases the information value of loss-throughput characteristics. A statistically secured comparison of combine harvesters is possible. Determination of broken- and husked grains was carried out by hand grading and sieve method. Both methods correlate weak when determining broken grains with 23.3 % (R^2=0.001) and correlate very strong with 83.7 % (R^2=0.215) by the determination of husked grains. The hand grading method is inevitable for the determination of broken grains and impurities such as husked grains.

1 Introduction

The performance and the resulting utility value of a combine harvester are determined internationally by the loss-throughput behaviour [1]. The handling of broken grain and impurities also has a direct influence on performance. To determine combine performance in field tests, re-threshing methods are used in addition to the pan method. For the determination of broken grain and impurities, grain tank samples are manually evaluated. A conflict within these tests occurs in the ratio of result to effort. This must be taken into account when selecting the test methods [2].

The pan method is an established method for determining total grain losses (TGL). Test results obtained with this method date back to the early seventies [3]. The pan method has been confirmed by the German Agricultural Society (DLG) as a sufficient method for determining TGL [2]. In earlier studies, however, the loss level of straw walkers combines varied in long waves, i.e. 1 to 3 m long straw swath sections [4]. It is not necessary to modify the combine harvester when utilizing the pan method for testing [5].

As a representative of exact measurement, the DLG re-threshing system is capable of differentiating grain losses by loss sources [6]. Grain losses are differentiated into separation-, cleaning- and threshing-losses. These can be presented and totalled to TGL over the MOG or grain throughput in separate loss-throughput curves. The DLG's re-threshing system consists of a pre-shaker and rethresher, as well as other measuring devices on the tested combine harvesters [7]. The measurement of the loss-throughput behaviour by using a rethresher is costly and time-consuming compared to the pan method [2].

Determination of broken grains and impurities by hand grading is criticized due to the time required and the subjective determination. The sieve method offers an alternative. However, studies show that the sieving method does not provide reliable results [8].

Within the framework of a combine harvester benchmark test, the results of the pan method and the DLG re-threshing system for TGL determination as well as the grain quality analysis by hand grading and by sieve method were compared.

2 Material and Methods

TGL were determined using the pan method in parallel with the DLG re-threshing system in winter wheat during swathing. Up to seven measuring points were carried out to generate a loss-throughput curve. The surface area of the loss pans used was 105 x 54.5 cm with an angled edge of 45 degrees. The total pan area was 0.57 m². Four pans were placed in succession, centred under the combine harvester, between the front and rear axle. The total sampling area is therefore 2.28 m² per measuring point. With the DLG-rethresher, grain losses were recorded differentiated over a distance of 17.0 m and a width of 2.8 m, totalling 47.6 m² sampling area. Separation-, cleaning- and threshing-losses were totalled to TGL.

The impurities of 85 grain tank samples were determined by hand grading and by the sieve method. Both methods used the same grain tank samples. For the analysis of the grain tank samples by hand grading, samples of 100 g [2] each were weighed in and the percentage of broken and husked grains were determined. For the analysis via sieve method, a sample of 300 g, was shaken for 15 s in a sieve box. Both husked grains (> 3.5 mm) and broken grains (< 2.0 mm, > 1.0 mm) were determined [8].

3 Results of the method comparisons

The results of the DLG-rethresher and the pan method correlate significantly (method Spearman), very strongly with 93.8 % (R^2=0.853) (Fig. 1). On average, the re-threshing method increases the TGL by 0.3 % compared to the pan method. In 95 % of the cases, the deviations are between +1.4 % and -0.8 % (Fig. 2). The mean coefficient of variation of the pan method is 32.5 %. The results obtained by the pan method are on average 0.2 % lower than those obtained by the re-threshing method since the pan method did not include re-threshing of the loss samples and therefore no threshing losses were measured.

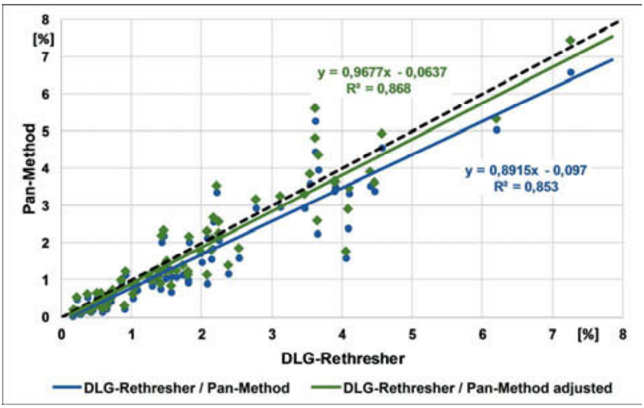

Fig. 1: Correlation of the results of re-threshing method and pan method in the determination of total grain loss

Adjusting the results of the pan method by the threshing losses determined by the DLG-rethresher (Fig. 1), both methods correlate very strongly (method Spearman), significantly with 94.5 % (R^2=0.868). The mean difference is 0.1 %, with deviations of +1.2 % and -1.0 % in 95 % of all cases (Fig. 2).

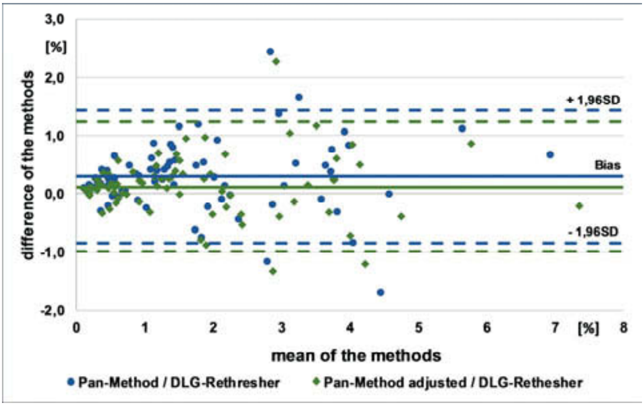

Fig. 2: Difference of the results of re-threshing method and pan method in the determination of total grain losses

When determining broken grains, hand grading and the sieve method show a significant, weak correlation (method Spearman) of 23.3 % (R^2=0.001). On average, hand grading increases the percentage of broken grains by 0.8 % compared to the sieving method. In 95 % of the cases the deviations are between +5.1 % and -3.6 % (Fig. 3).

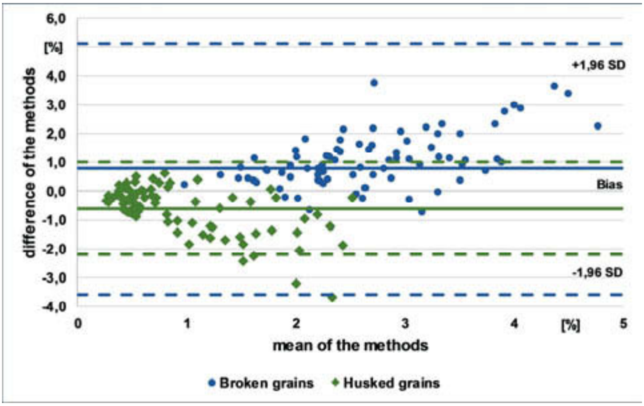

Fig. 3: Difference of the results between hand grading and sieve method determining broken and husked grains

When determining husked grains, hand grading and the sieve method show a significant, very strong correlation (method Spearman) with 83.7 % (R^2=0.215). On average, hand grading reduces the percentage of husked grains by 0.6 % compared to the sieving method. In 95 % of the cases the deviations are between +1.0 % and -2.2 % (Fig. 3).

4 Result representation of lossthroughput- characteristics

Fig. 4 shows loss throughput characteristics, based on the re-threshing method and pan method, of two combine harvesters. The characteristics based on the pan method are supplemented by 95 % confidence intervals. The characteristic curve of the re-threshing method runs above the confidence interval of the pan method. From approximately 18 t/h MOG throughput, there is a significant difference between Combine 1 and Combine 2, taking into account the confidence intervals.

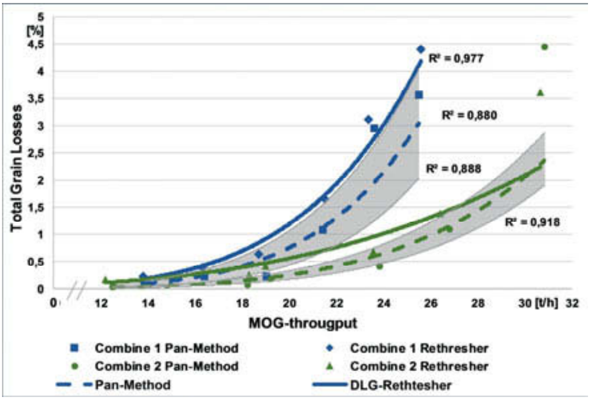

Fig. 4: Example of loss throughput characteristics (DLG-rethresher and pan method with confidence intervals) with 6 measuring points and high differences between loss levels

5 Discussion and Conclusion

The re-threshing method and pan method provide accurate results in the determination of TGL. Both methods correlate very strongly in the results. If the deviations over the range of the TGL are taken into account, the TGL of the combine harvesters to be compared should be determined in a uniform way, i.e. by the same method. The re-threshing method as an exact measuring method has an advantage in the field of research and development due to the differentiated and exact recording of grain losses. In contrast, the pan method, as a field measurement method, is characterized by a considerably lower technical and personnel effort, as well as lower costs and more measuring points per time with sufficient accuracy of the results [2]. To consider threshing losses, the re-threshing of the loss samples obtained by the pan method is recommended. The pan method is well suited for marketing purposes.

Hand grading and the sieve method do not correlate sufficiently in the results when determining the percentage of broken grains. The sieve method is more appropriate for the determination of husked grains, as the results of the hand grading method and the sieving method correlate very strongly. However, the difference in the results increases with the increasing percentage of the husked grains. For the determination of broken grains and impurities hand grading is more accurate and even mandatory. An alternative is the optical grain analysis. Studies with bread wheat show that the analysis of a 500 g sample is completed in less than 10 minutes and the detection reliability is more than 90 % [9].

To evaluate the threshing performance of a combine harvester, the loss-throughput characteristic is essential. To increase the informative value when using the pan method, it is recommended to display confidence intervals as shown in Fig. 4. The confidence intervals allow to include given measurement deviations, by the pan method itself or due to inhomogeneous crops, in the result representation. Consequently, statistically secured statements on the performance of the tested combine harvesters are possible. To reduce the width of the confidence intervals, the number of pans per measuring point can be increased. The benefits and efforts involved must be weighed up against each other.

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Challenges of calibrating grain loss sensors of combine harvesters

Observations on grain loss measurement using the pan drop method and resulting conclusions for grain loss calibration

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Abstract

The grain loss sensors in combine harvesters determine the throughput of the machine significantly. The automations on the harvester work strictly at the specified limits of the grain loss sensors, while these limits are handled more flexibly when harvesting without automatics. The measuring accuracy of the sensors for the grain losses are having physical limits, which is why they have to be calibrated or adjusted. For this purpose, the placement of grain loss pans under the machine has been established. In order to meet the requirements of a field study for the accuracy of the adjustment, a device was developed for deploying several pans in one measurement. By means of field studies, the error in the measurement of grain losses could be estimated and recommendations derived.

1. Motivation

Due to the physical nature of the separation process in separation and cleaning, the grain loss sensors have to be calibrated or adjusted to the technological harvesting conditions in the field, as the grain loss sensors can only detect a small part of the total grain loss. In Figure 1, using the example of winter barley, it shows, that different adjustments to the grain loss sensors are required for the two different harvest days.

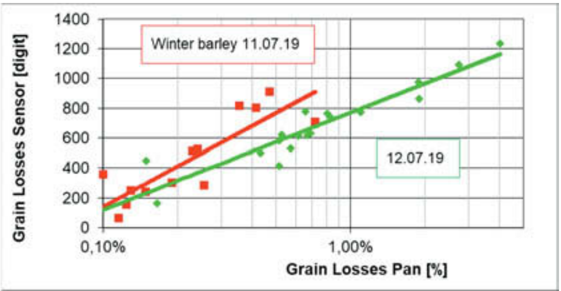

Fig. 1: Values of the grain loss sensors plotted against the grain losses measured with the grain loss pan for 2 days in winter barley

If the sensors for the grain losses are not sufficiently adjusted, the operator could simply drive at an other level of the loss display and so at an other throughput, for example higher level if he wants more power. However, if there is automation on board for adjusting the settings of the combine harvester and its movement, they control the machine strictly according to sensor values. Therefore, calibration and adjustment of grain loss sensors are of great importance today. The automation can only work as well as the adjustment of the sensors allow.
In the following, the term adjustment is used in a simplifying manner, since in the event of a deviation detected during a calibration, the sensitivity of the sensors must be adjusted.

For the adjustment of the grain loss sensors there are existing various aids from various manufacturers, which are based on the placement of collecting pans under or behind the machine to catch the material from cleaning and separation.
For the efficient use of combine harvesters, the following questions need to be answered:

- How high is the accuracy of the grain loss measurement?
- Do measurements need to be repeated and how often?
- Does measurements have to be taken over the course of the day?

Statistical studies have been carried out for this purpose.

2. Considerations on the influencing factors

For further considerations, the factors influencing grain loss measurement using collecting pans should first be examined.

They are influencing factors:

- Crop Uniformity
  - Differences in yield
  - Differences in crop moisture content
  - Differences in cutting height
  - Weed spots
- Uniformity of driving speed
- Uniformity of the crop flow from the cutter bar to the straw chopper
  - Correct cutter bar setting under difficult harvesting conditions
  - Even filling of the machine
- Swath placement
  - Swath former
  - Cleaning outflow and chaff spreader
  - Rotor or shaker combine harvester
- Distribution of chopped material
  - Do lost grains follow the flow of chopped material?
- …

It becomes evident, that there are many influencing factors whose influence on the grain loss measurement using collecting pans cannot be calculated in advance. Field tests are therefore required to determine the statistical data.

The following guidelines for the field tests result from the influencing variables:

- Selection of a uniform, weed-free crop, which, however represents the character of the field.
- Collect the loss grains over the entire width of the combine harvester channel if possible
- Wait for quasi-stationary status of the machine before depositing the pan
- Repetition of measurements

3. Test equipment and field studies

For the task at hand, test equipment was required that met the following requirements:

- Grain loss pan width approximately matches channel width of the machine
- No danger to the test personnel
- Several pans should be placed in one passage, preferably five
- Installation of a device for dropping the pans between the combine harvester axles
- Low overall height of the equipment to avoid damage
- Triggering of the pan deposition via machine bus
- Subsequent evaluation of the grain losses via a small cleaning device

At the time of the study, there was no test equipment on the market that met these requirements, so a pan dropping device and the associated cleaning device were developed using student work. The pan dropping device is shown in Figure 2 and the cleaning device is shown in Figure 3.

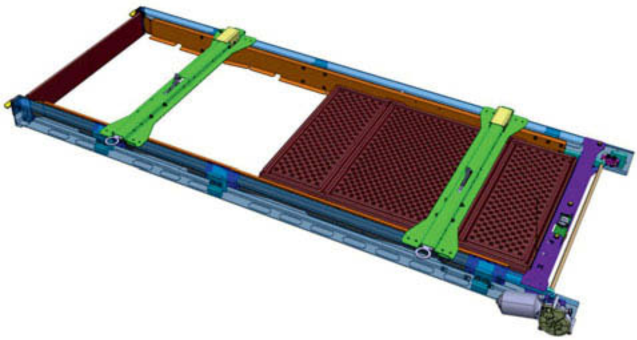

Fig. 2: Device for dropping pans [2]

For better handling two pans across the width of the machine channel are used, which are deposited at the same time.

Fig 3: Cleaning device [3]

The cleaning device can pick up the pans individually and separate the grain from the non-grain components via a sieve and sifting stage. This is operated via a 12V battery or via the on-board power supply e.g. of the escort vehicle.
When carrying out the field tests, attention was paid to compliance with the above guidelines. In order to record as many disturbance variables as possible on the adjustment of the grain loss sensors, the following test plans were run with 4 repetitions each:

- Drive the combine harvester to the grain loss limit indicated by the grain loss sensor, preferably with Cruise Pilot
- Throughput-grain loss characteristic curve; various speeds also beyond the indicated grain loss limit
- Recording of different harvesting conditions over the course of the day
- Recording of different harvesting conditions across the field

The last point could not be planned at the time of the study and is included in the results more as a disturbance variable. Of course, a certain selection of suitable test areas can be determined with satellite-supported growth maps, but this was not carried out for logistical reasons.

4. Results

Looking at the measuring points of the sensor values to the values of the grain losses, a relatively large scatter is noticeable (Figure 1). A glance at the literature shows that this is not a phenomenon of these measurements, but occurs in all measurements. The values of the grain losses over the grain throughput shown in Figure 4, which are borrowed from the Klüßendorf-Feiffer dissertation [1], also convey a high degree of variation (Figure 4). It is also evident that this variation can be very differently pronounced.

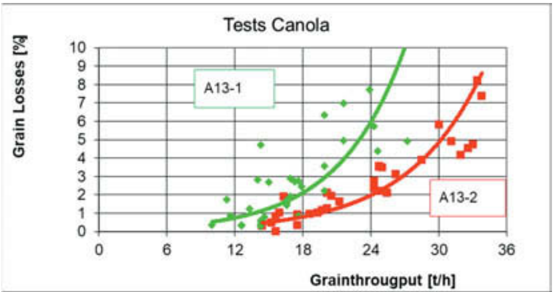

Fig. 4: Grain losses measured with pans over the grain throughput for various rapeseed crops [2, attachment A13-1, A13-2]

On the one hand, the reasons for these high variations are due to the very small sample size. If you calculate a field length of 100m for a pan deposition with e.g. 9m cutter bar width and take a pan area of 0.315m² as a basis, the ratio of the pan area to the total area is 1:2857. If three pans are dropped at the same time, the ratio is still 1:952. On the other hand, the time required to pass over the pan is very short. At a driving speed of 1.5m/s it takes about 0.3s depending on the pan. If you consider that the intake auger in the cutter bar rotates at around 3Hz and transfers the crop to the intake duct at this frequency, you can deduce that the grain losses in the field are also not quite uniform during this period.

Now it seems reasonable to conclude that if the pans are dropped via the on-board information system based on the driving speed, the sensor values can be assigned locally to the grain losses on the pan, even if one has to live with a certain irregularity in the real grain losses over time. For this purpose, studies have been carried out with very variable success and, as a result, a sliding mean value formation in a realistic time window has been used. The factors influencing an exact assignment were too diverse.

After this brief look at the causes of the measured value scatter and the result that one has to live with it, the results of the study should be considered a little statistical. For this purpose, measurements on a machine with various crops and days were analyzed statistically (Figure 5). The connection between Grain Losses Pan [%] = f (Grain Losses Sensor [digit]) and the day and the type of crop was investigated.

Term Significance	
Term	Log Grain Losses Pan [%]
Constant	0
Day and Crop	0
Grain Losses Sensor [digit]	0
R-Square	**0,8107**
Adj R-Square	**0,792254**
RMS Error	**0,397923161**
Condition No	**8,50056709**
Pure Error	**Missing**
Residual df	**72**

Fig. 5: Results from the regression of Grain Losses Sensor = f (Day and Crop, ln(Grain Losses Pan [%]), 0 in the green fields means highly significant

Of particular interest here is the RMS error [Root-Mean-Square Error], which reflects the standard deviation around the function. Since the target variable Grain Losses Pan [%] was logarithmzed here, the RMS error can be understood as a relative value. So the grain loss measurements have a standard deviation (around the best fit curve) of 40%!

The confidence interval is calculated as follows, with n = number of deposited pans (0.75m² each) and the t-distribution:

$$G = \frac{RMSError}{n} * t_{n-1,\alpha/2}$$

In Fig. 6 the resulting confidence interval for an error probability of 10% is shown.

Fig. 6: Influence of the number of pans on the confidence interval for a measurement

The consequence of the relatively high scatter of the grain loss measurement using pans is that at least 3 pans must be used for a measurement in order to obtain a confidence interval of less than 40%.

Finally, the results should be examined and confirmed as to whether measurements should be made over the harvest days and the course of the day. This is shown in Figure 7 using the normalized ratio of sensor values to the grain losses on the pans. The normalization means here that a mean value is formed over all ratios and the individual ratios are related to this.

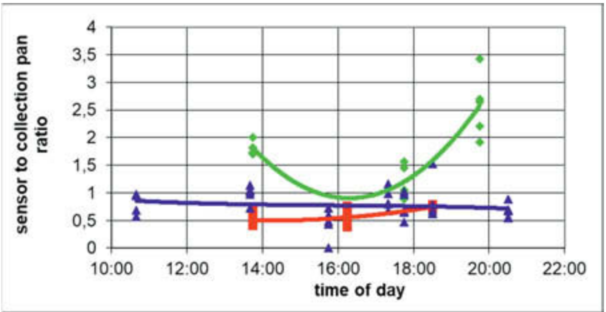

Fig. 7: Ratio of sensor values to the grain losses on the peel over the time of day and three different days

As indicated in Figure 1 and already mentioned, different harvest days naturally have a great influence on the adjustment of the grain loss sensors. The influence over the course of the day gives a differentiated picture. While the daily influence is very low on the days of the red and blue curves (or is lost in the spread of the values), a very strong influence can be seen on the day of the green curve. The night before that day it rained heavily, so that the harvest could only start in the afternoon. Here the drying of the crop and the subsequent rewetting by rising damp probably have a strong effect on the adjustment.

5. Conclusions

The following conclusions can be drawn from the observations above:

- The measurements for grain loss adjustment should be carried out at points in the field which are representative for the field.
- Only change the sensitivity of the grain loss sensors if there are high display values and / or high grain losses on the pan.
- The general advice to adjust the grain loss sensors if the threshing conditions change, i.e. at the change of crop and day as well as during the day, especially during changeable weather, can be confirmed from the results.
- Due to the large measurement error, it is necessary to place at least three grain loss pans.

The author is aware that currently none rather than one grain loss pan is being used. However, every farmer should also bear in mind that he will then lose hard cash. Of course, no measurements need to be carried out if the performance limit is not caused by the separation or cleaning, inasmuch as there appear to be very few grains on the ground.

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Experience gained in developing Autonomous Robots using AI and spot spraying to weed open field crops

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Abstract

This paper presents an overview of six years of development and validation of autonomous robots used for spot-spraying weeding in open-field crops. Among the many different possible design options of an autonomous agricultural robot, the paper presents the rationale behind key choices in the design of two autonomous machines equiped with a real-time plant classification system, and a centimeter-precision spot spraying tool to apply herbicide on a plant-by-plant basis. Practical aspects regarding robot usage and safety are also covered. The paper concludes with a comparison of the two machines and synthetic remarks about the coming deployment of autonomous robots in a large scale in Europe.

1. Introduction

In the domain of autonomous robots for agriculture tasks on crop fields, many different prototypes have been seen during these last 20 years, covering a broad range of design parameters such as size, driving and steering wheels configurations, obstacle clearance capability, autonomous navigation, faculty to perform various operations on crops or on fields, sensing, energy source, weight, and so on. These parameters strongly influence robot cost, performance, reliability, safety and usability, and therefore are of prime importance in the design of a commercial robot having sufficient benefits (economical, technical, environmental and societal) to be accepted by farmers and operated in real conditions.

The work presented in the following sections gathers six years of experience in designing, validating and operating autonomous robots for high-precision spot spraying weeding using artificial intelligence. This kind of machine cumulates several difficult design challenges : first, the plant recognition needs to be robust over a wide range of real conditions. Second, to get a high positioning accuracy to deposit micrograms of herbicide on a small plant with a moving robot in an uneven terrain, a careful design is a strict condition for success. Third, robust autonomous operation requires reliable positioning sensing in any condition and excellent machine trajectory control. Finally, getting a robust and cost-effective machine working fast and well in all conditions is a tough objective inevitably implying design choices and trade-offs that will be detailed below.

2. Robot main parameters

2.1 Robot size

The robot size has a fundamental impact. Too small machines have unacceptable low throughputs, and due to their need for technological components similar to a big robot (sensing, navigation...), their cost does not scale with their size. Consequently, the idealistic concept of a swarm of small robots does not work in practice : it is too expensive and too complex to use. On the opposite, too big robots do not differentiate enough from autonomous tractors. If they do not bring real advantages in terms of soil compaction, energy, safety or ease of use, they will be simply replaced by autonomous tractors once available, these latter relying on well-proven technology and low fabrication costs. Between the two extremes, there is a space for medium-sized robots with advantages over autonomous tractors due to 1/ lower weight (beneficial for soil compaction and energy needs), 2/ ease of deployment if carried to the fields with standard equipment, and 3/ higher safety thanks to low weight and speed. However, the throughput directly depends of the robot size and speed. It is important when sizing a robot to guarantee economically acceptable throughput.

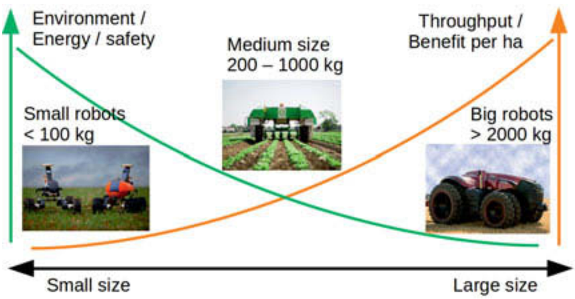

Fig. 1: Medium size robots combine costs/throughput advantages of big robots with environment/energy/safety advantages of small robots.

2.2 Robot task

Considering the operations involved in a field during a complete year, we see that soil preparation requires very high power, and harvesting needs to transport high masses. Between the two, there is a long time period with crop operations requiring much less energy and/or much less transport of materials: sowing, fertilizing, and crop protection (weeding / application of pesticides). They are ideally done by autonomous, light robots. We assume that soil preparation and harvesting will benefit from the power of autonomous tractors; they do not represent viable operations for dedicated autonomous robots.

Among the possible crop operations for an autonomous robot, by increasing order from the least demanding in energy or mass to the most, is 1/ the application of chemicals, 2/ the application of fertilizers, 3/ sowing, 4/ mechanical weeding. We established this as a priority list for the selection of operations done by the robots we developed.

Operation	Tilling	Sowing	Fertilizing	Protecting	Harvesting
Low energy	•	••	••	•••	•
High accuracy	•	•••	•	•••	••
Low mass	•	••	••	•••	•

Medium size autonomous robots

Fig. 2: Due to low energy/mass and high accuracy needs, sowing, fertilizing and crop protection operations are ideally suited for medium-size robots.

2.3 Power source

A thermal engine is the preferred solution for long range operation and for robots requiring high energy or equipped with hydraulic propulsion. However, this choice has drawbacks, such as higher maintenance costs compared to batteries and electrical propulsion. For low energy operation, a fully electrical vehicle with batteries is an interesting solution, but the need to recharged or replace the batteries can represent a serious obstacle for acceptation if a practical solution, such as in-site replaceable batteries, is not proposed. Adding solar panels to a robot allows to significantly increase the range by providing an important part of the energy, increasing the period of battery replacement/refill. Solar panels are relatively inexpensive, robust, and can provide up to 180 W per m^2 in a sunny day.

3. AI for plant recognition

Plant detection and recognition is mandatory for plant to plant crop protection operation. If there is sufficient difference with basic metrics such as size or color between the various plants, a simple detection and classification method can be used (simple size threshold). However, to render these operations as generic as possible, more complex plant recognition methods are needed, allowing for instance to distinguish plant species at any growth stage, and with various present species with identical growth stages or sizes.

3.1 Image resolution and spectrum

High resolution imaging is needed to access small plant features for classification. However, high details are not always useful, and they demand higher costs and complexity in processing. Most of the time, the minimal needed resolution to do the job is chosen, but this

minimal is not easy to identify. Our experience has shown that it is known after the classifier has been trained and tuned, thus at an advanced stage of the process. It is therefore better to work with resolution higher than needed during classifier development, and reduce it later.
Another parameter is the spectral response of the imaging device. NIR (Near infrared) images have been used in plant detection due to their good discrimination between leaf structures and soil. Their drawback is a loss of useful details such as color and texture. Another difficulty is in the annotation process : since the spectrum is naturally not visible for humans, it renders the annotation process more complex and prone to errors.
Multispectral or hyperspectral imaging allows to detect more features than visible spectrum images: signs of disease, fungis, stress of the plant, etc. But the sensors are expensive, and the recognition process requires complex annotation with features not visible by humans. Our experience has shown that standard RGB images allows to obtain good identification results, as long as the image quality is excellent.

3.2 Illumination

Outdoor imaging poses specific challenges in terms of image dynamic range due to high illumination differences between direct sunlight and shaded areas of the same scene. Using a standard camera with 60 dB of dynamic range to acquire an image results in poor signal to noise ratio in the dark/white zones. There are several ways to increase the dynamic range. The first is to use a HDR camera, working either in a non-linear (lin-log) signal integration mode, or using simultaneous dual exposure. These cameras are expensive. The second is to use a good dynamics camera (typically 70 dB or more) embedding a Look-Up Table allowing non-linear input-output mapping, typically a gamma correction, which compresses dynamics in the bright parts, and extends it in the dark parts. The third is to use a dual-exposure scheme. A fist image is taken with a short exposure time for the bright parts of the image. A second image is then taken immediately after, with a longer exposure time for the dark parts. The images can be recombined to form a high dynamic range image.
Uncontrolled (or natural) illumination imaging poses serious challenges when it comes to training a classifier. Indeed, to facilitate training, whether based on traditional machine learning or on Convolutionary Neuronal Networks (CNNs), it is desired to use normalized images. Reducing variability greatly helps the training, and reduces the number of needed images. For this, it is preferable to avoid image variability due to illumination, which can be very important. Minimize the dynamic range, suppress shadows, and flatten the differences between dark and bright portions of the image, all this helps in classification. Natural illumination poses also the challenge of colorimetry stability between direct sunlight and

clouded sky for instance. This affects directly the colors of the scene, adding variability which needs to be handled by the classifier during training.

3.3 Classifiers

There are two main families of classifiers : the first uses methods based on explicit description (model) of the features used for classification. The operators to extract the features have to be explicitely designed (edges, colors, shapes, geometries, etc.). The second includes the classification methods based on a pre-defined, vast list of generic feature extractors which are combined during training in a succession of processing layers, the last layers being in charge of the chassification itself. The whole process is almost transparent to the designer, who has no direct access to an explicit representation of the features used for classification. Such methods include CNNs (convolutionary Neuronal Networks) or DL (Deep-learning). The training process is mostly based on data. A large amount of images is required to efficiently train such data-based classifiers, but they usually outperform model-based ones, especially in variable environments like plant classification where no plants are the same, rendering mode-based recognition approach less efficient.

4. Practical aspects

The third important topic about autonomus robot is the acceptance of this technology by farmers. Autonomous machines shall not only have advantages in terms of costs and performance over man-driven machines : they should also be easy to use. Indeed, farmers are always looking for ways to simplify their life.

4.1 Robot transport

The successful deployment of autonomous robots in fields must take into account practical considerations. Farmers do not always have their fields in the direct vicinity of the farm. They must often travel kilometers between farm and field. For this, they use the tractor to carry the machines. Robots sould be transported the same way, and no other equipment than tractor should be needed to transport robots in the fields, excepted a device attached to the tractor and holding the robot. Any supplementary equipment that needs to be bought (trailer, etc) renders robot acceptance more difficult. Autonomous tractors have a problem: they cannot drive on the road. How will the farmer go back home once he has left his autonomous tractor in the field?

4.2 Safety

Safety of an ag robot involves three main risks: 1/ the machine leaves its working zone, 2/ the machine hits and rolls over a person while in operation, 3/ the machine falls from trailer during loadung/unloading and crushes operator. Risk 1 is solved by robust positioning systems, the residual risk being very low by design. It is also solved by conservative path planning with safety buffers on field boundaries. Risk 2 is more difficult to suppress and needs expensive perception sensors (usually safety Lidars). The residual risk can hardly be totally suppressed in reality (a small person lying on the ground is not detectable by a lidar) and for this reason lightweight and slow machines, whose weight per wheel (50-200 kg) is not sufficient to cause permanent injury or death, present inherent safety advantages over autonomous tractors with >1 ton per wheel of pressure.

5. First design (2016-2018)

The first robot we developed was designed for a working width of 2 meters and a maximal speed of 0.5 m/s, offering a theoretical throughput of 0.36 ha/h. A maximal machine simplicity was chosen to have a cost-effective design. With a differential steering, two front (fixed) driving wheels were sufficient to move and turn. A single camera working in uncontrolled illumination was used at the same time for navigation camera (row detection), positioning camera (visual odometry sensor) and plant classification image source camera. Dual exposure was used to cope with high scene dynamics. Two Delta robotic arms allowed centimeter-positioning of two nozzles in 3D to perform spot spraying. Two solar panels and a 20 Ah 36 Volt battery provided the energy to the 150 kg machine. Autonomous operation was guaranteed through a simple path planner and robust positioning using odometry (visual and wheels), visual crop row sensing, magnetic heading and RTK GPS.

Fig. 3: Robot at work in sugar beet (left), dual exposure and image combination to remove machine shadow and increase image SNR and plant identification rate.

In 2017, 10 machines were built and operated on 2 crops in about 15 locations in 4 countries, using standard machine learning technique as plant classifier. In 2018, CNN classifier was introduced, improving the weed recognition rate to 75-80%. Considerable experience was gained on the technology, spot spraying efficiency, user interfaces and general machine usage by early customers. The machine suffers however from a non-predictible throughput, due to the sequential operation of robotic arms causing the robot to slow down when weed density increases: with low weed density (<10 weeds/m^2), the throughput per day is 3 ha, but it falls rapidly with higher densities. Other machine limits are the difficulty to clear obstacles in uneven fields (due to 2 drive wheels over 4), and the variability of uncontrolled illumination causing unstable weed recognition rates. The machine remains nevertheless a very simple and lightweight machine, easy to deploy and use.

6. Second design (2019-current)

The experience gained on the first machine was used to design a second robot whose objectives were to provide the best performances in plant recognition rate, throughput and obstacle clearance, while offering true energy autonomy, ease of transport and modular tooling. To respond to the need for higher throughput while keeping a transportable machine, it was decided to keep the 2 m working width but doubling the speed of the machine and switching to a fixed spray bar with high density nozzles (1 every 4 cm). This allows to operate at constant maximal speed independently of weed density. Throughput is 0.72 ha/h.

Fig. 4: Second design in operation in sugar beet (left), high nozzle density spray bar (right).

The machine is equipped with four driving and steering wheels with amortization, allowing high manoeuvrability (u-turns of 1 m radius) and obstacle clearance. The steering angle is 350°. The steering rotation axis is shifted 75 mm from wheel center in the inside direction, thus by rotating the wheels by 180° the wheel lateral distance can be software-adjusted from 2.00 m to 1.70 m, allowing the machine to adapt to various bed and row crop spacings.

A volume of 2.2 x 1.6 x 0.8 m is available under the machine for receiving the spot spraying tool. The machine can be directly attached to a tractor 3-point hitch without any equipment for transport to the field. Four solar panels provide up to 1200 W of energy. A system of three hot-swappable removable batteries provide a total of 12 kWh of electric storage. Combined with the solar production, the machine can work up to 10 ha during 15 hours without recharge. The reservoir of 140 liters provides enough herbicide mixture to work >10 ha with average weed densities.

Regarding plant identification, the machine uses two RGB cameras with high intensity controlled illumination, resulting in constant colorimetry and reduced intra-scene contrast variations. The classifier is based on a CNN trained with a proprietary image database, and executed in real-time on the machine with an inference time of 200 ms. The high resolution spray ramp has a spray pixel of 25 cm^2 (8x3 cm) and allows to position a spray spot with 2 cm precision. Herbicide reduction depends on weed density, but typically reaches 80% with 20 weeds/m^2.

The robot was built in 4 units and tested in various locations in three countries and on four available crops during the 2020 weeding season. Weed recognition rate (recall) reaches 90% in sugar beet, while crop recognition rate (specificity) exceeds 96%. The classifier features good stability from field to field and under various operating conditions, showing the efficiency of working under controlled illumination. Effective herbicide reduction, weeding efficiency and benefits on crop yield are currently being investigated.

7. Conclusion

The paper outlined the benefits of medium-size agricultural autonomous robots, and presented the six years of experience gained by ecoRobotix in designing and operating two different autonomous robots doing spot spraying chemical weeding. Design trade-offs were underlined, especially simplicity versus performance. The most technically challenging function to develop and validate was the plant recognition system, mandatory to perform plant-by-plant application of herbicide. The gained experience led to very precise and robust intelligent spot-spraying engine, allowing important herbicide reduction. The perspectives of high precision spot spraying are good, considering the pressure to reduce pesticide usage, and the new capability offered by spot-spraying in using natural, non-selective herbicide as well as other organic compound becoming economically attractive and technically efficient when selectively applied. To reach the high needed precision, low machine speed is mandatory, rendering continuous operation, and therefore autonomous machines, attractive.

Medium-sized autonomus robots, thanks to their unique advantages over autonomous tractors in terms of soil compaction, energy needs and safety, will find their market niches in the coming years. To be successful, they must show acceptable pay-back time, high reliablilty and ease of use for the farmers.

Fast Prototyping of Autonomous Vehicles

Alexey Bogatyryov, CTO, eFarmer, Amstelveen, The Netherlands

1. About

My name is Alexey Bogatryyov, I'm a Mathematical Engineer and Data Scientist. I have applied mathematics education and 10 years of software development ERP systems. Now, for more than 12 years I've been working in agriculture with creating valuable IT solutions for farmers.

I want to tell a story about fast inexpensive prototyping of an autonomous harvester.

2. About eFarmer

eFarmer was founded in 2014. Together with Michael Utkin we've founded the company to help farmers with adoption of precision agriculture by using the latest advances in sensors and other technologies.

The company has developed:

- tractor navigation application
- RTK GNSS receivers
- Autosteer system

3. Interest from OEMs

Since the last two years we have identified that not only farmers need our products but also agriculture OEMs that use our products for both factory installed solutions and for the after-market.

4. Ready to use products and solutions for R&D projects

Our company has developed product and subject matter competences in hardware and software development specific for agriculture and agriculture machinery. Our products and competences allow us to create customized solutions to solve in shortest terms R&D activities for other companies.

5. Use Case

In July 2019, HuizingHarvest B.V., a company that specializes in the international exchange of agricultural knowledge, sent us a partnership invitation to join them in an innovative project.

The task was to make a self-driving harvester that operates in the autonomous mode due to September 13, 2019 - the 10-year anniversary of the company.
It probably seems impossible to make a self-driving harvester work in such short notice, however, we saw this as a great opportunity and quite an adventurous task. eFarmer team was together with the HuizingHarvest team made a self-driving harvester very fast and on time.

Before starting the project, we had a conversation with HuizingHarvest about their needs. We already had a product for navigation and RTK solution with high precision. Our company was planning to build autonomous vehicles, therefore partnership with HuizingHarvest seemed like a perfect opportunity to start working on this project.

For building an autonomous vehicle, we had limited resources – a small budget for development. We provided an agile methodology for building this and calculated 750 hours per developer. We estimated what we can do in this short time by clarifying the requirements, roles, and responsibilities with HuizingHarvest.

6. Details

HuizingHarvest decided to build a prototype based on a Chinese harvester that they have ordered on Alibaba. They allocated their talented electric and hydraulic engineers for this project.

From our side we added microcontroller, embedded development, navigation and android development competences.

We have used our FieldBee RTK GNSS products for 1 cm accuracy positioning for mission monitoring, we used FieldBee mobile app for the remote control. These components allowed us to accomplish this project in such a short period - 2.5 months.

In the beginning we validated the navigation concept with navigation directly from an Android application implementing only P navigation model. It had poor performance and we estimated that development of this algorithm will take a lot of additional time.

But we’ve found an open source project with autonomous navigation algorithms. We developed a driver from PWM to signal level converter.

Harvester was equipped with safety sensors and the system has two channels: radio and internet for interrupting autonomous processes for emergency reasons.

During the project we implemented the Mavlink protocol for managing missions from an Android navigation application. This set up helps us to provide prototypes even to our customers.

We had two weeks for calibration of autonomous navigation. During this period we made PID defining parameters. Biggest challenge was delays between the steering system and navigation controller.

But finally we calibrated and harvested one field.

7. Conclusion

In only 2.5 months, with the amazing effort of our 5 people team we have made a self-driving harvester. As a result, the autonomous harvester project was successfully presented on the 13th September 2019 during the HHX Agrobotix Demo event.

When we started this project we thought that this long-term solution is mostly applicable only for HuzingHarvest. But on the prototype stage, we decided to work on a unified solution. We specifically selected open-source libraries for simplifying the process of integration with different platforms.

We see that this use case is scalable to other companies who would like to create autonomous agriculture machinery solutions. This project is fully scalable to other prototyping stages for similar projects.

Modular and Scalable Automation for Field Robots

Lighthouse project "Cognitive Agriculture"

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Janko Petereit, Fraunhofer Institute of Optronics, System Technologies and Image Exploitation IOSB, Karlsruhe

Abstract

Agricultural technology is under pressure due to unsolved farm successions, labour shortage and climate protection goals. Precision farming and smart farming are expected to have a high impact on sustainability on a long time scale. The Fraunhofer lighthouse project "Cognitive Agriculture" (COGNAC) is working on increasing the efficiency and sustainability of agricultural processes by developing a living digital ecosystem called Agriculture Data Space. A short introduction to parts of the ecosystem such as the ADS-enabling platform and the automated charging field robots are presented.

Introduction

For the automation of field robots, a connection to an IT service is mandatory. There are countless different available IT solutions for the agricultural sector. Unfortunately, standardization is not yet very common. Therefore, one of the main challenges in the automation process of field robots is the lack of interoperability between different field machines and agricultural data hubs. Furthermore, there is hardly any exchange of information between the ecosystem of one company and that of another company. In addition to this, farmers have reported a loss of data sovereignty over machine data and sensor data. Digital transformation in the agricultural sector requires digital and accessible environmental data, sensor information and machine data. All of this taken together has the great potential to increase the efficiency of agricultural processes even more in the future.

Lighthouse project Cognitve Agriculture COGNAC

Eight Fraunhofer institutes are working together on a step towards digital transformation in the agricultural sector. The project mainly focuses on the creation of a living digital ecosystem, the so-called Agriculture Data Space (ADS) [1]. To achieve this vision, we are working on cognitive data services which are connected to field robotics applications and advanced sensor solutions. In the project, we will adapt current data ownership concepts from the “Industrial Data Space” (IDS) [2] and prove how they can be applied to the ADS. Different cognitive digital services will be developed. One goal is to create an information-based ecosystem for the agricultural sector.

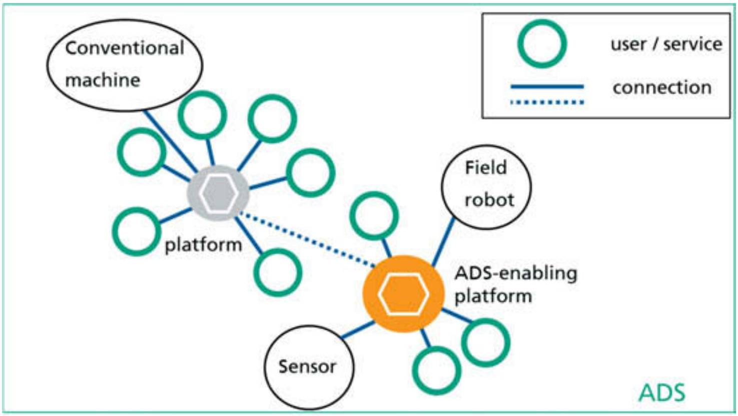

Fig. 1: Overview of the connectivity of the ADS-enabling platform

The ADS as a Modular Scalable Ecosystem

As visible in Figure 1, different sensors and field robots together compose the ADS. Another aspect aimed at by the COGNAC project is the networking between the ADS-enabling platform and other platforms. This concept can be scaled up to include more digital services or a broader connectivity to other platforms. A user or a digital service, such as a farm management information system, has direct connections to the ADS-enabling platform for transmitted information, e. g., the amount of pesticides applied or field size. Other examples of digital services can be planning of paths and missions or improvement of models for sensor data. It is important to mention that the data suppliers will be empowered to control their own shared data in the process by introducing usage control options. One aim is to take the quality of provided data into account when interpreting the decision models. This comprehensive amount of data in the ADS-enabling platform can be used to improve the automated interpretation of sensor information and field robot data. It offers an additional decision basis for different time horizons. Some examples of decision processes are time controlled weed regulation and need for fertilization of a specific ground.

Automation of the Field Robot

There are different requirements for the automation of field robots. The robots serve as modular sensor platforms and contribute to the data acquisition by collecting data automatically. First of all, the field robot needs a mission planner. When the mission is defined, data acquisition can take place. In the following data processing step, a model provided by the ADS-enabling platform will be used. With regard to the aspect of data usage control, data can be transferred to the ADS-enabling platform for further use. After a certain amount of time, a field robot will run out of power. Therefore, a reliable energy supply with an automatized charging process is of high relevance. To maximize the robots' availability, the charging time should be reduced to a minimum.

In our project, we will build an automated underbody charging system that will be demonstrated on our field robot called CERES. Besides CERES, a second, slightly smaller and lighter field robot, CURT, with additional features is currently under development. As a first application, we focus on mechanical weed control. Both field robots benefit from their connection to the ADS-enabling platform (Fig. 1) by improved data models, secure data handling and access to geographic field information.

Automation of the Charging Process

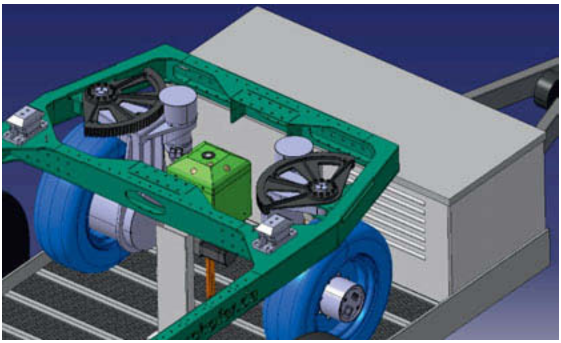

Fig. 2: CERES frame (dark green) with underbody charging system (light green) on a trailer

In Figure 2, the underbody charging system is displayed in light green. It consists of an automated charging device (bottom part) and the vehicle counterpart (top part). For better visibility, only the frame of the CERES field robot is shown (width of 1.8 m and length of 3.6 m). The system itself was developed for automotive applications at the Fraunhofer IVI [3]. When the field robot runs out of power, it will approach the charging trailer automatically. To avoid interferences with other sensors and agricultural equipment, the vehicle counterpart is positioned at the front of the robot. The system is based on a conductive charging principle. In comparison to inductive charging, the transmission of high powers up to 2 MW are possible. To start the energy transfer, the automated charging device will move upwards automatically until a contact to the vehicle counterpart is achieved. When the battery is fully charged, the automated charging device will move downwards again and CERES is prepared for the next work task. Work tasks are controlled using the highly efficient online yard Operating System control system (helyOS).

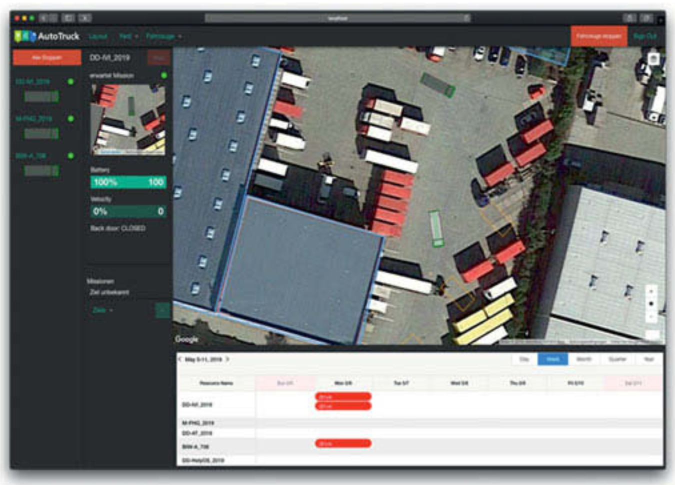

Fig. 3: Web-based helyOS user interface

Scalable and Modular helyOS System

For the inclusion of the automated charging process, more complex, higher-level planning beyond the mentioned behaviors is necessary. In order to ensure that the field robot always reaches the charging station before it is running out of power, mission planning and power management have to be coordinated. The highly efficient online yard Operating System (helyOS) itself is a web-based mission planning software for planning, performing and observing work processes involving automated machines [4]. It consists of a web-based user interface (one example for logistics is shown in Figure 3) and a backend hosting the powerful business logic. A core component of the business logic is the central database, which stores field missions, battery status and information received from the machines. The data exchange is synchronized between the front-end, the business logic and the automated machines. The business logic uses machine and environmental knowledge such as battery state of charge and field geometry (provided by the ADS) to guarantee a reliable operation including intermediate recharging, if necessary.

Scalable and Modular Algorithm Toolbox for Autonomous Mobile Robots

To make full use of the potential of high-level mission planning, the autonomous machines need to be equipped with appropriate sensors combined with effective autonomy algorithms. For this purpose, the so-called "Algorithm Toolbox for Autonomous Mobile Robots" is being developed at the Fraunhofer IOSB. This algorithm toolbox offers a wide range of software modules that can be used on different platforms. The algorithm toolbox contains modules for sensor data processing focusing on environment detection. Other modules deal with algorithms for environmental mapping and the localization of agricultural machinery within the generated maps. The modular design of the ATB makes it possible to integrate cloud-based mission planning apps such as helyOS.

Conclusion

In this article, we presented an information-based cognitive agriculture platform which will be tested in specific field tests. Two field robots and various sensors will be part of the ADS ecosystem, thus contributing to cognitive digital services. To fulfil the requirements of automation, an automated charging process for the field robots is designed. The task of scalability and the modular approach are covered by the ADS-enabling platform, the Algorithm Toolbox and the helyOS control system.

Acknowledgement

The authors would like to acknowledge the Fraunhofer-Gesellschaft for funding the COGNAC Lighthouse Project.

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The application of mobile eye-tracking to improve the usability of touch terminals for farm vehicles: an example

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Abstract

Human-machine interfaces are subject to continuous refinement aiming to improve usability and user experience (UX). One method that is supposed to make it possible to verify the achievement of these goals in a simple and cost-effective way, is the combination of low-budget exploratory field studies and eye-tracking. Following this approach, this study explored aspects of UX for the newly developed CEBIS TOUCH operator terminal for the combine harvester CLAAS LEXION, generation 5000-8000, in order to both verify the method and to obtain indications for refinement of the terminal. Twenty participants performed various tasks on the touch terminal while their gaze behaviour was tracked with eye-tracking glasses. Supplementary data was collected with the aid of the 'Thinking Aloud' method and a subsequent survey. Results demonstrate that the applied method is conceptually suitable for identifying processes that work well and also difficulties in handling newly developed operator terminals for agricultural machines and thus for investigating aspects of UX. The fast and confident execution of the tasks by some participants points to an intuitive menu navigation and a mature product. Nevertheless, potential for optimisation of the terminal could be identified. Possible measures for optimisation are discussed.

1 Introduction

Advancements in sensing technologies enabling the monitoring of various subsystems of agricultural machines require effective, intuitive, and efficient operator terminals. Therefore, these human-machine-interfaces are subject to continuous refinement to improve usability and thus operator performance [1] and, as a wider concept, to improve user experience (UX) for increasing acceptance of these terminals [2]. Usability is defined as the 'extent to which a system, product or service can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use' [3]. Usability can be evaluated with different qualitative and quantitative approaches, e.g. by observing user behaviour during tasks to identify actual usability problems and/or by measuring user performance to obtain quantitative data on effectiveness and efficiency. Typical measurements of effectiveness are task completion or error rates, often used measurements for efficiency are the time taken for performing tasks or steps of tasks [4]. In addition, subjective information can be collected during or after tasks by asking open questions for attitudes or impressions to obtain qualitative data, or by measuring user satisfaction or perception quantitatively [5], usally through questionnaires [6]. UX as a more comprehensive approach is difficult to define, but there is a general consensus that UX is associated with a variety of issues ranging from traditional usability to beauty, hedonic, affective and experiential aspects of technology deployment [2].

In recent years, eye-tracking, i.e. the recording of gaze behaviour, has become increasingly useful in HCI studies [7]. There are several advantages in using eye-tracking in these studies: Eye-tracking removes the subjectivity of self-reported data, allows to track users' reactions on specific stimuli and can show which parts of a screen attract users' attention [7–9]. Eye-tracking metrics can be used to estimate cognitive load [7,9], which in turn allows conclusions about usability and UX [8,10]. Fixation-related parameters, such as time to first fixation in an area of interest (AOI), the duration and number of fixations within an AOI or the frequency of visits within an AOI are most commonly used measurements in HCI studies [11].

Ever-shorter times to the market require pragmatic, cost effective approaches to test newly developed human-machine interfaces. Due to these time constraints conducting sophisticated studies on usability and UX are not recommendable. Combining a guerrilla UX approach, i.e. low budget explorative field studies with only few subjects of the target group [12], with mobile eye-tracking is described as one method that allows practitioners to quickly acquire qualitative and quantitative field data with minimal interference to ongoing work [1,13].

Following this approach, the aim of our study was to explore aspects of UX for the newly developed CEBIS TOUCH operator terminal for the combine harvester CLAAS LEXION, generation 5000-8000. We used a mobile eye-tracking system to record the participants' gaze behaviour while they executed given tasks on the touch terminal. The operations performed by the participants on the terminal were recorded with an integrated camera in the eye-tracking glasses to determine the time required by the participants for each step of the tasks and to record participants' gaze behaviour. In addition, the test persons answered a questionnaire that supports and supplements the results regarding UX from the eye-tracking data. Our results demonstrate the suitability of the methodological approach and show potentials for optimising usability and UX in the given context.

2 Methodological approach

The experiment was carried out in autumn 2019 at CLAAS' headquarters in Harsewinkel, Germany. Twenty participants with different levels of knowledge on operating CLAAS combine harvesters participated in the study. All participants were male, with an average age of 43 (± SD 9.18) years. At the time of the experiment, 25 percent of the participants had been working less than five years on the product Lexion, 25 percent between five and ten years and 50 percent more than ten years. More than half of the participants rated their own expertise in operating the Lexion as 1 or 2 on a scale of 1 (very good) to 5 (not good at all) (Fig. 1).

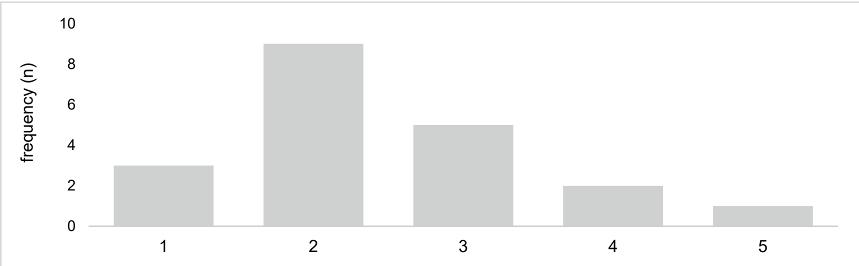

Fig. 1: Frequencies of participants' self-assessment of their expertise in operating the Lexion on a scale of 1 (very good) to 5 (not good at all).

The participants were asked to perform four tasks on the CEBIS TOUCH and to think aloud (TA) during the tasks. The tasks were performed on a parked CLAAS LEXION within a standard operator cab. Before starting the tasks, the participants were equipped with Tobii Pro Glasses 2 (100 Hz), a mobile eye-tracking system that allows to record the participants' gaze behaviour and to match it with the information in the front of the user captured by an integrated video camera. After the eye-tracking experiment, all participants filled out a self-administered personalised paper-pencil-questionnaire containing questions about UX aspects of interaction with the touch terminal.

For the presentation in this paper, we chose the two tasks that are able to demonstrate the potential of the study approach for optimising human-machine-interfaces in farm vehicles: One task was to deactivate the Cruise Pilot, a system that automatically controls the harvesting speed. For completing the task, the participants had to perform three steps: First, they had to switch from the main menu to the menu that contained the On-Off button for the Cruise Pilot, then they had to touch the On-Off button and finally they had to switch back to the main menu. The other task was to change the type of crop to be harvested from wheat to rapeseed. To successfully complete this task, the participants had to perform five steps: Firstly, they had to switch from the main menu into the menu for adjusting the crop-specific settings. Secondly they had to touch the button for selecting of the type of crop to open the submenu containing all crop types. Thirdly, they had to select the crop type “Rapeseed/Turnip rape” from the selection bar, and fourthly they had to confirm their selection by touching the Play Button. Finally, they had to return to the main menu.

For analysing the data, the eye-tracking recordings of the tasks were processed with the software Tobii Pro Lab, defining times of interest within the video material to calculate the time the participants needed for each step of the respective task. In addition, AOIs were defined for a deeper understanding of gaze behaviour in areas that were important for completing the respective task. For the task of deactivating the Cruise Pilot, the On-Off button was defined as an AOI and for the task of changing the crop type, the Play button was defined as an AOI. For statistical analysis, the processed eye-tracking data was merged with the data from the questionnaire and imported into IBM SPSS Statistics, version 25 [14].

3 Results

3.1 Deactivation of Cruise Pilot

Eighteen participants deactivated the Cruise Pilot (CP) with the On-Off-button (OOB) and returned to the main menu, i.e. they completed the task successfully. The time required to perform the task varied considerably between participants. A quarter of the subjects finished the task within about 10 seconds, the median time span from start to finish was 18.35 seconds. The challenges the participants were confronted with during the task can be derived from the temporal key data of the task, presented in table 1.

Table 1: Temporal key data of the task: deactivation of Cruise Pilot (time spans in seconds)

	start of task to entry into CP menu	entry into CP menu to first fixation of OOB	first fixation of OOB to first touch on OOB	entry into CP menu to first touch on OOB	first touch on OOB to end of task	task duration
n	19	17	17	18	18	18
Q1	2.46	0.60	1.21	2.84	2.55	10.19
Median	4.82	1.38	1.96	3.86	5.72	18.35
Q3	13.85	5.25	3.22	7.93	11.69	52.86

CP Cruise Pilot; OOB On-Off-button for activating/deactivating the Cruise Pilot, *Q1* lower quartile; *Q3* upper quartile

The first difficulty for the participants was to find the correct button in the main menu for entering the Cruise Pilot menu. While 50 percent of the participants were able to enter the Cruise Pilot menu in less than 5 seconds, the remaining participants needed more time. Only 25 percent of the participants found the button very quickly, indicated by a first Quartile (*Q1*) of less than 2.5 seconds. The next critical point was the visual perception of the On-Off button in the Cruise Pilot menu, even if this button was placed prominently at the top of the menu. Only 50 percent of the participants fixated the button within a time span of less than 1.5 seconds. After perceiving the button by a fixation, the further procedure seemed initially to be clear to most participants. A share of 75 percent touched the On-Off button within about 3 seconds to deactivate the Cruise Pilot. Actually, the test persons could have then returned directly to the main menu and the task would have been finished. However, only a smaller part of the participants succeeded in doing so within a relatively short time, indicated by a *Q1* of about 2.5 seconds for the time span between the first touch of the button and switching back to the main menu. The median of 5.7 seconds and the third Quartile (*Q3*) of 11.7 seconds show that a considerable part of the participants had problems recognising whether the task was completed or not. Eye-tracking metrics suggest that these difficulties were related to the On-Off button. The longer participants needed to switch back to the main menu, the longer was their fixation duration (r_s = 0.85, p < 0.001) and the higher were their number of fixations (r_s = 0.72, p = 0.001) and number of gaze visits (r_s = 0.64, p = 0.005) within this AOI. It was further indicated by repeatedly touching the On-Off button by six participants and by comments captured with the TA protocols that some participants apparently had problems in determining whether the Cruise Pilot was on or off. This presumption was confirmed by a subsequent questionnaire, in which eight participants stated that the status of the Cruise Pilot was not clear to them. Some of them criticised an unfavourable colour selection of the On-Off button (status on = green; status off = grey). The perceived difficulties of the task had a significant influence on UX since the longer the participants needed to complete the task, the less comfortable they felt during the task (r_s = -0.58, p = 0.012).

3.2 Changing type of crop

Table 2 gives an overview of the time required for the individual steps to change the crop type to be harvested. As a *Q3* of 3.5 second indicates, the participants found smoothly the button for switching from the main menu into the crop type menu. However, the further procedure did not seem to be so clear to most participants. While some participants touched the button that opened the crop selection bar quickly, half of the participants needed more than 10 seconds to find this button. Some participants searched within other submenus or tried to change the type of crop by typing ‘Raps (rapeseed)’ in a submenu that opened a keyboard display. After locating the correct button, a *Q1* of 9.4 seconds illustrates that even ‘fast’ participants spent much time with searching ‘Rapeseed/Turnip rape’ in the crop selection bar. In the subsequent questionnaire, participants criticised the perceived arbitrary order of the crops in the selection bar.

Table 2 Temporal key data of the task: Changing type of crop (time span in seconds)

	start of task to touching CTMB	touching CTMB to touching SCTB	touching SCTB to choosing rape	choosing rape to touching PB	start of task to touching PB
N	20	20	20	12	12
Q1	1.38	5.51	9.37	2.43	23.81
Median	1.95	10.22	14.83	17.16	32.03
Q3	3.55	18.63	24.71	45.29	113.47

CTMB button for switching from the main menu into the crop type menu; SCTB button for opening the submenu with the crop types; PB Play button; *Q1* lower quartile; *Q3* upper quartile

However, the most important result was that only twelve participants completed the task successfully. And, perhaps more importantly, the remaining eight participants believed they had successfully finished the task. None of the ‘unsuccessful’ participants confirmed the change of crop type by touching the Play button. Compared to those participants who were successful, these participants significantly less frequently perceived the AOI that contained the Play button visually (Fisher’s exact test, $p = 0.019$), i.e. most of them had not even detected the button. Nevertheless, as can be derived from the green colour shades of the heatmap in Fig. 2, there were fixations within the AOI even in the group of unsuccessful participants. These test persons obviously did not realise the confirmation function of the Play button. Successful and unsuccessful participants did neither differ in age (t (18) = 1.43, $p = 0.17$) nor in the time they worked with the product Lexion ($U = 46$, $p = 0.91$) nor in their self-assessed experience with the product Lexion ($U = 41$, $p = 0.62$).

Although a quarter of the successful participants touched the Play button within 2.4 seconds after choosing rapeseed from the crop selection bar, many of these participants also had problems recognising that they had to press the Play button to finish the task. This is indicated by the Median of 17.2 seconds for the time span between choosing rapeseed from the selection bar to touching the button. Excerpts from the TA-protocol of a participant exemplify the challenges some participants were faced with: [After switching back to the main menu in the belief that he had successfully completed the task] "This should have worked. …But rapeseed is not displayed there" [He looked at a second screen] "There is still wheat here" [He looked back at the touch screen] "No, the task is not finished yet. There it still says wheat. Huh, are you kidding me?" [He switched back to the menu for crop type selection] "But here it says rapeseed." [He switched into the crop selection bar] "Are you kidding me? There's a check here.... Do I still have to press play?" [After touching the Play button, he switched back to the main menu] "Yes, ok, you probably know that after receiving a briefing."

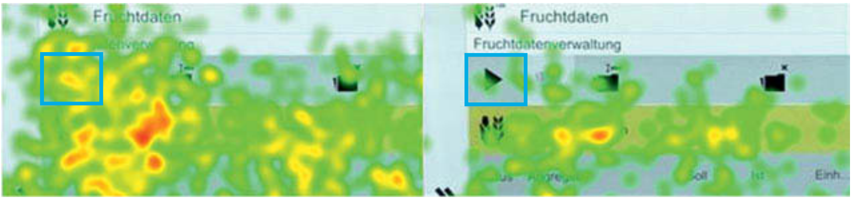

Fig. 2: Heatmaps visualising gaze behaviour within in the area of interest containing the Play button (framed light blue) of participants who successfully completed (left side) and who did not successfully complete (right side) the task. Colour changes from green to yellow to red indicate an increasing number of fixations.

The number of visits within the AOI containing the Play button varied considerably between the successful participants with a minimum of zero and a maximum of ten visits. At the median, the participants visited the AOI three times. The more often the successful participants visited the AOI, the less pleasure (r_s = -0.68, p = 0.015) the less comfortable (r_s = -0.69, p = 0.013) and the more challenged (r_s = 0.79, p = 0.002) they felt during the task. Furthermore, the number of visits within this AOI was negatively correlated with the rating of comprehensibility (r_s = - 0.58, p = 0.047) of the touch display and in tendency with the rating of usability for novices (r_s = -0.53, p = 0.074). In other words, the more difficult is was for these participants to identify the Play button and its function the more negative was their evaluation of UX aspects.

4 Discussion

The two terminal operation tasks demonstrate that the applied method is conceptually suitable for identifying processes that work well and also difficulties in handling newly developed operator terminals for agricultural machines and thus for investigating aspects of UX.

As data show, some participants were very fast and confident in performing the tasks. For these participants, operating the touch terminal seemed to be very intuitive indicating a fundamentally clear menu navigation and a mature product. Nevertheless, there is potential for further developing the touch terminal and make it even more user-friendly.

Even without the data from the questionnaire and the TA protocols, the eye-tracking data indicate that it was not easy for some participants performing particular steps of the tasks. Longer fixation durations and more fixations within the AOI that contained the On-Off button suggest a higher cognitive load related to the content of the AOI and the task [9] and uncertainty [15]. This interpretation is confirmed by the scene video and the TA protocols. The same applies to the Play button, if it was perceived by the participants. An increasing number of visits within an AOI, as observed for some participants for the Play button, is associated with increasing difficulties in operating instruments within vehicles [16]. But this was not the only issue of the Play button. The fact that 40 percent of the participants did not touch this button and most of them did not perceive this button visually indicates a low potential of this area to attract visual attention [9,17]. The main problem here is that touching the Play button was essential for successfully completing the task, but the participants did not realise that they were not successful. This not only leads to a low effectiveness, as an aspect of usability, in performing the task. In practice this could have unpleasant consequences, if the work is continued in the belief that everything was done correctly.

In addition to the gaze behaviour within the AOIs described above, the wide range of time periods required by the participants to complete the tasks or individual steps of the tasks indicate different levels of cognitive load and points to potentials for improving efficiency in operating the touch display [10].

As previous research show, a higher cognitive load is associated with lower user satisfaction, the third aspect of usability, and impairs UX [10]. This is also confirmed for the present study that shows strong correlations between aspects of UX, measured by the subjective evaluations based on the questionnaire, and the objective measurements of the eye-tracking part.

To improve effectiveness, efficiency and satisfaction in the operation of the touch display, results could be used to refine the design of the touch terminal, e.g. to make the state of the On-Off button more obvious, to make the function of the Play button clearer and to make this button more salient, or to integrate pop-up-windows for confirmation functions. Additionally, they could be utilised to develop appropriate training materials or courses since after overcoming an initial learning curve, users become more productive in performing specific HCI tasks [18]. These measures could help to eliminate uncertainties in operating the touch terminal, improve the UX and thus the acceptance of the new technology. Setting the *Q1* for task duration as a benchmark, a further objective of these measures could be enabling all machine operators to successfully complete the tasks within the time span of the respective *Q1*.

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Evaluation of Human-Machine Interactions with Autonomous Agricultural Systems through Cyber-physical Prototypes

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Abstract

The agricultural sector is massively influenced by today's social and economic situation worldwide, for example by a constantly increasing demand for agricultural products. Especially autonomous machines have the potential to be the next level in the course of digitizing production systems as they allow more flexibility and increased productivity. Introducing autonomous systems means a fundamental change in terms of machine processes and operation tasks which require new solutions for human-machine interaction and operator's terminal in the agricultural sector [e.g. 1]. As such systems and processes are not fully established, there is little to no knowledge in this field to rely on. To overcome a gap, these approaches have to be tested as quickly as possible using the potential of iterative prototyping in early stages of the development process.

The Feldschwarm project implements the idea of using a swarm of lighter and smaller autonomous machines as a cyber-physical system for soil cultivation, that still has to be supervised and managed by a skilled operator. The concept, presented at Agritechnica 2019, shows how advanced technologies for highly automated systems, can be implemented. The realization of a real scale fully working machine demonstrator represents a milestone in bringing these to the market [2].

Using such systems, the operator's task range expands from just controlling a single machine towards managing a whole swarm and its peripheral production system. Therefore, the operator has to make decisions requiring more knowledge of overall process and technology. At the same time the machine changes to an unmanned self-acting system without any human relation. This challenges the way of how these machines will be perceived and accepted by farmers and society. We developed a HMI to enable future machine operators to be in charge of such systems, providing advanced process management assistance and machine performance and status overview. Additionally, the whole machine design as well as the machine's status light concept addresses the issues of providing transparency and predictability of autonomous systems.

To develop and evaluate these approaches, we used a broad variety of prototypes with different fidelity levels [3]. They range from rapid (physical) prototypes through interactive models with final design integrated in suitable scenarios (picture 1) to digital VR twins in real-life size. To provide interactive setups, we expand these by modifying the software “Farming Simulator 19” [4]. With its advanced machine, process and environment simulation it enables us to control the swarm via a display-based controller representing our HMI concept, also presented at Land.Technik Conference in Hannover 2019 [5].
However, the implementation of the entire prototype was based on a low effort framework but still achieved an advanced level of fidelity by using existing software and accurate prototyping tools. This also supplies a flexible testing environment not limited by actual technological insufficiencies or complexities. This way, the development process could be also accelerated and reduce the uncertainty connected to designing autonomous machines [6].
With the prototype-based evaluation of our novel HMI concept for highly automated systems, the study aims to contribute to the general discussion about implementing autonomous machines in agricultural applications and deepen our understanding of requirements and approaches when it comes to user-oriented and prototype-based development processes and machine design. The prototyping framework we want to share offers not only a new toolset for developing autonomous machines, their perception and communication with humans. It also provides a safe and flexible environment to test and examine interaction concepts and roles of future farmers to accelerate development processes and reduce uncertainties when it comes to autonomous machines. It further gives insights into the design of cyber-physical systems and their HMIs.

Fig. 1: Interactive prototype at Agritechnica 2019

1. Introduction

Prototyping is an elaborated tool in product development for evaluating concepts and features. Especially in user-oriented development, it is necessary to evaluate different variants in form of comprehensible test objects that can be placed into the context of the application. Functional models help to anticipate certain functions and properties of the final product without the need to be fully developed. Various prototyping approaches can be used in the early phases of development. Deficiencies identified here can still be reviewed and implemented relatively easily in the further elaboration. Prototyping is broadly used in various development areas, regardless of whether they are targeting physical or digital products. With the use of digital technologies like VR, the possibilities for creating prototypes are more diverse than ever before and enable great flexibility and choice.

Within the advancing digitization of agricultural systems, research and development are being carried out on systems and technologies, some of which are fundamentally new to the industry. The greater the functional difference between these and conventional ones, the greater the development uncertainties of whether these systems will meet the expectations and requirements of the users. An example of such a disruptive technology is the introduction of autonomously operating machines. In addition to the purely technical challenge of achieving safe operation and affordable purchase, the question of acceptance together with new operating systems play a certain role. For a successful market launch, such autonomous systems not only have to prove their reliability relatively quickly, but also have to implement new functionalities for communication and monitoring.

A development task is the joint project Feldschwarm, which carries out the research and technical implementation of fully autonomous machines for green area cultivation. The Feldschwarm is a modular system of the units operating in the field semi-autonomously with the farmer actively involved in the process as a part of swarm or fully autonomously within the overviewed area. The aim of the project overall is to finish in Technology readiness level 6, with continuous development of the system itself and therefor moving towards TRL7 [7]. Therefore, from the humanistic point of view we need to solve and test and design various aspects of interaction and elements allowing us to fulfill them.

With the Feldschwarm project and the development heading for fully autonomous field cultivation machines, completely new processes and operating scenarios are presented. In order to enable the gradual change from conventional machine and operating scenarios, these must be understandable and traceable. To evaluate the functional and technological approaches in these areas, seven very different prototypes have been used so far to support stakeholders from development in their cooperative work and to involve investors, customers and users in the development. Table 1 gives an overview of the prototypes created, their structure, functionality and application.

Table 1: Overview of different prototypes used in the development of the Feldschwarm

1	Physical prototype on a scale of 1: 4 as a modular working tool for defining the technical structure	Developer
1	Physical prototype as a modular working tool for defining the technical structure using Lego parts	Developer, Investor
2	Physical prototype on a scale of 1: 15 as a more detailed but less modular demonstrator of the systems structure	Developer, User, investor
3	Interactive physical-digital demonstrator on a scale of 1:6 to communicate the functionality of the system for investigating accessibility and the effect of physical appearance on a 1:1 scale	User, investor
4	Virtual prototype for investigating accessibility and the effect of physical appearance on a 1: 1 scale the application scenario	Developer, user, investor
5	A second virtual prototype to communicate the functionality with a stronger representation of the application scenario of the HMI concept	User, investor
6	Interactive digital mockup of the operating concept to evaluate the basic functionality and the structure of the HMI concept	Developer, user, investor
7	Interactive physical-digital prototype of the operating concept for evaluating and communicating the HMI concept	User, investor

In the following, the problem with the selection of the prototype tools and their functional scope are described and the individual prototypes are presented. These are classified in a literature and experience-based approach. In addition, the analytical examination resulted in concrete scientific questions that are necessary for a systematic and resource-optimized use of prototypes, which are discussed in the outlook.

2. Design and Prototype Requirements

In order to be able to use prototypes in the early phases of product development, they have to predict the development result. It means that they often abstract more or less of the final product in terms of function and appearance. The question arises how much the individual aspects can be reduced and which prototyping tool is best suited for the representation.
Blomqvist and colleagues [8] have presented a framework for this, as shown in Fig. 2. Accordingly, the phase in the development process, the purpose and the target group (audience) must be taken into account when selecting the quality of representation. When developing technical

products, two aspects are of particular interest to us. On the one hand, the use as a communication tool and on the other hand, the use of prototypes for evaluation. When considering the target group, the existing knowledge of the application, functionality and purpose of the product to be developed is relevant for the scope of the information to be displayed in the prototype.

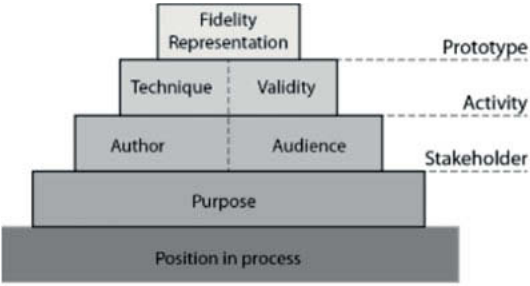

Fig. 2: Framework of perspectives on prototyping and prototypes, taken from Blomqvist [8]

The quality of representation within the prototypes can be described by the construct of fidelity. Fiorineschi and Rotini have brought together various sub-dimensions of this construct [3]. These sub-dimensions are suitable for taking various aspects into account with regard to their realism in scope and depth. The dimensions are shown in Table 2.
These frameworks were used when designing the Prototypes of the Feldschwarm and its human-machine-interface (HMI) concept.

Table 2: Set of dimensions identified for the different meanings of fidelity, taken from Fiorineschi and Rotini [3]

No.	Dimensions	Illustrative example from literature	Reference
1	Data	"How representative of the actual domain data is the data employed by the prototype?"	(McCurdy et al., 2006)
2	Form/ Visualization	"How refined should the prototype be from a visual standpoint?"	(McCurdy et al., 2006)
3	Functionality	"How broadly is the functionality represented within the prototype?"	(McCurdy et al., 2006)
4	Interactivity	"How are the interactive elements (transitions, system responses to user inputs, etc.) captured and represented to the user by the prototype?"	(McCurdy et al., 2006)
5	Prototyping technique	"how well does the technique meet the required level of detail?"	(Mathias et al., 2018)
6	Material	"These are preliminary prototypes constructed with materials that are easy and fast to work with and thus facilitate explorative conversation with materials. These low fidelity prototypes…"	(Bao et al., 2018)
7	Performance	"To what level of detail is any one feature or sequence represented?"	(McCurdy et al., 2006)
8	Environment	"The fidelity of the testing situation may differ from the future usage situation on four dimensions. First, the participant in a usability test may be different from…"	(Sauer et al., 2010)

3. Prototyping stages in the Feldschwarm project

3.1. Prototyping for system design

To fully develop the a properly functioning autonomous swarm, user has to see and understand all the relevant and necessary interactions, so the overall novelty of the solution would not be overwhelming. Additionally, the swarm control and solutions for autonomous machines are relatively unmapped territory there is not much research and functional solutions, which could supply us relevant information about the user behavior and routines to build on. A transparent representation of the system processes and their status and behavior is decisive for the implementation of autonomous machines in the applications in the field. There is even additional challenge in bringing bigger and heavier machines with the more power to open environment whilst comparing to areas such as industrial production and logistic halls with robotic implementation.

3.1.1. Lego based prototype

The first physical prototype of Feldschwarm unit concept was created purely as an ideation and communication tool utilizing capabilities the modularity of Lego system. Based on the previous tests, the use of preexisting Lego bricks created a different possibility to find a solution to a problem, purely on live and vastly iterative testing. Lego Technic as a constructive toolset removed the mental blocks occurring in the ideation process, shifted it to playful experience and did not require any explanation of the whole system. With the low effort we were able to use premanufactured bricks and tiles and move them around to create first design of concept platform. In addition, other components of various machine parts not included in the set were created using CNC mill and 3D printing in the proper scale. This way prototype could be protype used as previously mentioned first concept ideation as well as a discussion object for project partners from other industrial backgrounds developing various parts of the machine and creating more unified vision. The demonstrator was used in the early stage of project, the overall fidelity was low. In addition, the time invested was also low and if it was necessary, we were able to bring more parts to the table for further ideation. However, this was not necessary and based on input and experience after we were able to further develop a project and thus were able to create more complicated and more advanced demonstrators targeting wider audience.

3.1.2. 1:15 Model

The model created in march 2019, was built and presented together with HMI Click dummy and Feldschwarm unit implemented into Farming Simulator 17. The technical concept of the machine and all defined components were already included and it mainly presented the modular options of the machine, such as possibility to quickly disconnect and replace the power unit or to change the working tools. In this phase the demonstrator's scale was slightly increased, but stayed on the smaller side of the spectrum, so the model itself could be handheld and used directly during the discussion. The target audience was already informed about overall project Feldschwarm and was also mostly from the research or agricultural sector therefore the model was not built with the intention to display full design of the machine, but to show of the ideation process that already happened. The prototyping tools implemented were more homogenous than on the model before and using multi jet fusion 3d printer created parts that without any finishing could be connected and used as a representative model. The printing of each part also reduced the possibility of changing the constellation of the parts into the other design. Additionally, as all of the parts shown on the model will be built in the reality from metallic materials, no material and color difference were displayed which also enhanced the homogeneity of the product design.

3.1.3. 1:6 Interactive Demonstrator

Our final scaled model was created to visualize and present the final exterior design of the autonomous Feldschwarm unit and it was shown at Agritechnica 2019. The interactive presentation table was connected with the model which was controlled through self-developed interface. In the model itself was integrated electrical engine and LED lights reacting to an input and synchronized with the soil projection on the field and rotation of the wheels as well as the sign of the status through lighting. Status light signatures displayed on the machine were built upon the ISO norm for autonomous machines. The exterior design was a current state of the development and all the colors and shown material differences were representing the final design which is and will be applied to functional and final demonstrator. The main technology for creating such a model in this level of detail we again chosen 3D printing as the best solution. All the parts of the system: model itself, control panel from tablet and the interactive table; were all connected wirelessly and communicated through MQTT Broker. The complexity of this model was higher and so was the time invested into development, but relevant in this phase of the project and based on the scale of the audience was this solution allowed us to present the visitors and partners the interactive object which was communicated the Feldschwarm units visual appeal and visual communications in the live field through pre-defined scenarios and situations.

Nonetheless it gave us also an object, where we can discuss and present other aspects of the machine such as machine architecture and modularity of the units. Through this discussion we were also able to get the relevant feedback from international visitors and potential users as well as increase the acceptance of the fully autonomous machines, discuss farmer's role in the future of farming and learn more about specifics of agricultural sectors in other parts of the world.

3.1.4. 1:1 Virtual Reality Demonstrator

A natural perception of the designed machine design is only possible to a limited extent via the physical models, as the true-to-scale images do not reflect the actual proportions of the viewer. Transmission via the digital CAD tools is also necessary for a realistic impression. Digital 1: 1 models were set up in VR scenarios to ensure that the evaluation of the decision-making processes was as unadulterated as possible in the early phases of product development. With their help, both the overall effect of the machines can be understood and investigations such as accessibility and space requirements studies or tests for the visibility of danger points and status lighting are possible.

It was important to avoid a large development effort, as would also be necessary for physical model making. A simple implementation took place via direct data porting into the 3D visualization software Autodesk VRED. In this way, no model preparation of the native CAD data formats had to be carried out separately for the real-time simulation. The transfer to a tessellated mesh model took place via the internal import function of VRED. Oculus Quest VR glasses were available as output devices, which were operated via SteamVR and the OpenVR HMD API using a USB 3.1 cable connection. This resulted in a simple and mobile setup that is ready for use without a tracking system or calibration. On the hardware side, there are limitations and drawbacks in the display quality of the head mounted device, which is one of the entry-level models equipped with two OLED displays with a resolution of 1440 × 1600 pixels each, a refresh rate of 72 Hz and a fall of view of 95 °. For the intended question of the rough effect and the ergonomic consideration, it was rated as sufficient. The most photorealistic representation in VR was initially dispensed with. No suitable API was available in VRED for the actual advantage of a wireless connection of the VR glasses, which allows unrestricted movement around large objects such as the real-size machine. Setting it up in an alternative environment such as UNITY, on the other hand, involved effort in preparing the model and transferring it to the VR glasses themselves.

The interaction of the machine was also limited to immersive viewing in virtual space. In order to display the Feldschwarm interactively and contextually in a realistic environment, this VR setup did not seem suitable, given the effort involved in implementing the environment, the process simulation and all control commands. Switching to an existing simulation environment appeared to be more efficient and promising.

3.1.5. Farming Simulator

For the investigation of the human-machine interaction, an environment is required that to a certain extent already provides the behavior of the entire system. Virtual realities offer the advantage of simulating the system in an environment that is safe for people and technology, regardless of the actual state of development. In addition, data can be easily changed, exchanged or processes can be tracked. This step was a special focus, especially in the case of autonomous swarm systems, where no established system can be used. A resource-saving approach was the expansion of the computer simulation game Farming Simulator 19 by the software developer Giants, which depicts agricultural processes on an abstractly simplified level, but holistically in a realistic context with a high level of interactivity and functionality. In addition, tools and good documentation for in-house developments, so-called modifications, are provided. Under the concept of "Serious Gaming", Giants also offers the possibility of greatly increasing the simulated process depth and even integrating original CAN bus control signals and real machine behavior [9]. Within the Feldschwarm project, three goals were defined for the expansion of the virtual test environment for autonomous swarm systems:

- Implementation of the Felschwarm machine concept
- Defining the infrastructure for autonomous swarms
- Provision of an interface for your own HMI concepts

In preparation, existing CAD models from the construction were converted into mesh models and partly rebuilt manually. Here again the problem of reducing complex CAD data into mesh models suitable for real-time simulations becomes apparent. A guideline value of a reduced number of polygons of less than 50,000 is recommended for large machines. The Feldschwarm machine concept was successfully implemented in the existing simulation structure using its own vehicle and tool class definitions. In detail, simplifications such as the height adjustment of the attachment to the two-stage state (active / inactive) were necessary to ensure functionality within the simulation.

After all, this simulation environment would not only be shown and used within the development team and in front of stakeholders (investors and operators), but also publicized to the broad audience of the Giants community, who as gamers but also as potential current or future farmers which can transmit customer feedback at an early stage. Additionally, it offers the potential to develop an understanding of autonomy and to learn a new generation through play. The inclusion of users, especially in highly technology-driven developments, in which people will still be an essential part in the future for a successful paradigm shift.

3.2. Prototyping for HMI development

The defined context of use covered: partial task management, process-preparing steps and the actual monitoring during the work on field. This should ensure that a holistic HMI concept will cover all the basic necessities relevant to the other development areas with the intersection to smart farming solutions and not to create an isolated individual solution.

The usage requirements were based on the work tasks of certain user roles, which include both experienced operations managers and assisting machine operators. A detailed description of the HMI and a classification of the solution approaches such as adaptivity, assistance and learning, is described in the publication " FELDSCHWARM©-UI: A User Interface for Controlling Swarm Technology" [5]. At this point, the methods used for an iterative and exploratory solution are explained and how they were evaluated within the developer group, whereby user feedback from various trade fair demonstrations was also incorporated.

3.2.1. HMI Clickdummy

Based on the user requirements and the functional description, static drafts for the layout and screen design for a graphic user interface of the Feldschwarm HMI were created. On the other hand, dynamic or interactive prototypes are suitable for displaying the user guidance and operating logic in a comprehensible and verifiable manner, especially if the UI is characterized by a high degree of content complexity and strongly linked content. A well-known prototyping technique from the field of human computer interaction are look-like prototypes, so-called click dummies. It is characterized by a high simulated fidelity, whereby as a no-code creation it requires relatively little effort. In the past few years, the number of platforms offered and, above all, their functionality has increased (see Adobe XD, Protopie, Figma, Framer...). Even if they often do not reproduce dynamic content, they can either provide a rough overview of the operating structure or even map a single action in detail using deeper interaction steps. This prototype technique is rather unsuitable for combinations of widely ramified and associative content. Protopie.io already offered open interfaces / APIs. An interactive click dummy was created that covered both the GUI for the first draft of Feldschwarm management with a focus on order creation and a multi-layer monitoring system, as well as allowing interactions with physical models by reading in model states via RFID or identifying attachments that act as trigger The event as a result was summarized as a milestone in a demonstrator with a 10" Pokini industrial tablet and a self-designed case and provided the basis for discussion within the development team but also at trade fair presentations and public events at the university.

For the further development of the HMI, prototyping was used across platforms and devices. A web-based click dummies enabled the implementation of individually required interfaces, especially communication with the MQTT broker, as is already used by the interactive 1: 6 machine model. With the uniform communication standard, a framework was set up internally to wirelessly network different prototypes with one another. For a similarly flexible UI development as with the already used UI prototyping tool Protopie, a structure using the content management system WordPress seemed promising. With the help of the Elementor Pagebuilder plugin, the revised design could be implemented as an HTML page using predefined page elements and animations using drag-and-drop, without having to rely directly on programming knowledge. It was extended with a JavaScript WebSocket client for MQTT communication. Another separate JavaScript file evaluates incoming and outgoing commands. Finally, the UI can be called up via the browser on a laptop, smartphone, tablet or smartwatch. A Samsung Tab A 10.1, which is lighter and smaller than the previously used industrial tablet, was used for the control terminal. Further ergonomic improvements included new haptic control elements, which were also functionally integrated into the prototyping framework. The large range of functions of the prototype with partly highly individual solution approaches reached the limits of the predefined modular system of the page builder. Missing modules could be added using further plugins, but significantly increased the development effort and reduced the clarity in the backend. Designs that have similar structures to commercial websites are particularly suitable. But also in the Feldschwarm project, the approach presented supported rapid interaction with end users in an agile design process for industrial applications. The toolkit enables the development of user interfaces (UIs) for joint research and validation of new operational concepts and new technologies for decision making and situation awareness.

3.2.2. Connecting UI prototypes and digital simulation environment

In preparation for further investigations, the developed operating terminal including GUI could be merged with the farming simulator. As already described, an MQTT communication standard was used. In addition to the web socket client of the GUI, an MQTT client was set up on the Arduino module. This functioned as an interface both in the control terminal for the control commands via the physical control units and on the base station of the HID for the farming simulator. However, there were limitations in terms of performance. In particular, the continuous transmission of analog control signals when operating the joystick was subject to a latency of 550 ms to 1360 ms and is thus beyond the tolerated reaction delay of humans, especially when it concerns sensitive control commands for remote-controlled driving. At this point, a radio or Bluetooth connection with lower latency is recommended. In addition, the interface to the Farming Simulator is one-sided, i.e. only input signals are processed. Log files for tracked simulation data could only be saved locally and were not sent to the HMI in real time. The existing structure is therefore more suitable for interactions such as manual driving and less for monitoring swarm processes.

4. Summary and Classification of the Prototypes

During the course of the project, prototypes were created with an exploratory, evaluative and communicative objective. The respective target group had an impact on the choice of prototype technology. For questions relevant to interaction, looks-like prototypes appear to have a higher priority, provided that the operating performance does not restrict the use of the prototype. As a first approximation, what level of representation should be fulfilled and to what degree of quality is described below by comparing the prototypes with the eight sub-aspects of fidelity. The Feldschwarm project also shows that prototypes can be mapped real, virtual or hybrid. To what extent this affects the evaluation remains to be discussed.

4.1. Classification of the prototypes with regard to their physical-digital characteristics

The prototypes for the system design are purely physical models and stand in contrast to the otherwise often digital product development in CAD. As real objects, they made the Feldschwarm appear tangible in the early phase of the project. Very abstract, the Lego and 1:10 models illustrate the structure, kinematics and modularity of the machine concept. In order to increase the intelligibility for a wider audience, a digital environment was added as a realistic contextual reference for the 1: 6 model. In addition, a first digital interface was available for a simple HMI, so that the machine was also perceived as a complex cyber-physical system by external parties. The VR scene, on the other hand, is a purely digital image. The first UI click dummy is also characterized by a strongly digital expression. Only the associated 3D printed terminal with physical operating elements raises the interaction to a real level. Even if the Farming Simulator is a purely virtual environment, interaction also takes place via physical control elements. Fig. 2 gives an overview on their different physical and digital characteristics.

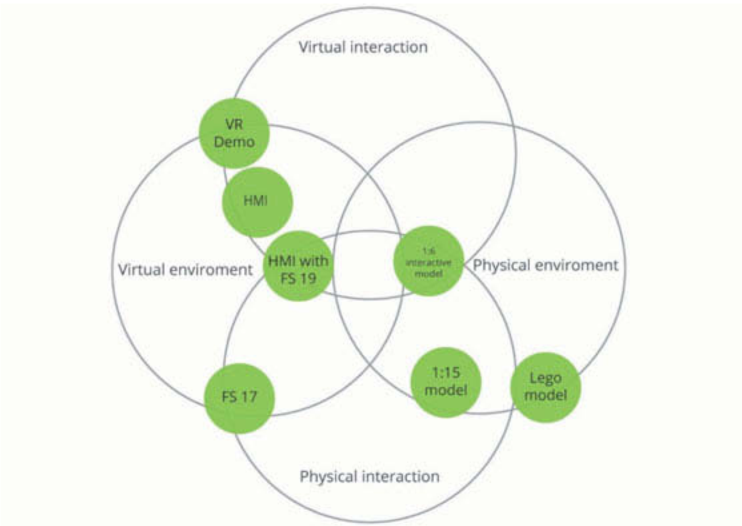

Fig. 2: Classification of the Feldschwarm prototypes with regard to their physical-digital characteristics

4.2. Classification of the prototypes in terms of their fidelity

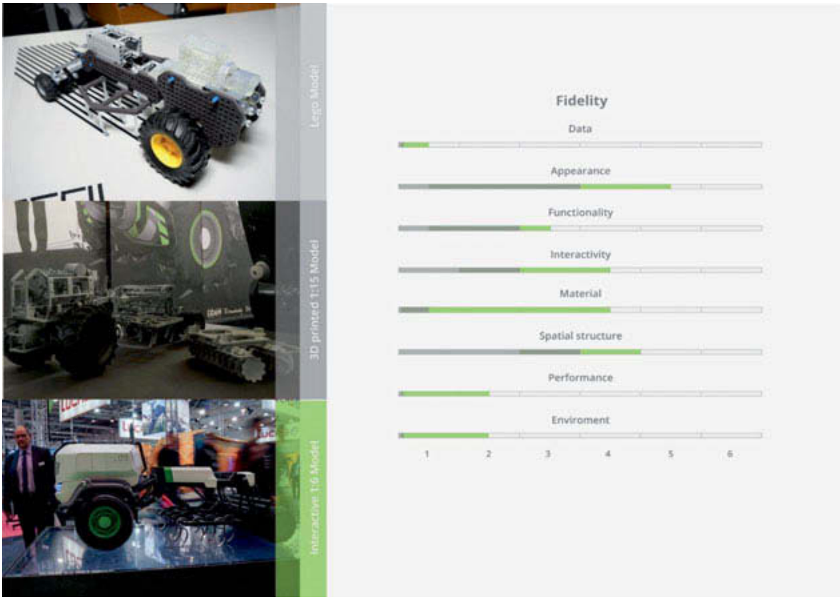

Fig. 3: Fidelity rating of prototyping for system design

The prototyping for the system design took place in stages and changed from exploratory prototyping with low-threshold physical models to generate ideas and as a proof of concept method to interactive demonstrators that put the system in a realistic usage scenario and predict full-time behavior. Based on the description of the basic functionality of the machine through simple Lego and 3D printed machine structures, the functionality represents the focus of these prototypes and was evaluated with MID (middle) Level. The same applies to the appearance, even if the highly abstract rendering is limited to the form. The presentation of the first system components is reflected in the mean assessment of the spatial structure. Since these models functioned primarily as a process prototyping method, the interactivity was also classified with MID. All other aspects of fidelity are irrelevant. The interactive 1: 6 model, on the other hand, supplements the first environment and performance aspects in the low range. At the same time, the interactivity increases, since a first HMI was already connected. In addition, final color and material impressions are shown in detail.

Fig. 4: Fidelity rating of HMI prototyping

Through the use of virtual realities, it was possible to generate a high perceived fidelity of the environment despite relatively less effort. It was only through the expansion of the Farming Simulator that it was not the individual machine but the swarm idea that was shown and tangible for the first time. This also evaluates the interactivity and functionality in the MID area. The appearance of the machine includes shape, color and sound. The viewer also gets a visual impression of the material thanks to the simple UV mapping. However, the render qualities are not sufficient to reflect a final physics of the machine, so that these aspects remain in the MID area. Even if it is only shown virtually, the animations and the specific performance data provide initial indicators for the performance of the Feldschwarm system. As with the previous prototypes, no real data is used.

The UI click dummy with NFC is characterized by an interactivity from LOW to MID. In connection with the design and implementation of the HMI case, a high fidelity for the appearance is achieved. The material ranges from rubberized grip surfaces to the smooth touch surfaces of the display. With the housing printed using the MultiJet process, the material has an MID rating. The functional prototype integrates prototypical microelectronics, which in its approach is comparable to the package of the final operator terminal, but not identical, which is why Spatial

Structure is rated as MID. An environment is hardly reproduced via the HMI prototype and functionality is not implemented either. This is only achieved by linking the HMI prototypes with the simulation environment of the Farming Simulator.

4.3. Overview of Prototyping-Framework

Fig. 5: Worksheets of Prototyping-Framework for system design prototyping (left) and HMI Prototypes (right)

The prototypes were developed on the basis of the framework shown in Fig. 5, which initially requires the discussion of the purpose, the audience and the scope. Already known specifications were listed in the template creating a working tool for prototype development. Building on this and especially in comparison to the existing and classified prototypes, guidelines and necessary requirements for the further development of the prototype can be derived. The framework shows the achieved implementation quality of the prototype over the key value of fidelity, which is summarized as the average of the sub-dimensions. In retrospect, this overview can also be used to derive the dependency between purpose, audience and required fidelity. For this, the sub-dimensions would have to be described more precisely with a measurable quantity. The classification shown here is based on an assessment within the expert group.

5. Discussion

The modular system structure with Lego building blocks and 3D-printed components provided an intuitive and interactive basis for discussion in order to advise on various configurations quickly and easily. Even if such a setup can now easily be mapped completely digitally, the use of a physical structure in face-to-face meetings has proven its worth, primarily due to its intuitive and quick adaptability. From our point of view, this approach is ideally suited for fundamental questions about the structural design of technical systems and their discussion in face-to-face workshops.
The presentation of the system concept for external stakeholders such as investors and users particularly benefited from the physical aspect of the hybrid demonstrators. Simple interactive extensions of the physical models supported the understanding of the actual functionality and were able to complement the limited interactivity of physical models very well. Gamification approaches through the interaction with the digital extensions support an inspiring staging of the product. The detailed physical model in turn made the product tangible and supported the demonstrator's presence. The survey from the purely digital also helped to increase the credibility of the project implementation.
The HMI prototypes showed that a simple and less interactive implementation was particularly helpful for discussion within the development team. Certain new aspects of machine operation and monitoring could also be discussed with experts. For a helpful evaluation of the approach by the user, however, a significantly more complex implementation with extended functions and the coupling to the application were required in order to generate the necessary depth for the correct classification of the functions. The use of the Farming Simulator as an easily accessible and widely used application simulation in the industry has proven itself in our first experiments. With our developed workaround for the integration of physical operating elements, flexible operating environments with specific application scenarios can be implemented in very realistic test setups for further investigations and projects.

6. Outlook

After differentiating various interactions with the machine that had to be targeted, we researched and listed various tools, our earlier experience with them and evaluated options from the low to heavy effort platforms. In the decision process we found out that the overall testing will not be possible with only one toolset and we need to split in-between physical, virtual and hybrid test platforms. This way we were able to cover various topics through various demonstrators and cover the problematics of the Cyber physical system in the agricultural sector.

With the physical, digital and hybrid prototypes used, the complex relationships and, in some cases, fundamental new technological and functional aspects of the Feldschwarm could already be implemented in high-performance prototypes in the early phases of development. The selected configurations have proven themselves in the respective tasks. In particular, the Developed Workaround for integrating the farming simulator runs a powerful and flexible platform to analyze and evaluate new system and operating concepts with developers, users and investors in future projects in the agricultural and construction sector. With the use of the frameworks by Blomqvist and Fiorineschi, the approaches could initially be classified systematically with regard to their characteristics based on their contexts of use and the target groups to be addressed and described in a comparable manner. A further analysis and evaluation should provide the further scientific discussion with insights into which implementation depth of the individual fidelity sub-dimensions is necessary at which point and in which task context the prototype is necessary. The knowledge gained at this point can help to use various hybrid prototypes in a targeted manner in the development of innovative and disruptive technologies in the field of mobile work machines. With the use of the right prototype setup, these can be used even more efficiently and with less resources in order to secure future development projects with the use of these prototypes and to increase the quality and performance of the developed systems.

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Remote Sensing im Feldversuchswesen

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Zusammenfassung

Wissenschaftler, Züchter, Agrochemieunternehmen und Landwirte nutzen Feldversuche seit langem um die Wirkung ausgesuchter Anbautechniken (z. B. Düngung, Sorten, Pflanzenschutz, Bodenbearbeitung) auf Pflanzen, Boden und Atmosphäre testen zu können [6]. Ein Feldversuch ist im Allgemeinen so gestaltet, dass er statistisch gesicherte Ergebnisse ermöglicht. Dazu sind Messungen, Zählungen und Bonituren nötig, die teilweise einen erheblichen personellen und technischen Aufwand bedeuten.

Fernerkundung und bildbasierte Techniken können dabei wesentliche Vorteile gegenüber manuellen Bewertungsverfahren bieten:

- Quantitativ und qualitativ, maschinell ermittelte Daten reduzieren menschliche, individuelle Fehlerquellen und führen zu einer Objektivierung der Versuchsauswertung.
- Bildbasierte Techniken und Softwarewerkzeuge ermöglichen einen hohen Grad an Automatisierung bei der Datenerfassung und -verarbeitung.
- Drohnengestützte Fernerkundung kann im Vergleich zu manuellen Prozessen ein größeres Gebiet der Versuchswesens schneller und frequenter erfassen.
- Die Fernerkundung kann das gesamte Gebiet einer Versuchsfläche messen, nicht nur die vom Feldarbeiter individuell ausgewählten Punkte.
- Fernerkundungsdaten werden im Laufe der Zeit und unter verschiedenen Umweltbedingungen vergleichbar.

Drohnengestützte Fernerkundung kann dabei mehrere Aspekte der Phänotypisierung und botanischen Bewertung adressieren:

- Flächenmessungen in multispektralen Orthomosaiken geben einen genauen quantitativen Überblick über Biomasse, indirekte N-Verteilung, Stressfaktoren oder Trockenmasse.
- Photogrammetrische Techniken helfen bei der präzisen Berechnung der Wuchshöhe auf einem Feld oder einer Versuchsparzelle. Im Vergleich zu Laserscannern ist diese Lösung kosteneffizienter und bietet eine höhere Datenauflösung.

- Statistische Mittelwerte und Standardabweichungswerte für Indexkarten und digitale Oberflächenmodelle lassen sich automatisch ermitteln.
- Spezielle Indizes ermöglichen die Quantifizierung des Bedeckungsgrads der Parzellen.
- Hochauflösende Orthomosaike ermöglichen eine präzise Zählung von Pflanzen oder sogar Blättern.

In einem zehnmonatigen Projekt hat Pix4D in Zusammenarbeit mit dem Institut für Agrar- und Stadtökologische Projekte an der Humboldt-Universität zu Berlin (IASP) wurden Methoden der Fernerkundung im Feldversuchswesen anhand typischer Mess- und Bonituraufgaben auf der Versuchsstation Berge in Brandenburg getestet und mit herkömmlichen Ansätzen verglichen.

Es geht hierbei weniger um die wissenschaftliche Auswertung konkreter Feldversuche als vielmehr um die Bewertung der technologischen Methodologie.

Technologische Grundlagen

Feldversuche

Wissenschaftliche Feldversuche dienen dem Ziel den Einfluss einer Anbautechnik auf Pflanzen, Boden und Atmosphäre vergleichend bewerten zu können. Biologische Systeme sind räumlichen und zeitlichen Schwankungen unterworfen. Die wissenschaftlich korrekte Durchführung eines Feldversuches muss deshalb immer auf die räumliche Variabilität landwirtschaftlicher Flächen eingehen. Dazu werden die zu vergleichenden Anbautechniken (Düngung, Sorte, Bodenbearbeitung etc.) parzellenweise variiert und wiederholt in einem Feldversuch angeordnet. Da sich die Untersuchungen auf den definierten Raum der Parzelle beziehen, ist ihre (Zentimeter-) genaue räumliche Abgrenzung wichtig. Die Bewertung der untersuchten Anbautechnik erfolgt auf Basis der gemessenen, gezählten und bonitierten Merkmale. Eine statistische Verrechnung ermöglicht es, signifikante Unterschiede festzustellen. Seit jeher wird in Feldversuchen spezielle Versuchstechnik eingesetzt, da die hier gestellten Anforderungen oft andere sind als die in der sonstigen Landwirtschaft. Gleiches gilt für den Einsatz von Drohnen im Versuchswesen. Die Anforderungen an Drohnen im Versuchswesen unterscheiden sich insbesondere hinsichtlich der möglichen Auflösung und der erreichten Genauigkeit der georeferenzierten Positionierung. Die zu befliegenden Flächengrößen sind dagegen meist deutlich geringer als jene in der Landwirtschaft.

Drohnenbasierte Photogrammetrie

Die Beschreibung photogrammetrischer Methoden geht zurück auf die 1850er Jahre. Erste mechanische photogrammetrische Systeme sind seit Ende des 19. Jahrhunderts bekannt. Doch erst mit der Einführung leistungsstarker Computer ist es möglich, große Bilddatenmengen in angemessener Zeit zu verarbeiten. Softwarealgorithmen berechnen dabei über die Erkennung wiederkehrende Eigenschaften von Einzelaufnahmen einer Szenerie aus unterschiedlichen Blickpunkten 3D-Punktwolken, Orthomosaiken oder Vermaschungen (siehe auch [2]-[5]).
Obwohl photogrammetrische Methoden mit einer Vielzahl von unterschiedlichen Kameras und Sensoren möglich sind (Digitalkamera, Handykamera, Luftbildkamera im Flugzeug, Multispektralkamera, Rigsysteme, ...), gelten unbemannte, preiswerte Luftfahrzeuge - Drohnen - als wesentlicher technologischer Impuls der rasanten Entwicklung der letzten Jahre. Drohnen wiederum wurden erst ermöglicht durch einen Durchbruch in der Batterie- und Motorentechnologie. Nur Lithium-Polymer-Batterien haben ein hinreichend kleines Gewicht, große Energiedichte und Leistungsabgabe, um Drohnen in der Luft zu halten. So bildet die Verfügbarkeit von Digitalkameras, leistungsstarken Prozessoren, preiswertem Speicher und Drohnen die technologischen Grundlagen für eine breite Anwendung der Photogrammetrie in der Vermessung, Bau, Bergbau, Landwirtschaft, Infrastrukturinspektion und vielem mehr. Der Zeitpunkt dieser Entwicklung lässt sich auf die Jahre 2010-2013 festlegen.

Zukünftig werden sich durch preiswerten, cloudbasierten, nahezu unbegrenzten Speicher und Rechenleistung weitere Anwendungsfelder ergeben. Machine-Learning basierte Klassifizierungsmethoden werden zu einem maschinellen Verständnis in digitalen Karten und 3D-Modelle führen und die Entwicklung entscheidungsunterstützender Systeme auch in der Landwirtschaft ermöglichen.

Multispektrale Bildanalyse

Wenn die von der Sonne ausgesandte elektromagnetische Strahlung auf die Erdoberfläche trifft, werden Teile der Strahlung reflektiert und anderer Teile absorbiert. Das Reflexionsvermögen ist eine charakteristische Eigenschaft, die genutzt werden kann, Materiale zu identifizieren und zu klassifizieren. Zum Beispiel absorbieren gesunde Pflanzen vor allem den roten und blauen Anteil des sichtbaren Lichtspektrums, da Chlorophyll diese Teile des Lichts in der Photosynthese als Energiequelle nutzt. Gleichzeitig reflektieren sie viel stärker den Nahinfrarotbereich.

Gestresste Pflanzen ändern ihre spektrale Reflexionssignatur. Sie reflektieren stärker den sichtbaren Bereich des Spektrums und weniger den Nahinfrarotbereich. Auch ist die Steigung im Übergang von niedrigen Werten im visuellen zu höheren Werten im Nahinfrarotbereich weniger steil. So haben Böden typischerweise ein flaches Spektrum ohne einen ausgeprägten Übergang zwischen visuellem Bereich und Nahinfrarot.

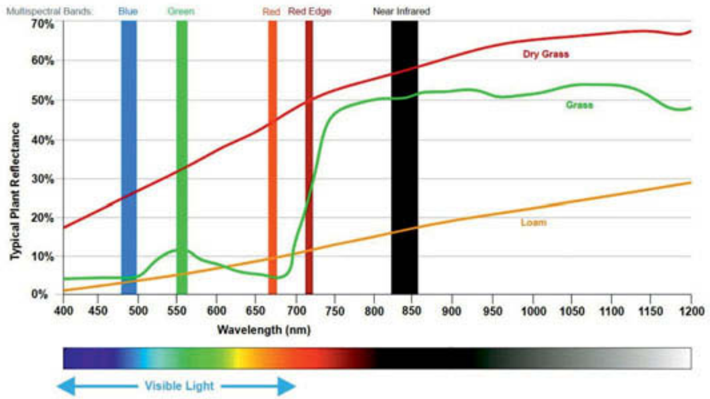

Bild: Beispielspektren für Erde und Gras. Multispektralkameras erfassen dedizierte Bänder des Gesamtspektrums.

Multispektrale Bildanalyse umfasst die Messung von Multispektralsensordaten, die Erzeugung präziser Orthomosaiken für Reflektion und Indizes, sowie die agronomische und statistische Auswertung der digitalen Reflexions- und Indexkarten (siehe [1]).

Lidar

Lidar-Sensoren emittieren Laserstrahlen und erfassen die Reflektion des Lichts des untersuchten Objekts. Die Zeitdifferenz zwischen Laseremission und Sensormessung wird genutzt, um die Entfernung eines Bildpunkts zu bestimmen.

Bei UAV-basierten Lidar-Messungen für eine landwirtschaftliche Anbaufläche werden die Laserstrahlen von unterschiedlichen Ebenen des Bewuchses reflektiert. Das Sensorbild liefert eine 3D-Tiefenstruktur. Insbesondere bei Anwendungen in der Forstwirtschaft lassen sich so Art, Form und Anzahl der untersuchten Bäume einer Fläche bestimmen, sowie das unterliegende Höhenprofil.

Thermografie

Bei der Thermografie wird die Infrarotabstrahlung eines Objekts sensorisch bestimmt und als Temperatur des Objekts interpretiert.
Thermalsensoren können ebenfalls in Drohnen verbaut werden und mit z.B. dem Softwaretool Pix4Dmapper zu 3D-Modellen und Orthomosaiken verarbeitet werden.
Thermalsensoren können im Feldbau dazu dienen, Trockenstress zu erkennen.

Drohnen und Sensorik

Im Rahmen der Versuche kamen folgende Drohnen mit RGB- und Multispektral-Sensorik zum Einsatz:

- Parrot Bluegrass inklusive Sequoia+ Multispektralkamera
- DJI Phantom 4
- DJI Phantom 4 Multispektral RTK
- Parrot Anafi
- Parrot Anafi Thermal
- DJI Mavic 2

Lidar-Messungen wurden bisher nicht durchgeführt.

Vergleich mit bisherigen Zähl-, Mess-, und Boniturmethoden

Neben Messungen und Zählungen werden Merkmale in Pflanzen bonitiert. Eine Bonitur ist eine fachgerechte, qualitative Beurteilung landwirtschaftlicher Betrachtungsobjekte. Im Feldversuchswesen werden Bonituren durchgeführt, um Parameter des Wachstums und der Entwicklung von Pflanzen aufnehmen zu können, die nicht oder nur mit großem Aufwand direkt gemessen oder gezählt werden können. Die Qualität der Bonitur ist abhängig von der Erfahrung und Fachkompetenz der Bonitierenden aber auch von der physischen (Sehvermögen) und mentalen (Müdigkeit) Verfassung. Für die Weiterverarbeitung der in einer Bonitur erzeugten Daten (z.B. statistische Verrechnung) werden meist vorab Boniturnoten definiert (z. B. 0 - 9), die dann, während der Bonitur entsprechend der Merkmalsausprägung vergeben werden.

Im Folgenden wird anhand von drei Feldversuchen exemplarisch gezeigt, wie Drohnen bei der Datenerfassung in Feldversuchen eingesetzt werden können. Insbesondere wird auf die Mess- und Boniturparameter

- Allgemeiner Zustand der Parzellen (Z. b. Stand nach Winter, zeitliche Veränderungen im Pflanzenwachstum)
- Pflanzenzählungen
- Höhenmessung
- Homogenität eingegangen.

Pflanzenzählung bei Sonnenblumen Mai 2020 - Oktober 2020

Versuchsbeschreibung

Die Verteilung von Pflanzen auf einer Versuchsfläche ist wesentlich von der Verteilung des Saatgutes, dem Feldaufgang, und der nachfolgenden Beschädigung aufgelaufener Pflanzen durch Schaderreger abhängig. Grundsätzlich ist eine gleichmäßige Verteilung von Pflanzen vorteilhaft, die jeder Einzelpflanze einen definierten Standraum zuweist. Auf einem sandigen Boden der Versuchsstation Berge (Havelland) wurden Sonnenblumen in Reihenabständen von 75 cm angebaut. Die Zählung der Pflanzen erfolgte im Vier- bis Sechsblattstadium manuell auf definierten Streckenabschnitten der Reihenkultur. Dabei sollten nur die Kulturpflanzen und nicht etwaige Unkräuter berücksichtigt werden.

Zählung der Pflanzenanzahl

Das Sonnenblumenfeld wurde mit einer DJI Phantom 4 in einer Höhe von 7 m beflogen. Das Orthomosaik wurde mit Pix4Dfields erzeugt und hat eine Auflösung von 0,2 cm / Pixel. Die Schattierung resultiert aus wechselnder Bewölkung während der Befliegung. Mithilfe des Softwareprodukts Global Mapper wurde ein Bereich von 2 m x 2 m frei an verschiedenen Orten platziert, um die Anzahl von Pflanzen zu zählen und die Keimrate zu beurteilen.

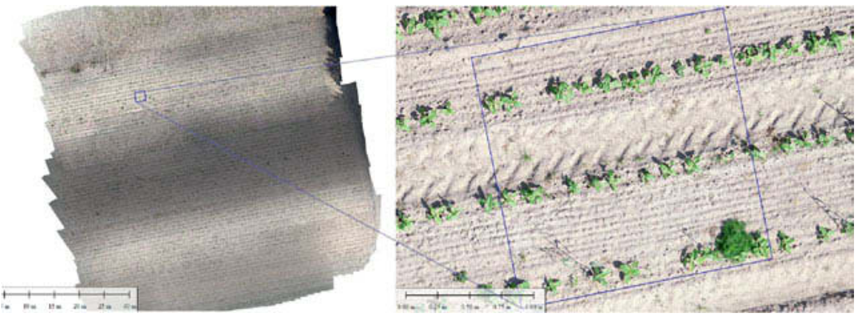

Bild: Markierter 2m x 2m Bereich

Ergebnis: Mit Hilfe der Drohne gelang es, die Sonnenblumen-Pflanzen zu zählen und die Abstände der Pflanzen innerhalb einer Reihe zu erfassen. Nur in wenigen Fällen unterschieden sich die manuellen Zählungen von der Erfassung per Drohne. Wo zwei Pflanzen direkt nebeneinander standen erschienen diese bei der Zählung per Drohne als eine Pflanze. Außerdem wurden Unkräuter, die in der Drillreihe standen und in Form und Farbe der Sonnenblumen ähneln, als Sonnenblumen gezählt. Es ist deshalb davon auszugehen, dass die Genauigkeit der Zählung per Drohne sinkt, je mehr Pflanzen in sehr geringem Abstand voneinander stehen und je mehr störende Strukturelemente Elemente (Unkraut, Steine) vorhanden sind. Dem kann mit einem erhöhten Aufwand bei der Befliegung und Nachbearbeitung begegnet werden.

Bonitur des allgemeinen Zustandes von Parzellen im Winterroggen
Oktober 2019 - Juni 2020

Versuchsbeschreibung

Um die Wirkung diverser Biogas-Gärreste auf den Boden und auf das Pflanzenwachstum zu bestimmen, wurde 2011 ein Feldversuch mit einer Grünroggen-Silomais-Grünroggen-Sorghumhirse Fruchtfolge angelegt. Seitdem werden regelmäßig Parameter des Wachstums und der Entwicklung aufgenommen. Zu den regelmäßigen Bonituren gehört auch die visuelle Inaugenscheinnahme, um den Wachstums- und Entwicklungsfortschritt der Pflanzen sowie Unregelmäßigkeiten in den Parzellen bewerten zu können. Die Bonitur des allgemeinen Zustandes der Parzellen dient auch der Qualitätskontrolle von Versuchen. Im Folgenden wird dargestellt, wie diese Aufgabe mit Hilfe einer Drohne erledigt werden konnte.

Zeitlicher Vergleich des Pflanzenwachstums

Der Versuch zum Winterroggen vom 31.3.2020 und vom 21.4.2020 wurde visuell verglichen. Die Bilder wurden mit einer DJI Phantom P4 ohne RTK aufgenommen und mit Pix4Dmapper verarbeitet. Die Georeferenzierung erfolgte mit QGIS über die Zuordnung charakteristischer Geländepunkte.

Die Befliegungen ließen sich bei guten Witterungsbedingungen durchführen. Starker Wind ab ca. 35 km/h führte in unseren Versuchen dazu, dass die Einzelbilder der Parzellen sich so stark voneinander unterschieden, dass diese nicht mehr zu einem Orthomosaik zusammengefügt werden konnten.

Bild: Vergleich hochaufgelöster RGB Orthomosaiken

Ergebnis: Auf den mit der Drohne produzierten Bildern sind Unregelmäßigkeiten (Stellen mit geringer Anzahl Pflanzen) in den Parzellen gut zu erkennen. Der Wachstums- und Entwicklungsfortschritt lässt sich ebenfalls ausreichend genau abschätzen. Die regelmäßige manuelle Inaugenscheinnahme der Parzellen lässt sich durch den Einsatz der Drohne grundsätzlich ersetzen. Ein Vorteil der Drohne ist dabei die Draufsicht, bei der sich Lücken auch in der Mitte einer Parzelle gut erkennen lassen während der Betrachter vor Ort die Pflanzen nur in einem bestimmten Winkel sieht. Insbesondere bei hohen Pflanzen ergibt sich hier ein Vorteil.

Messung der Pflanzenhöhe und Biomasse von Roggen

Das Versuch mit Winterroggen wurde mit einer DJI Phantom 4 am 21.4.2020 in einer Höhe von 15m beflogen. Mithilfe von Pix4Dcloud wurde das digitale Höhenmodell (DSM) berechnet und anschließend in Global Mapper importiert. Dort wurden die zu untersuchenden Parzellen ausgeschnitten und die Histogramme erstellt. Die Histogramme können in verschiedenen Auflösungen berechnet und exportiert werden. In z.B. Microsoft Excel lassen sich dann Mittelwerte und Standardabweichungen berechnen. Die Wuchshöhen dicht beieinander liegender Parzellen können quantitativ verglichen werden.

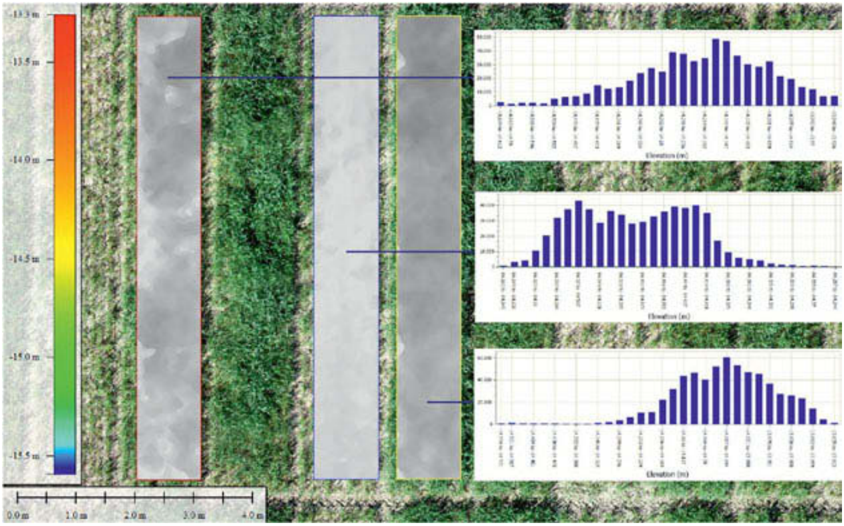

Bild: Photogrammetrische Höhenmessung über ein digitales Höhenmodell (DSM)

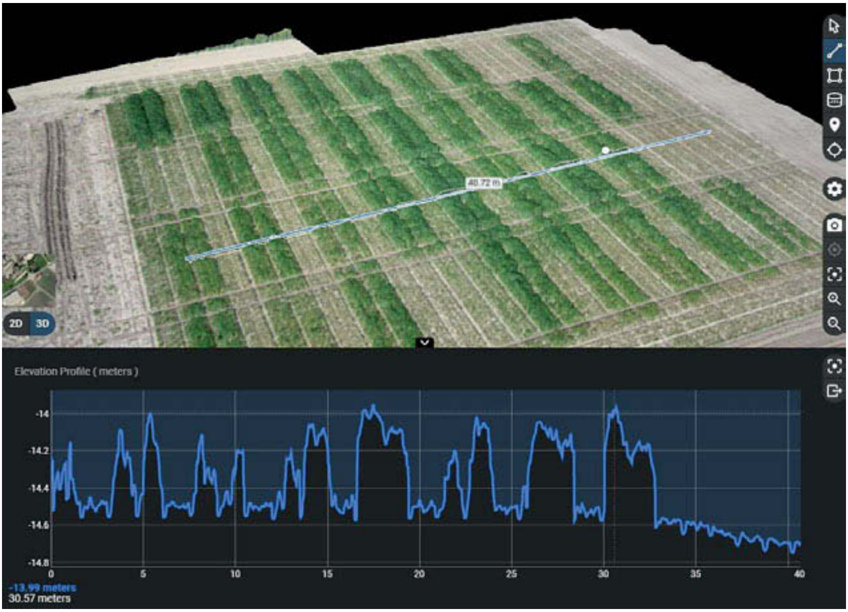

Bild: Alternative Höhenmessungen über Profile. In der Pix4Dcloud kann innerhalb der Punktwolke ein Höhenprofil entlang einer beliebig festgelegten Strecke angezeigt werden, die die relative Wuchshöhe der Parzellen darstellt. Die Daten können als csv-Datei exportiert werden. Die Profillinien können an beliebigen Stellen im digitalen Modell platziert werden.

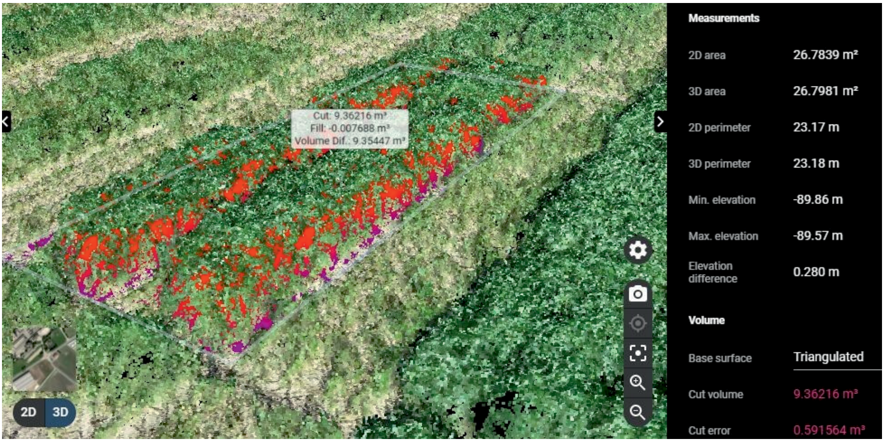

Bild: Aus der 3D-Punktwolke kann auch das Volumen der Bewuches bestimmt werden. Dazu wird die Bodenfläche der Parzelle markiert. Die Software berechnet das zugehörige Volumen und dessen Dimensionen.

Ergebnis: Die Datenerhebung und Berechnung sind vergleichsweise einfach. Es wird keine spezielle (und teure) Lidarsensorik benötigt. Einfache Kameradrohnen liefern bereits gute Resultate in hoher Datendichte. Anders jedoch als bei Lidarmessungen werden bei der photogrammetrischen Messung nur die sichtbaren Punkte verarbeitet. Ist der Boden nicht sichtbar, fehlt die Referenzhöhe für die Wuchshöhenmessung, was insbesondere problematisch ist, wenn das Terrain des Versuchs uneben oder abschüssig ist. Hier können digitale Oberflächemodelle helfen, die ohne Bewuchs erfasst und berechnet wurden. Wenn z. B. bei der Aussaat der Parzellen ein RTK-Lenksystem eingesetzt wird, ist eine ausreichend genaue Aufzeichnung der Höhe der Antenne über NN möglich. Die so erzeugte Höhenkarte kann als Basis für die Höhenberechnung einzelner Parzellen verwendet werden. Die Differenz der Höhenmodelle liefert die absolute Pflanzenhöhe. Gegebenenfalls müssen zusätzlich Fehler der vertikalen GNSS-Messung korrigiert werden.
Über Volumenmessungen lässt sich die Biomasse der Parzellen qualitativ abschätzen.

Bedeckungsgrad

Auf einem multispektralen Orthomosaik wird ein NDVI-Index in Pix4Dfields berechnet. Ein Teil des Spektrums, der charakteristisch für Boden ist, wird maskiert. Eine Analyse der Histogramme der einzelnen Parzellen (wie schon oben beschrieben) lässt Rückschlüsse auf den Bedeckungsgrad des Versuchs zu.

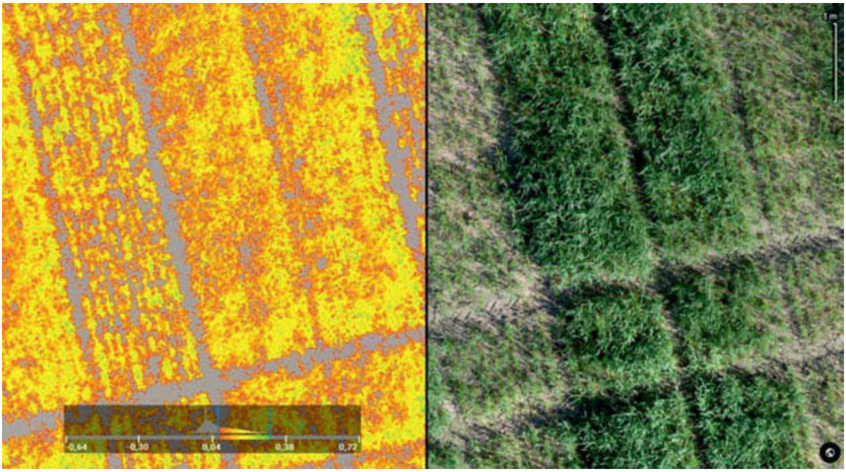

Bild: Messung des Bedeckungsgrad

Ergebnis: Bislang wird der Bedeckungsgrad von Parzellen meist in einer zeitaufwändigen Bonitur festgestellt. Aus RGB-Bildern und aus multispektralen Sensordaten lassen sich relativ einfach qualitative Aussagen zum Bedeckungsgrad einer Kultur gewinnen. Die Auswahl des Index sowie die Eingrenzung der Histogrammwerte sind von Fall zu Fall unterschiedlich, können aber recht einfach interaktiv gefunden werden. Die Maskierung des Bodens kann auch verwendet werden, um Indexmessungen sowie statistische Messungen auf den Bewuchs einzuschränken.

Indexmessungen

Es soll untersucht werden, ob die Biomasse der einzelnen Parzellen und dessen zeitliche Veränderungen mit multispektralen Messmethoden quantifiziert werden können.
Das NDVI wurde mithilfe einer Parrot Bluegrass und einer Sequoia Multispektralkamera aufgenommen. Das NDVI wurde mit Pix4Dfields berechnet. Georeferenzierung und Nachbearbeitung erfolgte mit Global Mapper. Die NDVIs zeigen eine leichte Grünverschiebung entsprechend der Versuchentwicklung über einen Monat. Die Histogrammverteilungen korrelieren mit den visuell sichtbaren Unterschieden der Parzellen und können als csv-Dateien für die statistische Auswertung exportiert werden.

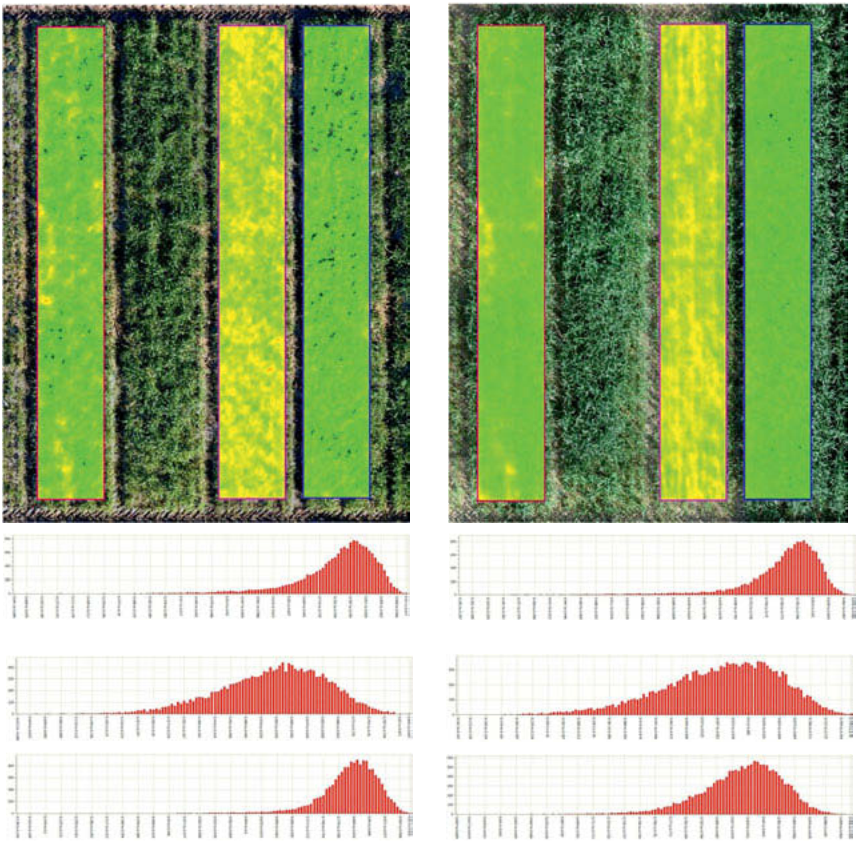

Bild: Zeitliche Veränderung der NDVIs dreier ausgewählter Parzellen. Die Daten wurden links am 31.3.2020 und rechts am 28.4.2020 erhoben. Die Diagramme zeigen die NDVI-Histogramme der zugehörigen Parzellen.

Ergebnis: Die Histogrammdaten korrelieren mit dem sichtbaren Wachstumsfortschritt der Parzellen. Die Standardabweichungen der Verteilungen beschreiben gut die Homogenität der Parzellen. Die Verarbeitung der Daten erfordert allerdings viele wiederkehrende Softwarearbeitsschritte. Hier wäre ein höherer Grad der Automatisierung wünschenswert.

Hirse Mai 2020 - Oktober 2020

Versuchsbeschreibung

Im zuvor beschriebenen Versuch mit Winterroggen wurde nach der Ernte im Mai 2020 Sorghumhirse angebaut. Wachstum und Entwicklung sind im Versuch durch differenzierte organische und mineralische Düngung beeinflusst.

Höhenmessung

Die photogrammetrische Höhenmessung im Hirseversuch gestaltete sich schwieriger als im Roggenversuch. Die Pflanzen stehen in größeren Abständen. Die Pflanzen sind sehr verschieden groß. Die Größenverteilung ist inhomogen.
Zur möglichst umfassenden Bestimmung dieser Eigenschaften wurde die Versuchsfläche in einer Höhe von 10m mit einer DJI Phantom 4 beflogen, um eine besonders hohe Datenauflösung zu erzielen. Die Eingangsbilder mit einer niedrigen Subzentimerter-GSD (Ground S ampling Distance) wurden in Pix4Dmapper verarbeitet, um eine 3D Punktwolke und ein digitales Höhenmodell zu berechnen.

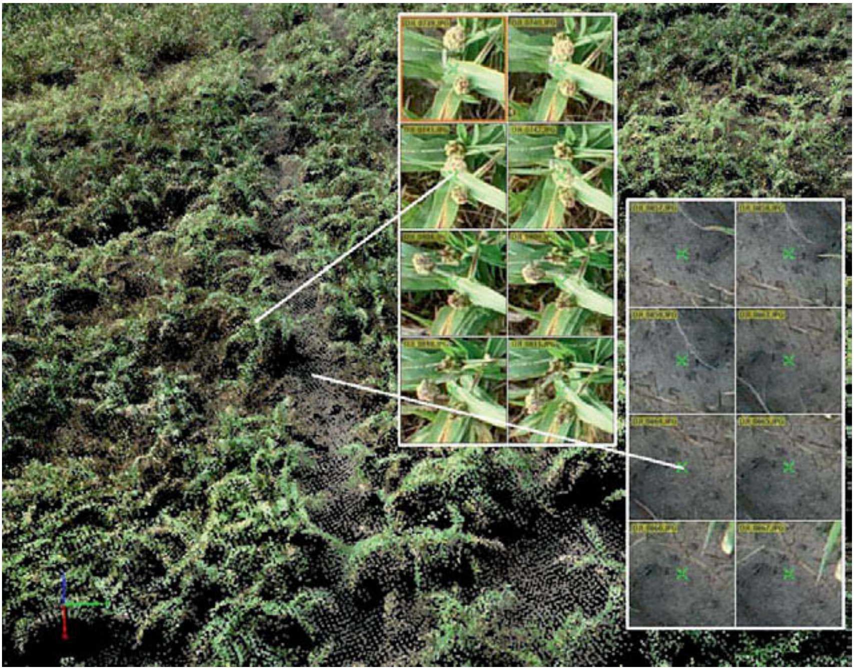

Bild: 3D-Punktwolke des Versuchs. Jeder 3D-Punkt korrespondiert zu einer Anzahl von Pixeln in den Eingangsbildern. Im Modell lässt sich der vertikale Abstand zwischen Boden und Fruchtstand genau als Differenz bestimmen. In diesem Fall 75 cm. Die Messung kann natürlich an mehreren frei gewählten Punkten wiederholt werden.

Ergebnis: Erfolgt die Datenerhebung mit einer zu großen GSD, d.h. in einer zu großen Flughöhe, kann das digitale Höhenmodell des Versuchs nicht hinreichend genau berechnet werden. Einzelne Merkmale der Pflanzen werden nicht erfasst und Messungen in der Punktwolke sind nicht möglich.

Kompatibilität zu bestehender Feldversuchstechnik

Bei Verwendung einer Drohne im Versuchswesen stellt sich die Frage, wie sich diese Technik in vorhandene Versuchstechnik integrieren lässt. Auf vielen Versuchsstationen sind inzwischen RTK-Lenksysteme und spezielle Software zur Erstellung von Parzellenplänen verfügbar. Insbesondere die Aussaat und die Düngung wird meist auf Basis, der auf der Versuchsfläche erzeugten oder vorab definieren AB-Linien durchgeführt. Diese Linien oder auch shp-Dateien aus der Software zur Erstellung des Parzellenplans lassen sich auch für die Drohne nutzen. Zu beachten ist dabei, dass RTK-fähige Drohnen das Korrektursignal von einem Server beziehen und Versuchsstationen oftmals eigene Referenzstationen nutzen, die per Funk mit den Fahrzeugen verbunden ist. Um eine hohe Genauigkeit zu erreichen, empfiehlt es sich daher, für alle Nutzer des Korrektursignales eine einheitliche Quelle zu verwenden.

Fazit

Drohnenbasiertes Remotesensing führt zu einer Objektivierung der Messergebnisse bei bestimmten Boniturmethoden. Preiswerte Drohnenmodelle und Sensorik ab ca. 700 EUR liefern bereits sehr gute Daten zur Analyse der Pflanzenanzahl, Bedeckungsgrad, Höhe und Homogenität. Drohnenmodelle ab ca. 5.000 EUR ermöglichen durch die Verwendung von RTK zentimetergenaue Messungen und damit zeitliche Vergleichbarkeit der Daten ohne zusätzlichen Aufwand zur Georeferenzierung. Multispektralsensorik erlaubt in dieser Preisklasse qualitative Messungen der Biomasse und Stressfaktoren.
Die Datenauswertung erfolgt manuell interaktiv, ist zeitaufwendig und erfordert aktuell die Verwendung unterschiedlicher Softwaretools. Der Austausch der teilweise sehr umfangreichen Daten zwischen den Tools ist dabei teils aufwendig. Automatisierte Auswertungsschritte sind nur ansatzweise verfügbar.
Beide Aspekte sollten zukünftig verbessert werden, um eine höhere Akzeptanz der Technologie im Feldversuchswesen zu erreichen.

Die Autoren

Dr. Andreas Muskolus
Dr. Andreas Muskolus studierte Agrarwissenschaften an der Humboldt-Universität zu Berlin und Natural Ressource Management an der Cranfield University (UK). Nach Abschluss des Studiums promovierte er zum Thema "Anthropogenic Plant Nutrients as Fertiliser" im Jahr 2007. Nach Forschungstätigkeiten an der University of Southampton, School of Biological Sciences und dem Institut für Zuckerrübenforschung (IfZ) an der Georg-August Universität Göttingen übernahm er die Leitung der Versuchsstation Berge. Seit 2012 ist er stellvertretender Geschäftsführer des IASP und lehrt an der Humboldt-Universität zu Berlin.

Henrik Battke
Henrik Battke studierte Informatik und Mathematik an der Humboldt-Universität zu Berlin. Im Jahr 2002 gründete er das Unternehmen bit-side GmbH mit und stand dem Unternehmen bis

zum Verkauf an Nokia im Jahr 2009 als Geschäftsführer vor. Nach verschiedenen Leitungsfunktionen bei Nokia und HERE Technologies in der Plattformentwicklung und dem B2B-Geschäft übernahm er 2017 die Leitung und den Aufbau des Standorts der Firma Pix4D in Berlin.

Firmenprofile

Institut für Agrar- und Stadtökologische Projekte an der Humboldt-Universität zu Berlin (IASP)

Im Sinne der Klassifizierung der ostdeutschen Forschungsstrukturen ist das IASP eine gemeinnützige „externe Industrieforschungseinrichtung". Es versteht sich als wissenschaftlicher Partner für kleine und mittelständische Unternehmen (KMU), insbesondere für solche ohne eigene Forschungskapazitäten. Das IASP ist Mitglied der Zuse-Gemeinschaft. Es ist darüber hinaus Partner für zahlreiche Institute von Universitäten und andere wissenschaftliche Einrichtungen des In- und Auslandes und erfüllt damit eine Brückenfunktion an der Schnittstelle zwischen universitärer Forschung einerseits und gesellschaftlicher bzw. unternehmerischer Anwendung andererseits.

Seit 2010 betreibt das IASP die 1951 durch die Humboldt-Universität zu Berlin gegründete Versuchsstation Berge im Havelland. Dort werden auf 15 ha Versuchsfläche pflanzenbauliche Parzellenfeldversuche zu aktuellen wissenschaftlichen, gesellschaftlichen und wirtschaftlichen Fragestellungen im Acker- und Pflanzenbau durchgeführt.

Pix4D

Pix4D ist der weltweite Marktführer im Bereich professioneller Softwarelösungen für Drohnenkartierung und Photogrammetrie. Das Unternehmen mit Sitz in der Schweiz und Büros in San Francisco, Denver, Shanghai, Berlin, Madrid und Tokio bietet Softwarelösungen, mit denen Einzelpersonen ihre Karten von sich verändernden Umgebungen sofort erfassen können. Bilder, die von Hand, mit einer Drohne oder einem Flugzeug aufgenommen wurden, werden automatisch in georeferenzierte 2D-Mosaike, Index- und Zonenkarten, 3D-Oberflächenmodelle und Punktwolken umgewandelt.

Pix4D-Produkte nutzen moderne Prinzipien der Photogrammetrie, Computer Vision, Radiometrie und des maschinellen Lernens.

Das Produkt Pix4Dmapper wurde im Jahr 2012 erstmals veröffentlicht. Mit der Entwicklung von Pix4Dfields für die Landwirtschaft im Jahr 2018 und Pix4Dreact im Jahr 2019 für die BOS-Industrie erfolgten weitere Schritte zur Diversifizierung Pix4D's industriellen Produktportfolios. Mit klarem Fokus auf den professionellen Anwender gilt Pix4D damit als Pionier und Wegbereiter photogrammetrischer Softwareprodukte.

Als Teil der Parrot GroupHoldings arbeitet Pix4D eng zusammen mit den Schwesterunternehmen senseFly und Micasense. senseFly ist Marktführer auf dem Markt der Starrflügeldrohnen, während MicaSense ein führender Hersteller von hochauflösenden Multispektralkameras ist. Mit einer eng aufeinander abgestimmten Hard- und Softwareentwicklung bietet die Parrot-Unternehmensgruppe weltweit führende drohnenbasierte Sensortechnologie mit leistungsstarker Analytik, die speziell für den globalen Agrarmarkt entwickelt wurde.

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Automatic weed spectrum and weed pressure assessment with RGB imagery

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Abstract

An informed assessment of the current situation on a field is the first step to develop a successful weed management strategy. The observation points that are essential are: the spectrum of weed species present, their distribution, their number per area, their growth state and the ground area already covered by weeds. A system for a further automated system for hyperlocal weed management is presented in this paper. The technology is able to provide in real time a weed spectrum and weed pressure analysis based on simple RGB imagery. To allow farmers an easy self-assessment of his weed situation the technology is today available as part of the xarvio™ SCOUTING app and will be scaled into further embedded applications for improved weed management. The newly made available component *Multi-Weed Identification* is capable to deliver the most important weed stress indicators from a single photo.

Introduction

Latest research indicates that weeds are the most dangerous threat to the yield potential of a field. Especially in Wheat, Rice and Soybean weed can cause a dramatic economic impact [1]. In cereal fields the weed biomass present in a field can explain up to 31% of the variation of yield loss [2]. As various as the weeds present in a field can as complicated an optimal weed management strategy can be. Automatic and semi-automatic decision support systems have been developed in the last years to support the farmers in different regions of world with their weed management program.

However, all of those systems require at a certain point an informed assessment of the current situation to deduce the correct strategy. Some common observation points are the spectrum of weed species present, their distribution, their number per area, their growth state and the ground area already covered by weeds. A system for a further automated system for hyperlocal weed assessment is presented in this paper. The technology is able to provide in real time a weed spectrum and weed pressure analysis based on simple RGB imagery. To allow farmers, contractors or advisors an easy self-assessment of their weed situation the technology is today available as part of the xarvio™ SCOUTING app and will be scaled into further embedded applications for improved weed management in near future. The newly made available component *Multi-Weed Identification* is capable to deliver the following weed stress indicators from a single photo:

- number of weeds present in the picture
- percentage of weeds covering the area observed
- number of weeds per square meter
- a list of weed plants identified

In the following parts we will present the general idea and main elements of the system.

Weed Assessment System

System overview

To deliver this tool, we use latest technologies like deep learning, augmented reality and an annotated imagery data base from more than 2 million users collected during the last 5 years. The workflow is the following: First, the farmer goes to his field and takes a photo of a spot of his field. During the camera activation phase the app is building a 3D model of the underlying scene. From this knowledge we can estimate the area covered by the field of view of the camera lens, when taking a picture. Secondly, this information is passed together with the picture to a server-based application, where further analysis is done. The content of the picture is passed through a multi-task neural network. This network is trained to detect potential weeds in field situations. For each potential plant detected a multi-task classification is performed. The algorithm at hand is using the taxonomy information available and thus is able to identify the species, genus, family and category of the plant. However, sometime, for really small plants, e.g. in the seedling growth state, not enough features are visible to identify the species with a high confidence. In that situation the algorithm tries to identify the genus. If also this is not possible, it tries to identify the family. If even this is not feasible, we still identify the category of the plant, e.g. is it a dicot or monocot. Having this information for each plant we are able to deliver the weed spectrum present.

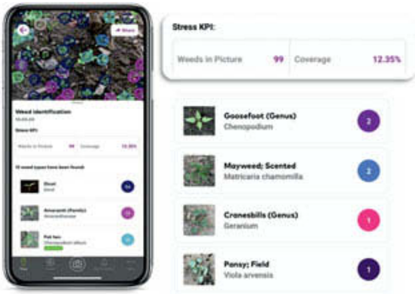

Fig. 1: Result provided by xarvio™ SCOUTING app. Shown are the different weed stress KPIs the app is able to infer from a single image.

Image acquisition and model training

The weed assessment system is trained and developed based on RGB imagery, which is collected from various source, like hand-held cameras, smartphones, robots, drones and cameras attached to standard agricultural machinery like tractors and sprayers. The data collection was performed for the last 5 years and has a global scope with a special focus on Europe, North and South America. Nevertheless, also the region of south-east Asia is present in the training data. This data collection is conducted with field technicians and advisors on the individual fields. Hence, it is mostly equipped with annotation information on the present weed spectrum. To further increase the image collection capabilities an image collection app has been developed und made available globally (called KOLEKTI). Experts in the weed management segment where equipped with this app and contributed to build an extensive annotated data source. However, the most important data source to build a robust and reliable weed assessment system that can be used by anybody in a field is the imagery data that is provided by the users of the xarvio™ SCOUTING app. Here we have a huge variation of image acquisition techniques and different styles of picture taking. This is data is the key value to develop a robust system and is by far the most difficult to analyze and annotate.

The data coming from the users is not annotated by a human. Here we only know the algorithm response from the currently deployed model version.
In order to train a robust weed identification model, we are annotating those images with weed experts from different continents. Those persons are marking and identifying the plants visible in the pictures.

As we could observe the identification capabilities from experts looking only on images are significantly lower in comparison to the identification capabilities of the same persons identifying plants directly in the fields. Hence, we are using a quality assurance approach that included multiple persons reviewing the work of each other and learning from the insights of others. In addition, computer vision experts also review those images for their value and usability in model training. Having this process, it enables us to only use high quality input data, and hence a robust and reliable model.

To support the experts in their work and to speed up the manual annotation process, each image is passed through a two-step algorithm. In the first step each incoming user image is verified for its applicability for the weed assessment, i.e. is it an image of a plant, is it an image from a field or is it a photo from a person or an artificial object, e.g. a bottle. The non-agronomic images are sorted out from the process. In the next step a lightweight version of the weed assessment algorithm is pre-boxing each image, i.e. it automatically marks all plants it can find with a box, so that the annotators only have to assign an plant *EPPO code* to the box. We have found it very useful in the communication between engineers, data scientists and agronomist to rely on a standardized system like the global EPPO code, developed by the European and Mediterranean Plant Protection Organization [4]. With that a plant can be marked exactly with only 5 letters in all its taxonomic levels.

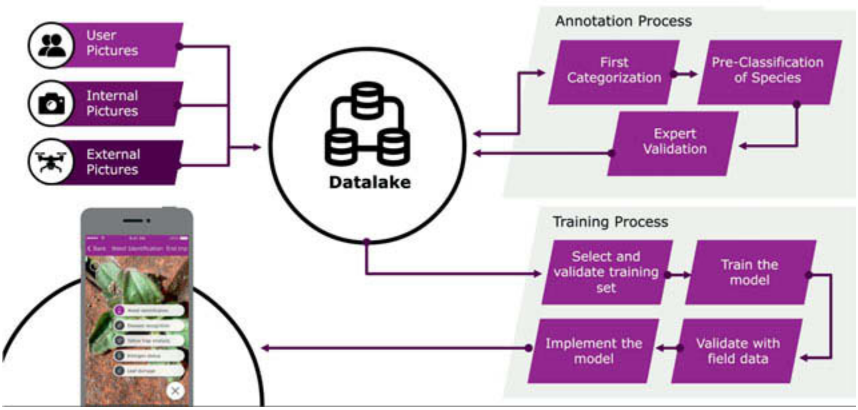

Fig. 2: Data flow used for model training. Images of various sources are stored together with their meta data in a data lake. During the annotation process the human experts and the algorithms work together to speed up the through put of annotated images.

General model architecture

The backbone of our Multi-Weed identification is a deep learning based neural network. It this application we use a multi-object detection network which is based on the network design families of *Faster R-CNN* and its successors [5].
In the context of weed identification, especially in the growth stages where a weed management decision is needed, out-of-the-box training and application of such networks to this task is not yielding in a good result, see Fig. 3. Especially for seedling growth stages, the plant physiology is significantly different from an adult plant. Features which are visible in later stages, where the true leaves are visible cannot be used by the network for classification of very young plants. Also, for human experts a species identification is not always possible in that state. Because of this we have developed a multi-task classifier in the last layers where each task is connected to the other based on the plant taxonomy. The following four tasks have been defined: category level (Dicot vs. Monocot), family level, genus level, species level. The loss function used, forces the network to choose the correct path in the taxonomic hierarchy. With this the loss value will be very high during training if the classifier tries to fit the plant into a species that does not match to the genus prediction.

Fig. 3: Plant appearance for different growth stages and picture taking conditions. The variety of plant appearances and picture taking conditions is too difficult for out-of-the-box training.

During the inference phase the network is allowed to not solve a specific task if the confidence in the prediction is not high enough. This means that for very small plants or plants with non-visible features the network may decide to return an identification result from a higher taxonomic level. To force the network on the other hand to be as specific about the taxonomy as possible a penalty term is introduced to increases the loss if the ground truth annotation is higher than the prediction.

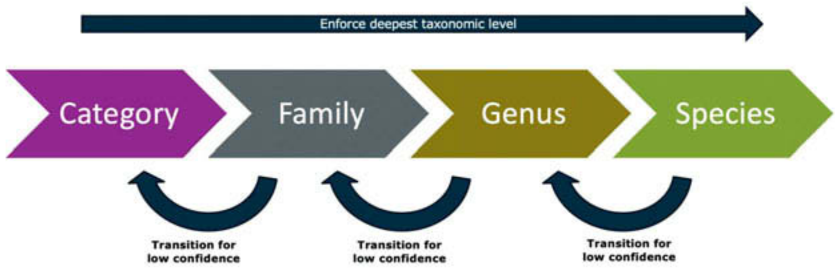

Fig. 4: Taxonomy used by Weed-Identification algorithm as multitask classification problem.

Additional Weed Stress Indicators

In addition to the detection and classification of each plant present in the picture we compute the following weed stress indicators:

• *number of weeds present in the picture*
• *percentage of weeds covering the area observed*
• *number of weeds per square meter*
• *a list of weed plants identified*

The *number of weed plants identified* in the picture is a direct deduction from the above algorithm response and hence easily to obtain. The same applies for the *weed spectrum identified.* The *percentage of weeds covering the area observed* is calculated using the following schema. For each identified plant the algorithm returns the bounding box for this plant. This information is used as a region of interest (ROI) indicator to a green area identification algorithm that used the HSV-color space to identify the plant from the non-plant parts in this region of interest. With that we have the weed area coverage in percent for this ROI. In the next step all those ROIs are fused to a global value for the input picture.

In order to automatically estimate the *number of weeds per square* meter in a picture without an external supporting device, we use the algorithms that are used for augmented reality, e.g. the measurement tools in smartphones, to estimate the ground plane on the ground and track here feature points. Together with the gyroscope and accelerator information available in modern smartphones we can fuse this information to an absolute measurement on the ground covered by the field of view of the camera. This enables us to calculate the area covered by the image in square meters. Combining this with the response from the neural network we can calculate the desired value.

Validation & Conclusion

We have tested the capabilities of the application on a representable set of pictures provided by users and in field evaluation campaigns. In addition, [3] has proved that our application is well suited to identify weeds, especially in young growth state. With xarvio^{TM} SCOUTING *Multi-Weed Identification* we propose the first solution in the world that is able to deliver an essential data layer for a targeted weed management to the farmer - with a single photo of his field.
Important to notice is that the proposed approach is not only valid on smartphones but can also be used with slight modifications for any kind of imagery data to perform weed assessment automatically.

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Full digital video solution as a forward-looking technology for High Speed ISOBUS

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Abstract

The use of analog video systems consisting of one or more cameras is currently experiencing increased demand in the context of advancing automation in agricultural engineering. But analogue video technology is outdated and image artifacts can be easily reproduced through interference signals in the line and power supply. Based on the research project "Next Generation ISOBUS" between ANEDO GmbH and the Hochschule Osnabrück, ANEDO GmbH developed a modern Ethernet based digital video interface for current and next generation ISOBUS HMIs to replace the analogue technology. This interface is also intended to lay the foundation for digital camera communication on the High Speed ISOBUS (HSI).

This paper starts with the current state of the art of used camera systems, the resulting user problems and the current state of the specification of High Speed ISOBUS. Thereafter the advantages of Ethernet based digital video are described and the added value when combined with a High Speed ISOBUS wiring harness and the ISO17215 "Road vehicles - Video communication interface for cameras" for dynamic video systems is stated out. As a first step to digital video in ISOBUS apps are presented, which were developed by ANEDO and combine a digital video stream and ISOBUS implement operations through a native integration in the Universal Terminal or with the help of windows masks. Finally the paper explains the custom video stack that is the core of these applications and enables low latency video streaming.

State of the art and user problems

Especially self-propelled mobile machines can accomplish several work steps in parallel in order to make the work process more efficient. As a side effect these machines are becoming bigger and less overviewable. For this reason, analogue camera systems with several cameras are used as standard today to monitor their work processes. ISOBUS terminals or dedicated video monitors serve as display systems. Meanwhile, however, also more and more manufacturers of mobile implements want to offer camera solutions. This is why electronics suppliers like ANEDO GmbH see themselves contrasted with an increased request to ISOBUS terminals with video interfaces.

Although the PAL format is established as an analogue video interface in Europe, it is limited and does no longer justice to modern technology. A major disadvantage of the analog interface is the susceptibility of the analog video signal to interference from signal crosstalk from other lines or from interference signals from the operating power source [1]. Apart from the susceptibility of the signal, there are further restrictions due to the prescribed format of analogue video signals (in Europe PAL) such as a maximum of 576 image lines and 25 frames per second (FPS) [2].

Another problem of the analogue video technology is that only one video stream can be transmitted per video line. To view several video streams on a display a monitor either needs several video inputs, a switcher or an external video multiplexing device to switch sequentially between the video lines. In all cases an additional wiring harness is needed, which leads to higher costs and complexity for the whole electronic system on the machinery. A further aspect is the demand for multi view systems to monitor several work processes at once. Though there are static analogue monitor solutions at the cost of a complex wiring harness, customers have no flexibility e.g. to customize the video layout.

Current State of High Speed ISOBUS (HSI)

In the AEF group PT10 for HSI Ethernet is already set as the transmission medium. For the transmission of ISOBUS messages the carrier protocols OPC Unified Architecture (OPC UA), Scalable service-Oriented MiddlewarE over IP (SOME/IP) and OneM2M come into question. Currently the decision has to be made whether to pursue only one or more of the carrier protocols in parallel to build up demonstrators. Regardless of the decision, the international standard ISO17215 “Road vehicles - Video communication interface for cameras” is pursued for the integration of digital video into the HSI. [3]

As SOME/IP [4] is also the carrier protocol of the ISO17215 [5] it will generate synergy effects when also used for the transmission of ISOBUS messages. Cameras or camera services can be a native part of the HSI communication to provide ECUs directly with image processing results like object distances, sizes or positioning while streaming the live stream to ISOBUS terminals.

Why digital video over Ethernet?

Digital video over Ethernet in general offers the same base features as its analogue PAL / NTSC counterpart but at a higher quality, as the bandwidth offers the possibility to stream variable resolutions up to Ultra HD to adequately supply a modern operator terminal's high resolution display. While the cost of a digital camera remains higher than an analogue version, the cost difference for a whole video system is more and more declining, especially because of the simpler wiring harness. On top of that the Ethernet based digital cameras offer additional features like digital image stabilization to counteract vibrations, digital pan, digital zoom or high dynamic range colours to solve contrast problems e.g. through bright sunlight.

Furthermore several video streams can be transmitted over the same cable using Unicast, Multicast or Broadcast to address one or more destinations at the same time, also wireless. As the used transmission medium Ethernet is the same as in HSI, it fully integrates into the same wiring harness and results in a cost and complexity reduction when a video system shall be integrated or retrofitted into a HSI machine. Compared to the analogue multi view systems the monitoring of several work processes at once requires no complex wiring harness anymore.

Digital Video According to ISO17215

The in 2014 released and SOME/IP based ISO17215 standard "Road vehicles - Video communication interface for cameras" defines the detailed behaviour for service discovery (camera identification), error handling, timeouts, events and remote procedure calls. A Plug-and-Play functionality is reached due to the SOME/IP Service Discovery (SOME/IP SD) whereby the digital camera broadcasts its service or an operator terminal can request the specific camera service in the network. During the initial step the camera and the operator terminal do not need to know their counterpart's IP-Address or the machine infrastructure. [5]

In comparison to the static analogue video systems this is a huge advantage on tractor implement combinations as camera changes are recognized dynamically and settings can be applied based on the specific camera use case. Where an analogue video system cannot identify a camera at all, the digital cameras are identified by their unique MAC-Address.

The remaining definitions of the ISO17215 refer to the configuration of a camera and the streaming process itself. On the configuration side the ISO17215 enables these configurable main features and more during runtime [5]:

- Start and Stop of a stream
- Camera sensor input area (Region of Interest)
- Camera stream output resolution
- Camera side image rotation / mirroring
- Used video codec (e.g. MJPEG, h.264, RAW)
- Variable Framerate
- Maximum stream bandwidth (on the cost of image quality)
- Unicast, Multicast and Broadcast of a video stream
- Camera manufacturer specific configurations / features via I/O registers

For the streaming process the transmission protocol AVTP is specified, which is part of Time-Sensitive Networking (TSN) (formerly known as Audio/Video Bridging (AVB)). This enables lower latencies compared to the standard TCP / IP communication, but requires physical support in the Ethernet PHY [5][6].

Because most of the current generation of HMIs do not have hardware support for AVB / TSN, ISO17215 compliant digital cameras often implement a hybrid mode. The service discovery and configuration is done via ISO17215. Using the manufacturer specific register configuration the streaming via AVTP is disabled and the camera switches to the Real-Time Transport Protocol (RTP). [7][8]

This means a maximum compatibility of the cameras to operator terminals. On the other hand operator terminals have a manufacturer independent plug and play compatibility to any ISO17215 compliant camera.

Results

Based on the results of the research project “Next Generation ISOBUS“ ANEDO pursued the digital video aspect further. As a result ANEDO developed a digital video core stack and created several applications that support digital video.

Fig. 1: Current panel apps with digital video support; Cam-Digi (top), UT (bottom left) and Layout Manager (bottom right)

panel:app Cam-Digi (see **Fig. 1**) displays and customizes video streams for each individual use case based on end user settings. It supports full screen view, snap shots and an automatic toggle mode through a configurable range of cameras. The app generates video widgets that allow other apps to integrate a video stream into their GUI. An important use case here is the combination of a digital video stream and ISOBUS implement operations.
Therefore ANEDO integrated digital video into the UT server panel:app UT (see **Fig. 1**) to place a video stream directly into the data mask of an UT client without the need for window masks. With standard ISOBUS objects the client defines the camera source, position and size of the video stream and the UT server adjusts dynamically while staying AEF compliant. Because of this native integration on the client side no critical machine information are mistakenly concealed. As an example a baler application could display and hide the video stream as needed in critical situations like driving backwards or bale release.

For UT clients that support window masks, panel:app Layout (see **Fig. 1**) enables operators to build a custom layout made of several window masks also combined with a digital video stream or widgets of other internal apps.
This leads to maximum interoperability between the apps and UT clients of several generations. Additionally implement manufacturers can build up and manage their own video system independent from a tractor's video system or simply combine with it.

The video core

The heart of the apps is a video stack that covers middleware and backend functionality to offer app developers a comfort video interface API. After the initialisation the stack works fully autonomous so that developers focus on the user interface and use the stack on a functional level.

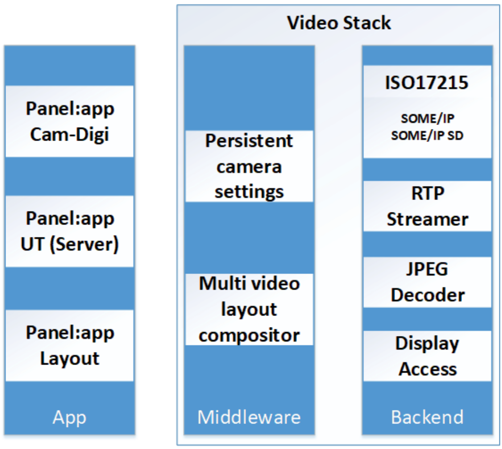

Fig. 2: Overall video system overview

In detail the stack's Backend consists of four main components (see **Fig. 2**). The ISO17215 client offers the full API for camera configuration and service discovery. The service discovery feature is enhanced so that not only ISO17215 cameras but distinct cameras and their manufacturers are identified to support manufacturer specific additional features like the hybrid mode for video streaming. Currently the Stoneridge-Orlaco EMOS camera [7] is supported for manufacturer specific settings but the component is designed modular so that additional camera models can be added any time. The RTP Streamer receives the video stream and forwards the data to the hardware accelerated JPEG Decoder. The decoded da-

ta can be either written into a buffer provided by the app or it is handled by the hardware accelerated component Display Access to forward the stream directly to the display, as long as a device context is provided. As a result these low level implementations reach a mean latency below 100 ms from the frame recording to the image display on the operator terminal.
The middleware is essential for the comfort API for app developers. It stores all known cameras and their settings on persistent memory and makes them accessible for read and write commands. Further it informs an app when new cameras are found or camera settings have changed, so the app always has an overview of the current state of the video system. For the use case of multi view on an operator terminal ANEDO also developed a multi video layout compositor that enables video layout configurations and the positioning of video streams to set up split and also layered views like picture in picture. Apps can position horizontal and vertical border lines to define the position and size of the different video streams.

Summary

Compared to analogue cameras the Ethernet based digital cameras offer additional features like digital image stabilization, digital pan, digital zoom or high dynamic range colours at a higher resolution quality. Additionally digital multi view solutions need a less complex wiring harness compared to their analogue counterparts and the compatibility to the High Speed ISOBUS wiring harness simplifies the matter even more. In the context of Ethernet based communication the standard ISO17215 “Road vehicles - Video communication interface for cameras” offers an interface to set up flexible digital video systems with dynamic plug and play compatibility and specific camera identification as well as configurations for any compliant camera. Hybrid modes on cameras also provide the streaming protocol RTP and guarantee the compatibility to operator terminals that do not fulfil the hardware requirements for AVB / TSN.
ANEDO developed several apps with the support for digital video compliant to ISO17215 to combine ISOBUS implement operations with a video stream on the GUI. To reach maximum interoperability ECU clients without the support of window masks natively define position, size and source of the video stream and the UT Server displays it dynamically. Additionally operators can create their own layouts to combine a digital video stream, window masks and other internal app widgets on the GUI. The hardware accelerated low level implementation of the video core provides a mean latency below 100 ms from frame recording to the display on the operator terminal. Simultaneously it offers a comfort API to integrate digital video functionality into new apps, also on other platforms.

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Topology-optimized body structures and possibilities of realization using the example of a combine – feeder house

Structural lightweight design

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Abstract

In modern agriculture, apart from the efficient use of machinery, vehicle weights and sustainable land management are becoming more relevant. The further development towards ever more powerful and also consequently heavier agricultural machinery is demanding that development teams reduce weights below a set target for their projects. Compromises in terms of operational safety and productivity cannot be accepted.

Lightweight design methods, material databases, modern manufacturing and joining techniques form the basis for any weight reduction project.

This paper will demonstrate the development of a new product design using the feeder house as an example. The target is to achieve cost-neutral weight reductions while maintaining a high level of customer benefit such as reduced soil compaction.

1. Introduction

The ability of a structure to carry and resist all loads depends on whether the structure provides a continuous load path. In the development of lightweight structures, knowledge about load paths is crucial and is the basis for weight reduction measures. In order to identify those load paths, a FEM analyzation and subsequently a topology optimization which utilizes the information is generally performed. Designs which have been optimised for low deformation or a given mass target using topology optimization are mostly framework structures, since these have a homogeneous stress distribution and a high material utilization. However, based on the optimization results different design methods can be derived. Converting these designs into thin-walled sheet metal structures is a challenge in terms of manufacturing. They often require the use of an excessive number of parts and joints which has a negative impact on structural strength and costs. To prevent this and to obtain an efficient and homogeneous structure, deep-drawn sheet metal parts are generally used. CLAAS has developed new production processes capabilities such as hydraulic deep drawing and refined existing ones. This involves the use of various active media such as elastomers and fluids. These processes offer a high degree of flexibility in terms of tooling and enable rapid prototyping due to the low number of tools requiring changes between iterations [1].

2. Topology optimization of a combine feeder house

The basic process of developing structures based on topology optimization is shown in Fig. 1. The development process requires a design space which contains the initial geometry that includes functional requirements and boundary conditions of the structure.

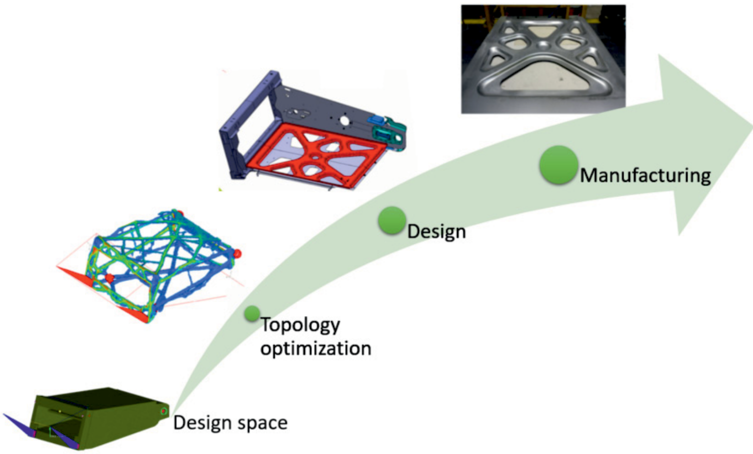

Fig. 1: Basic process of the structural development using topology optimization

Topology optimization gives us the ability to design closer to the axiom of uniform stress which means that the optimization avoids superfluous material and weakening [2].

A topology optimization was performed using the simulation tool OptiStruct and with the target of maximizing structural stiffness while restricting the allowed mass to a reduced percentage of the total weight of the design space. The same load cases and the same idealizations as for a standard FEM calculation is applied to the design space (Fig. 2). After the iterations the topology was developed as shown in Figure 3.

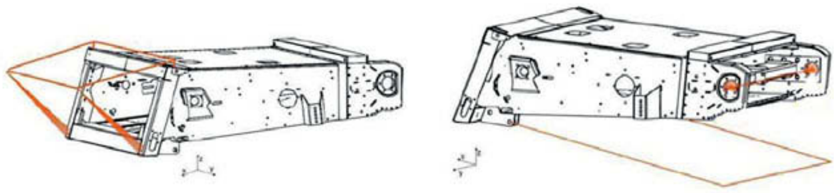

Fig. 2: Boundary condition and load application for the optimization

It can be seen that a closed solid front frame and framed cross bracing in the roof and floor were created. The design of the optimization is very similar to organically grown structures in the flora and fauna. Therefore, it must also be interpreted in a similar way as in bionics which provides approaches to develop a lighter and stiffer structures [2].

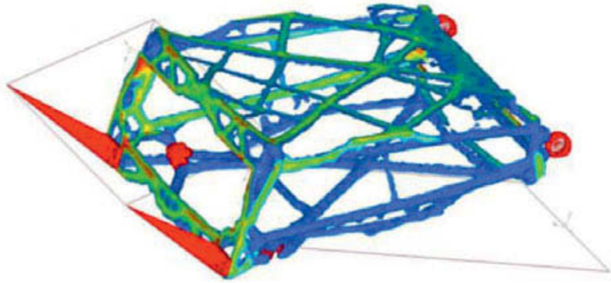

Fig. 3: Topology optimization result of a feeder house [3]

3. Design derivation from topology optimization

Due to the functional requirements of the feeder house, a shell construction is preferable to a frame construction. A reinforcing structure is added to the base plate which is the main load-bearing component [3]. There is no separation between components that are only subjected to bending, torsion or shear loads and those that are used for sealing/cladding. The stiffness is achieved by hollow sheet cross-sections which are designed to have the largest possible cross section and thus section modulus.

To achieve this, a deep-drawn sheet is joined to a cover sheet. By joining both parts together failure due to buckling can be prevented and thus a higher structural performance can be realized. However, cross-section sizes are limited by deep-drawing ratios and material. The design derived from the topology has been simplified to avoid these limitations. Nevertheless, the uniform and harmonic design has been maintained.

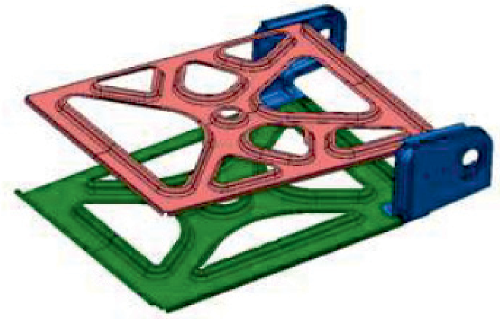

Fig. 4: Design derivation from topology optimization

To have a practical design, the component must meet requirements in terms of weight, stiffness and durability on one hand and manufacturability and joining technology on the other. Manufacturing and development of such parts take a considerable amount of time. The reason for this seems to be a gap between how sheet-metal parts are designed and how they are fabricated [4]. In order to improve this, CLAAS uses a hydroforming manufacturing process [5].

4. Manufacturing of the Sheet metal using rubber pad forming

Deep-drawn parts produced by rubber pad forming conform to shapes which cannot be achieved by conventional deep-drawing methods. This is due to the fact that conventional deep-drawing is limited to one direction [1].

Due to the multidirectional force which is applied to the sheet a more uniform elongation can be reached. Moreover, the rubber pad produces a variable radius during forming further enhancing the uniform elongation of the work piece. Furthermore, the absence of a hard-upper tool, as shown in figure 5, means less thinning in tight areas as material stretching is more evenly distributed, and strains are less concentrated compared to conventional deep drawing [1].

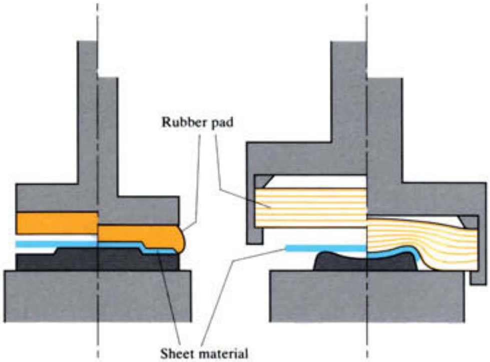

Fig. 5: Guerin Process before and during load application [6]

This allows higher drawing ratios and lower production costs. However, only a limited range of sheet metal parts can be produced with this process due to the limited forming pressure of the elastomere.

With this manufacturing process the reinforcements shown in figure 6 have been manufactured. This demonstrates the possibilities of this forming process regarding the complexity of the deep-drawing geometry

Fig. 6: Formed sheet metal part using rubber pad forming

5. Final remarks

The rubber pad forming process enables CLAAS to produce complex components rapidly and cost-efficient. Considering the example of the feeder house, CLAAS has saved about 20% weight at the same level of stiffness without increasing costs. This shows the potential for lightweight design using topology optimization and appropriate production methods for rapid prototyping.

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Automation methods in computational frame development

Standards in FEA modelling and evaluation allow a high degree of automation in virtual strength verification processes

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Abstract

Proactive product development and approval procedures require an absolute statement about the durability of a support structure and thus reliable load assumptions.
Agricultural machinery comes in a variety of different load-bearing systems and the operating loads are manifold. Furthermore, measurement data collection is time-consuming, costly and not possible in an early phase of product development.

This lecture presents a methodically applicable and thus fully automatable path to a purely computational strength assessment of agricultural machinery chassis. Since all steps from model setup, load definition and calculation processes up to the evaluation of the results are mutually dependent, the entire process is described. At each step, the relevant techniques are introduced. Some techniques are new, others fall back on old literature.

The authors consider this method as a proposal for a future standard method for virtual strength testing of agricultural machinery chassis.

Data management and automation in CAD and FEA pre-processing

In order to calculate the machine's correct inertia, full CAD geometry data of the entire machine is imported to the FEA pre-processor. For an efficient modelling process, each component is classified regarding its role in the mechanical system, first.
For the classification process, each part's and assembly's metadata are needed. These data were taken over from the CAD/PLM system and transferred along with the geometry files to an independently working FEA pre-processor.
However, there is not even a need for these metadata in the pre-processor. If specific data from the material database can be accessed, for example via simple csv-files, it is sufficient when each part's identity number is given as component, respectively assembly name.

The classification is helpful for quickly selecting a large number of geometries for further processing according to different modelling approaches:

- 3D: Volume meshes for casted parts and thick-walled sheet metals
- 2D: Shell elements for sheet metal parts
- 1D: Beam elements for bolts, shafts, bars, etc.
- 0D: Mass inertia modelling as described in [1] (fig. 1); calculated from CAD geometry and mass or density information to obtain a full mass inertia distribution.

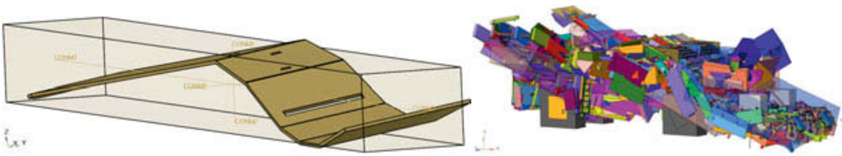

Fig 1: Geometry-based inertia modelling: Comprehensible point mass arrangements allow arbitrary transformations while avoiding errors in inertia moments formulation [1].
Left: Inertia equivalent cuboid and mass cross of a single sheet metal part [1].
Right: Full inertia equivalent model of a self-propelled 4-row potato harvester [1].

Once each geometry is modelled in FE, further scripts create mechanical connections such as weld seams, bolt connections or hinge joints between the components. For assigning the correct connection types, geometry, metadata and assembly structure is analysed in combination.
Since every single component – down to each single washer – is considered, a full mass inertia distribution is achieved.

Standardization of load assumptions

Type approvals according to EU regulation 167/2013 require availability of specific analyses regarding vehicle structure strength [2]. When GRIMME decided to approve all top selling machines in 2019, a credible and broadly consistent load assumption method was needed.

According to [3], agricultural machinery is exposed to the highest loads during transport. Typically on headland or rough terrain. Since these ground interaction forces contain high horizontal dynamic force components, they cannot be estimated by simply scaling the static (vertical) component by some “safety factor”, as often proposed.

A method described by *Boto Kritzner* at TU Dresden in 1984 [4] provides empirically-based assumptions for external load peaks especially on agricultural machinery. It is suitable for all types of support structures and thus provides consistent evaluation results across the entire GRIMME product range.

The approach is to substitute the total operational load by a program of defined impact events applied to the boundary points (drawbar hitch point, wheel contact point) as shown in fig. 2. A series of specific force vectors (3-component) are applied to each coupling point - 13 force vectors to each wheel contact point and 24 to the drawbar hitch point.

Fig. 2: Dynamic ranges of interaction forces on boundary nodes. The displayed polyhedra in force space are formed by maximum force events (green arrows) that can be calculated according to [4]. Red arrows: static reaction forces.
From left to right, images 1-3 show the force events on a drawbar hitch point, images 4-6 show dynamic forces applied to a wheel base point. Images: [5]

Additionally, six acceleration values (3 translational + 3 rotational) are obtained.

All of these values are determined solely through physical machine parameters, such as machine mass, static wheel load or hitch point coordinates, etc. As an example this is shown for a wheel interaction force component in fig. 3.

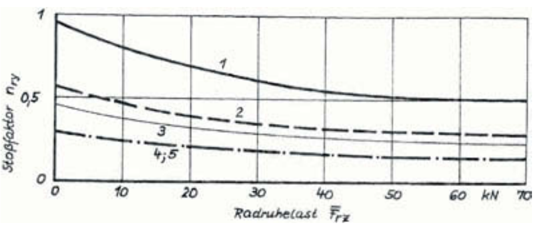

Fig. 3: Graphs for obtaining dynamic forces [4]. The five curves in this example provide factors for calculating dynamic lateral forces, depending on application case (1-5) and static wheel load. Such graphs are given for each force component on wheels and hitch point and for acceleration in six axes.

These parameters can be obtained analytically from the FEA model. Thus, the examination can be performed at a high automation level on the virtual product, while preventing from discussions and uncertainties about application factors, etc. and without collecting measurement data.

The entire process outlined above is defined separately for five different application cases:

1. Driving on extreme sections
2. Driving on dirt roads and paved roads
3. Headland drive
4. Driving on asphalt and concrete roads
5. Field operation

So far, expected values according to [4] have been compared with measured data on a few machines (fig. 4).

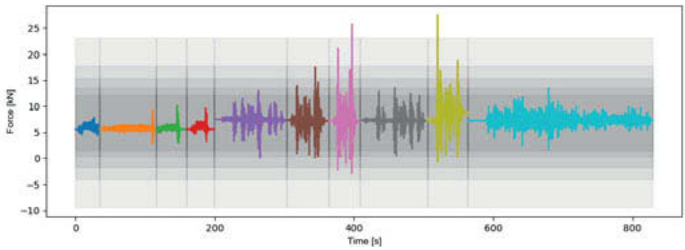

Fig. 4: Exemplary interacting force, measured in different driving situations. For comparison, the force's estimated expectation ranges, depending on the five application cases according to [4], are displayed as grey-scaled areas.
From left to right: Samples 1-4: Braking and cornering on smooth asphalt. Samples 5-9: Driving over ground obstacles at different speeds. Sample 10: Fast ride on uneven dirt road.

Evaluation

To efficiently calculate the many load events as displayed in fig. 5, they are formed by modal synthesis instead of calculating each one individually.

That means structural analyses on accelerations in six axes and some specific forced displacement constraints, depending on the support structure. The reaction forces on each of these normalized *load modes* are put into a *reaction matrix*. The matrix product of the inverse reaction matrix and an arbitrary combination of reaction force vectors at the boundary points returns an appropriate linear combination of six-component acceleration and static constraints.

For example, if each boundary point its static reaction force is applied to, this will result in an acceleration vector equal to earth gravity, since the machine mass inertia is fully modelled.

Thus, once a result file is calculated by the FEA solver, every load event can be built instantly in the post-processor by linear superposition.

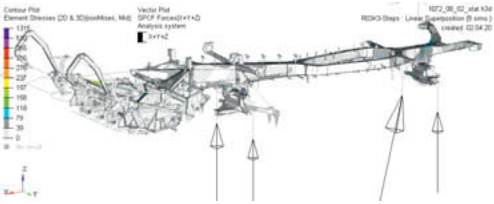

Fig. 5: Example of an impact event: A certain transient force vector is applied to a coupling point, while the other coupling points are subjected to their static reaction force. This applies a six-component acceleration vector. This is done for each coupling point on all relevant operation modes. The total of several hundred impact events simulates the total operating load.

Finally, the maximum stress values among the results from all impact events over several operating modes are rated in one single FEA result display, showing all highly stressed areas at once (fig. 6).

A macro that indicates each area exceeding a certain stress criterion and assesses by size and stress value is easy to set up.

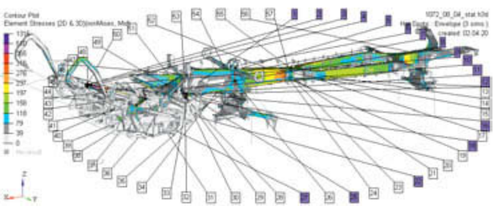

Fig. 6: Distribution of the maximum von Mises stress to be assumed in a supporting structure. Areas exceeding a certain value are marked with a note.

However, an explicit fatigue strength analysis is not included. That would require amplitude and number of load cycles of all applied forces which cannot be obtained from [4].
Instead, an *implied fatigue strength* is assumed [5]. That means that the load events in single appearance are assumed damage equivalent to the operational load over product lifetime: The described dynamic force peaks are expected to appear rarely in full magnitude, while a fatigue relevant number of similar load changes take place at a much lower amplitude (cf. fig. 4).
Hence, a structure detail that responds to a load event as shown in fig. 5 with a stress at or below yield point, a fatigue relevant number of similar load changes with lower amplitude will cause a lower stress amplitude. Therefore it is assumed to fulfil time- or fatigue strength – though even only roughly.

Conclusion

The results were verified by comparing with experience of known damage to various existing machines. Almost every known strength-endangered area was detected by this process – independent from experience. All of the few exceptions could be attributed to production problems.
By last recently including the load assumptions according to [4] into the described procedure, the entirety finally could be established as a standard for computational strength analyses at GRIMME.

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Energy analyses of different advanced drive systems for agricultural machinery

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Abstract

Currently, massive technological changes are taking place in drive systems for agricultural machinery. On the one hand, the use and the availability of internal combustion engines as power sources will remain for a long time, even if they have already been claimed as leaving. On the other hand, nobody can say exactly whether and when and to what extent the internal combustion engines will be replaced by new solutions with fuel cells, batteries, other energy storages, external supplies or other advanced solutions. In uncertain situations such as these, energy analyses of various drive systems have become very helpful in identifying promising development goals. Performed with an appropriate degree of accuracy, energy analyses can also provide a reliable basis for the determination of greenhouse gas emissions throughout the entire product life as well as important information for the determination of environmental impacts, and expenditures for supply of raw materials, production effort, total cost of ownership and recyclability. Therefore, after a basic introduction to the methodology of energy analysis, some example steps of the related accounting, standardisation and assessment are carried out for some likely and typical advanced drive systems for agricultural machinery. Then, based on the results, a promising development goal is marked. Furthermore, it enables also some notable savings potential in greenhouse gas emissions and the total cost of ownership for agricultural machinery via the increase of energy efficiency.

Introduction to the methodology of energy analysis

Energy analyses came into focus with the first energy crisis in 1973 at the latest and have become an important tool for evaluating and improving energy-intensive machines and processes. Early methodological approaches including a considerable (but now partly outdated) database were published as early as 1979 by Boustead and Hancock in the form of the "Handbook of Industrial Energy Analysis" [1]. A further method-oriented development, primarily related to mechanical engineering, took place from 1983 to 1996 within the Collaborative Research Project 144 (SFB 144) funded by the German Research Foundation DFG. There, the initially predominantly production-related perspective was expanded to include the product life phases of use and disposal, and the accounting, standardisation and assessment of energy requirements was methodically based. Furthermore, extensions followed to derive ecologically important data and to take their effects into account [2 and 3]. At the same time, research was carried out by others with regard to consumer goods and the determination and calculation of many more energy data. The state of research on agricultural production processes achieved up to the turn of the millennium is documented in the sixth volume of the book series "Energy in World Agriculture" and in the fifth volume of the book series "CIGR Handbook of Agricultural Engineering" [4 and 5]. The creation of energy and life cycle assessments has long been standardised, currently mainly through the current editions of the VDI guidelines of the 46XX- and 48XX-series published between 2012 and 2016 and the DIN EN ISO-series of standards 140XX. Thus, there is a broad methodological basis for carrying out energy analyses and life cycle assessments. The collection and provision of data in the form of the Probas database determined (mainly) by the German Federal Environment Agency on this basis is also very helpful. This database is freely accessible at https://www.probas.umweltbundesamt.de/php/index.php. In addition, numerous context-related specifications make it possible to simplify energy and environmental analysis, to keep their scope manageable and to focus them on the actual goal of the respective investigation.

Nevertheless, the application of the methodology described above by different actors and the use of different sources lead to considerable scatter in the database, which the user should be aware of and which effects he should eliminate as far as possible. Reasons for that can often be found in the handling of recycling processes and cascade products and in the choice of accounting method for energetic credits, and sometimes also in unjustified falsifications of the results through calculations with fiddle factors and cherry-picking. Technological differences and economies of scale can also lead to considerable bandwidths for individual data. The definition of the balance limit is also very important. Basically, the balance limit covers the whole world. But both for bench markings and for the determination of a promising development goal, which is intended here, it is more appropriate to carry out any energy analyses based on the state of the art in a highly developed country for which there is also a comparatively very good data availability. Therefore, Germany is set as the balance limit here. Despite all the standardisations and simplifications, the effort for comprehensive comparisons of advanced drive systems remains very high. Therefore, further restrictions and limitations are made here, which admissibility is obvious, but sometimes still requires a separate review.

Execution of example steps

Often proposed advanced drive systems for agricultural machinery are fuel cell-, hydrogen-, other e-fuels-, methane-, r-fuels-, hybrid (drivetrain)- and battery electric-tractors, swarm machinery of all kind, and externally supplied systems like John Deere's GridCon2-system [6]. Less often proposed drive systems may be Stone Age-, pressurized air storage- and steam tractors, and other externally supplied systems. In fact, some of the aforementioned systems are very similar in terms of energy requirements (hydrogen-, other e-fuels-, methane-, r-fuels- and hybrid (drivetrain)-tractors), or the required energy storage devices are obviously too large (battery-electric- and pressurized air storage-tractors) or the energy efficiency is known to be very low (steam tractor) or a system consists only of several machines with one of the aforementioned drive systems (swarm). To determine a promising development goal, here a comparison of the drive systems fuel cell, Stone Age- and conventional tractor, single unit of John Deere's GridCon2-system and CF-system (for CF-system see the corresponding article "Soil protection and energy savings through efficient energy supply to machines for primary and secondary soil tillage") is carried out. But even this limited comparison requires further restrictions.

Restriction to the load case "Heavy traction work"

According to the Powermix app of the German Agricultural Society (DLG), which is freely accessible at https://www.dlg.org/fileadmin/powermixapp/, conventional standard tractors cover eight load cases. Whether all eight load cases occur during use and which usage shares they have always depends on the respective operating conditions. In addition, individual load cases can (sometimes even better) be covered with other machines (e.g. pure road transports with trucks or various harvesting work with self-propelled machines), which in turn cannot cover all eight load cases. Energy analyses, especially for advanced drive systems, must therefore first be carried out specifically for individual load cases before suitable technology and usage-specific portfolios can be put together for case-specific comparisons. Due to its special importance and good comparability, the load case "Heavy traction work" (represented here by ploughing of heavy soil) is chosen as example.

Neglect of the product life phases of production and disposal

The energy requirement for individual load cases is made up of the direct energy requirement for the drive systems and an indirect energy requirement for the manufacture (plus maintenance during the phase of use and waste disposal if applicable) of the machines and systems analysed minus any energy credits from the phase of disposal. In the case of load case-specific analyses, the indirect energy requirement can also be taken into account by distributing it evenly over the service life. For a representative tractor mass of 10,000 kg and a cumulative energy demand in the order of magnitude of 100 MJ/kg (according to the Probas database, the cumulative energy demand for the production of steel before further processing is currently 25.5 MJ/kg, but according to [5] it is 138 MJ/kg for whole tractors) results in an indirect energy requirement of 1 TJ or 0.1 TJ per year for a service life of 10 years. In contrast, the direct energy requirement for the load case "Heavy traction work" with an annual use of 1,000 operating hours and a diesel fuel requirement of 25 l/h for a service life of 10 years is 11.7 TJ or 1.17 TJ per year. With an energetic residual value for steel scrap of 10 MJ/kg, recycling of the tractor at the end of its product life results in an energetic credit of 0.1 TJ or 0.01 TJ per year. The indirect energy requirement is therefore less than 8% of the direct energy requirement. Due to the high technical similarity, comparatively small differences between the cumulative energy demands for the manufacture of the various advanced drive systems can also be assumed. Therefore, for the sake of simplicity, the energy analyses of the various advanced drive systems can, as an exception, be limited to the use phase here.

Analysis of the product life phase of use

Such simplified energy analyses are now carried out for the load case "Heavy traction work" with the same key data for all five advanced drive systems to be compared: "Necessary net traction energy E_N = 50 kWh per hour" and "Traction efficiency η_T = 0.6". It is very advantageous that only the provision of the net traction energy has to be taken into account here, i.e. there is no (relevant) co-production. But even then, co-products such as waste heat that can be used for heating purposes could also be taken into account by additional heating systems in advanced drive systems that may be free of waste heat. Because of the traction efficiency selected here, which is typical for ploughing of heavy soil, gross traction energy of E_G = 83.3 kWh per hour is required. The determination of the energy requirement for the provision of this gross traction energy takes place in three sections:

1. Upstream processes for the provision of energy sources, e.g. exploration of primary energy sources, extraction and processing into secondary (or even tertiary) energy sources, storage (possibly multiple times), de-storage and transport as well as local supply (in the case of hydrogen and methane, additional multiple compressions; in the case of renewable energy, construction of plants, generation, fed-in, control and conversion as required and storage and de-storage if necessary).

2. Energy conversion into (here exclusively mechanical) drive energy by internal combustion engines or power electronics and electric motors, if necessary with upstream conversion into water vapour and (also alternatively) expansion in heat engines

3. Conversion of the mechanical drive energy into traction energy

Input variables for the first section can be the fossil primary energy sources natural gas, coal and crude oil, naturally occurring nuclear material and the regenerative primary energy sources wind, (solar) radiation and tidal energy, geothermal energy, biomass and the potential energy contained in water (or rocks). These primary energy sources are then processed in different ways for the conventional and advanced drive systems compared here, the standard tractor, fuel cell- and Stone Age-tractor, a single unit of John Deere's GridCon2-system, and CF-system. In detail, diesel fuel is required as a secondary energy source for the drive system of a standard tractor and electricity for the other drive systems. The energetic expenses incurred until these secondary energy sources are made available at a local filling station or power plug can be taken into account with sufficient accuracy using so-called primary energy factors f_P. Based on the repeated evaluation of relevant standards for such primary energy factors f_P such as the periodically updated German standard DIN 18599 and European standard EN 15603 (Annex E) as well as after making corrections due to different balance limits, the primary energy factors according to **Table 1** are used here.

Table 1: Applied primary energy factors f_P for different secondary energy sources

Secondary energy source	Diesel fuel	Electric energy (Germany mix)	Electric energy (only excess solar and wind energy)	Natural gas
Primary energy factor f_P	1.3	2.0	1.1	1.1

With regard to the primary energy factor, a very favourable development can be observed for the German electricity mix. For many years this factor was in the range of f_P = 3 and in 2015 it was f_P = 2.4, but due to the increasing use of regenerative primary energy sources it has already fallen below the value of f_P = 2 used here. And this despite the fact that the German government proclaimed this value as a target for 2050 in 2010. For electricity generated exclusively from wind and solar energy, a primary energy factor of f_P = 1.1 can be calculated (in accordance with the above definition of primary energy and taking cumulative expenses into account). One the one hand, however, there is not only increasing cherry-picking of this advantageous energy, but also (apart from island operations) the use of shared distribution networks, into which not inconsiderable amounts of recuperated energy of various origin are fed back. On the other hand, purified methane gas could also be used for the fuel cell-tractor system instead of electricity as a secondary energy source to produce the (grey) hydrogen storage medium. Since fuel cell-tractors are primarily operated with proton exchange membrane fuel cells (PEMFC) according to the current state of research, the generation of the required hydrogen (from electricity mix or green?) takes place by electrolysis for reasons of purity.

Results

Finally, the results according to **Table 2** are obtained.

Table 2: Results of energy analyses of conventional and advanced drives systems

Quantity \ Technology	Fuel cell-tractor	Stone Age-tractor	ICE-tractor	John Deere's GridCon 2-system[1]	CF-system[2]
Required net traction power P_N/kW	50	50	50	50	50
Traction efficiency η_T	0.6	0.6	0.6	0.6	0.9
Required gross traction power P_G/kW	83.3	83.3	83.3	83.3	55.6
Primary energy factor f_P	2.0 (1.1)	2.0 (1.1)	1.3	2.0 (1.1)	2.0 (1.1)
Secondary energy factor f_S	1.6	n. a.	n. a.	n. a.	n. a.
Conversion efficiency $\eta_{FC\text{-}E}$, $\eta_{SA\text{-}E}$, η_{ICE} or η_E	0.55	0.4	0.4	0.9	0.9
Drivetrain efficiency η_{DT}	0.9	0.9	0.8	0.9	0.9
Required primary gross traction power $P_{G\text{-}P}$/kW	539 (296)	463 (255)	339	215 (118)	137 (75)

References: multiple

Legend: [1]: for a single unit; [2]: for CF-system see the corresponding article "Soil protection and energy savings through efficient energy supply to machines for primary and secondary soil tillage"; n. a.: not applicable

Note: The fuel cell tractor produces additional water (or water vapour) emissions of approximately 0.25 kg/kWh and the Stone Age tractor 1 kg/kWh

Conclusion

Within the development and design process of future agriculture machinery, energy (and environmental impact) analyses should always be carried out. Significant simplifications are possible even when analysing and comparing the applied drive systems, which are very dominant for energy requirements. This concerns both restrictions with regard to the load cases and the neglect of the manufacturing effort as well as the expected values and times of any credits. Because of the very high (primary) energy demand, which has a particularly significant influence on the operating costs, the currently very often favoured further development from standard tractors with internal combustion engines to fuel cell-operated, (battery) electric standard tractors does not seem to be effective. The most promising development goal clearly looks to be located in the direction of systems like John Deere's GridCon2-system or far beyond it. Especially when the electricity required for the applied drive systems comes from the same source, the different energy requirements also result in significantly different, climate-damaging effects. This is remarkable insofar as the energy efficiency of drive systems is often no longer considered to be of any importance for climate change. For example, energy efficiency is not one of the sustainability goals formulated by the United Nations in the 2030 Agenda (which seems to be heavily wrong).

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Spray-IQ Top – An Intelligent PWM Valve For Field Sprayer Nozzles

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Abstract

Application rate control of field sprayers is necessary to reduce the overall amount of pesticides to a minimum. On the one hand, application maps, crop sensors or different driving speeds require a constant adjustment of the flow rate. On the other hand the limited working range of the nozzles and the capacity of the available control valves are only some of the boundary conditions, that pose limits on the rate control.

This article presents a new electric valve, that enables precise flow rate control on each nozzle over a wide working range. In combination with its extended diagnostic capability this valve ensures a safe and accurate application process.

Introduction

Automatic rate controllers are a standard feature on almost all new field sprayers. They ensure that the correct application volumes are applied all over the field. The rate controllers compensate for operator's actions such as speeding up or slowing down. A typical controller changes the flow by adjusting the pump pressure. The pressure, however, affects spray quality and spray patterns. Higher pressures result in finer sprays with a higher possible drift, and lower pressures will reduce the spray angle and cause a coarser spray. For each working range, the correct nozzle has to be selected to get the optimum droplet size. A commonly used solution to get a larger working range without changing the nozzles is the VarioSelect® nozzle holder with two or four nozzles. It allows the activation of single nozzles or a combination of nozzles by means of pneumatics. With combinations of nozzles different application rates on a section level are also possible. This is used, for example when applications maps or crop sensors are used to determine the application rate and when driving curves.

The limitation here is that this method only allows stepwise adjustment of the flow rate without the possibility of precise rate control. Furthermore compressed air is required to control the valve opening, which is not available on all tractors. Using electrical valves would reduce the costs and installation effort. Most of the electrical valves on the market only support switching nozzles on and off. A few are able to adjust the flow rate by switching on and off at a low frequency, wich results in an uneven spray pattern at higher driving speeds. Electrical solutions generally have high power consumption, which increases the costs for the wiring harness.

The Spray-IQ Top valve

The valve, developed by IWN and Müller-Elektronik, uses pulse width modulation (PWM) to adjust the flow to each nozzle. The PWM has a maximum frequency of 25 Hz and a variable duty cycle. This high frequency ensures that there will be no gaps in the spray pattern even when driving at higher speeds.

The following figure shows a valve and how it is mounted on the nozzle holder.

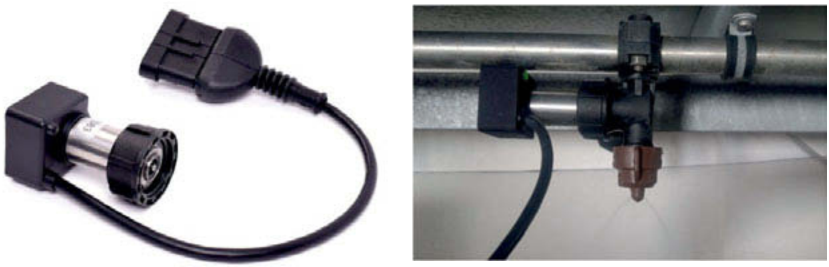

Fig. 1: The Spray-IQ Top valve (left), the valve mounted on a nozzle holder (right)

As you can see in the picture on the right it can be directly mounted on any ARAG-compatible nozzle holder by replacing the mechanical drop-stop. So it can be easily retrofitted. Each valve has an built-in microcontroller and a CAN interface to the parent ECU to receive the desired working state or to exchange diagnostic information.
All valves are connected in a daisy-chain layout.

Structure and operation of the Spray-IQ Top valve

The following figure (Fig. 2) shows the structure of the Spray-IQ Top valve. The left part shows the housing with the PCB and the electical spool. The LED shown in the upper part of the housing is used for status information.

With a union nut the valve is mounted on the housing counterpart of the nozzle holder, which is displayed in the right part of the picture. The valves replaces the anti drip protection, which is normally mounted at this position. If the valve is not powered it behaves exactly like the anti drip protection and opens as soon as the pressure exceeds 1.0 bar.

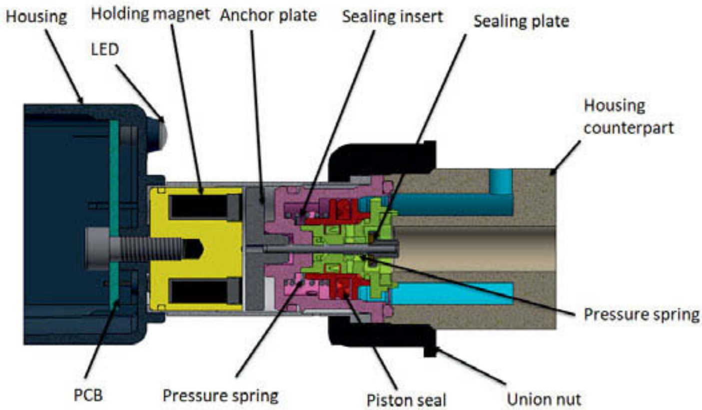

Fig. 2: The structure of the valve

By powering the holding magnet for 20ms with 10V, the anchor plate is pulled towards the magnet and the flow to the nozzle is closed by the sealing plate. After that, the voltage can be reduced to about 3V, which results in a power consumption of less than 1W to keep the valve closed.

While the closing of the valve takes about 20ms, the opening time is less than 10ms as the pressure of the fluid system pushes the sealing plate back to its open position. Thanks to these fast reaction times it is possible to control this valve with a pulse width modulation (PWM) signal of up to 25 Hz. This leads to high-frequency opening and closing of the valve and provides a uniform spray pattern without any gaps even at higher driving speeds. By changing the relation between the opening and closing time of this signal, the fluid flow through the valve is adjusted.

The flow control

During the opening of the valve caused by the pressure in the fluid system, the movement of the anchor induces a small current in the spool. The valve's electronics has an high-accuracy current measurement, that can measure this current.

By analyzing the characteristics of the measured current over time, the moment the valve opens is detected and the time, during which the valve is open can be precisely calculated, which is a more precise indicator of the flow rate. This way, the fluid flow through the valve is determined and controlled by the duty cycle of the PWM signal much more precisely than by just using a PWM signal without a feedback loop. The controller inside the valve only receives the set point in percent of the maximum flow via the CAN interface and adjusts the PWM signal to provide the desired flow rate to the nozzle. This leads to a linear relationship between fluid flow and set value over the working range of the valve, which is presented in the following figure (Fig. 3).

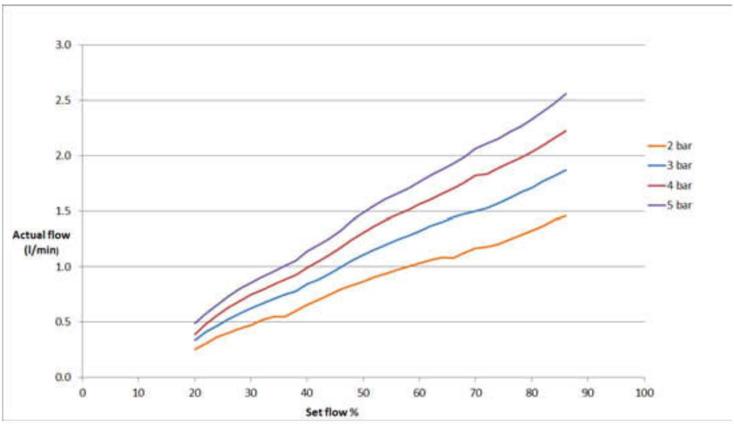

Fig. 3: Measured flow over set values at different pressures of a single valve

Based on the flow control capability of the single valves, it is quite easy to design a very precise control loop for the application rate of the entire implement.

Furthermore, the induced current is also used to obtain diagnostic information about the system. If the nozzle is clogged, the valve needs more time to open. The internal flow control of each valve can compensate for the clogging within a small range. But if the range is exceeded, a warning is shown to the implement operator, informing him about the malfunction of the associated valve. Thus the implement operator does not need to check all of the nozzles before he starts to work, and even a dedicated flow monitoring system is not necessary as this function is already provided by the valve.

The valve itself shows the diagnostic information via the built-in LED. The red/green LED can indicate internal faults as well as a clogged nozzle. So by looking at the boom, the affected valve or nozzle can be found quite easily.

Lateral distribution over a spraying boom

According to EU directive 2009/128/EC every crop protection implement has to be tested regularly by an authorized test centre to confirm that it still meets the current safety and environmental requirements.

According to the directive of the Julius Kühn Institute [1] one of the tests is the lateral distribution measurement of the flow rate across the boom width. It is evaluated by determining the coefficient of variation for the flow rate at each measuring point. This coefficient of variation has to be below 10% and each measured value may not deviate by more than 20% from the overall mean value of the flow rate across the boom.

The following figure shows the lateral distribution of the flow rate for a system equipped with Spray-IQ Top valves at a set value of 50% flow and a system pressure of 4 bar.

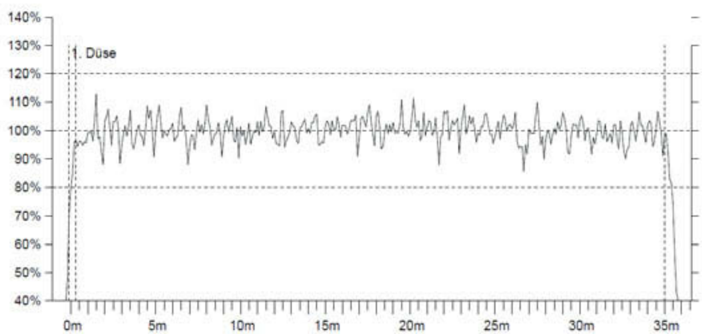

Fig. 4: Lateral distribution of the flow rate of a 36m boom (50% flow, 4 bar)

This test resulted in a coefficient of variation of 4.31 %, which is clearly below the required maximum of 10% and comparable to a system equipped with a simple mechanical drip protection.

Summary and perspective

With its internal flow control and flow monitoring, the Spray-IQ Top valve offers some unique features. The valve not only allows for simple section switching, but also provides precise control of the flow rate for every single valve independently.

The working range of the nozzle is significantly increased as the flow rate is adjusted by the valve at a constant system pressure which improves the overall accuracy of the application process. The changing of the nozzle sizes for different application rates is reduced to a minimum.

Furthermore the valve provides diagnostic information about its function status which is used to inform the driver about any malfunction of the valve or the nozzle. This ensures safe and correct operation at all times. As its power consumption is quite low, it will reduce the costs and effort for installation in terms of cabling.

The valve is currently being tested at the Julius Kühn Institute for certification, which is expected at the end of 2020. Several implements equipped with Spray-IQ Top valves are running under real conditions on our customer's farms.

[1] Julius Kühn-Institut Bundesforschungsinstitut für Kulturpflanzen Bundesrepublik Deutschland: Richtlinie für die Prüfung von Pflanzenschutzgeräten 3-1.0 Februar 2013

Investigation of tractor-trailer brake-systems

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Abstract

The distances between farm-site and fields are getting longer. Corresponding to that, the transport loads and speeds of agricultural tractor-trailer combinations do increase. Different types of braking systems are available, but the level of knowledge regarding brake systems is very low in practice. Apart from hydraulically or pneumatically operated systems, the speed of tractors with CVT transmission can be reduced by means of driving lever. But in this case the trailer has not received a braking signal up to now and applied a thrust force onto the tractor´s hitch. This could cause dangerous driving conditions.

Currently, there are no known studies dealing with this topic. However, within the framework of Regulation (EU) 167/2013, the so-called "Tractor Mother Regulation" (TMR), there are modified tractor approval procedures and new procedures for trailer (and towed vehicles) approval and type testing. Associated with this, there are technical changes for the new vehicles placed on the market from January 1st, 2018. The requirements for the braking systems of tractors and trailers have been tightened. In this project, the braking behaviour of various agricultural trailer and tractor combinations (old and new approval regulations), as well as the so-called "stretching brake" for CVT-tractors have been tested and evaluated in terms of function, interaction, and driving safety.

Introduction

Several regulations have been published in the recent years by the European Commission and Parliament with regard on the approval and market surveillance of agricultural and forestry vehicles [1] and vehicle braking requirements for the approval of agricultural and forestry vehicles [2]. Changed requirements (generally higher demands) for tractors and new ones for trailers (and towed vehicles) have been introduced.

The requested brake performance shall be higher for newly approved vehicles than for old types of vehicles. Therefore, combinations of new/old tractor and trailer will be found in practice.

The combination of “old“ trailers with low brake performance and “new” tractors with increased brake performance might result in dangerous driving situations. Such as with tractors equipped with CVT transmission. They are often braked (decelerated) by joystick (commanding the gearbox ratio) or accelerator pedal, rather than by using the brake-pedal. But the trailer´s brakes are not engaged in that particular moment as long as the brake pedal is not activated. The drawn vehicle generates push-forces in the drawbar acting onto the tractor which has to decelerate the whole load only via the tractor´s tires.
This can cause dangerous conditions (jack-knifing) in case of slippery road conditions or when driving through bends.
The investigation shall figure out some answers and guidelines for practice.

Regulation changes

Since January 2018 the co called “Mother regulation” for tractors, trailers, and towed vehicles is in place [1]. It shall increase the safety level of braking systems on agricultural and forestry machinery. The vehicles for which EU whole-vehicle type-approval is mandatory, or for which the manufacturer has obtained such type-approval under this Regulation, shall only be made available on the market, registered or enter into service if they are accompanied by a valid certificate of conformity.

The changes are (in excerpts) [1, 2]:

- Vehicle manufacturers shall not fit single-line braking devices to new vehicles after 2020. The connections of the compressed-air braking systems between tractors, trailers, and towed vehicles shall be one pneumatic supply line and one pneumatic control line; or one pneumatic supply line, one pneumatic control line and one electric control line; or one pneumatic supply line and one electric control line.
- The performance of service braking systems is higher with new vehicles (at the same brake pressure as before).
- The requirements on brake performance are increased significantly.
- Tractors with CVT transmission shall be equipped with an automatic commanded braking device resulting from automatic evaluation of on-board initiated information, instead of a manual activation by the driver.
- Electronically controlled braking system (EBS) are permitted.
- Tractors exceeding 40 km/h and not exceeding 60 km/h shall be equipped with anti-lock braking systems from Jan. 1st, 2021.

Measuring equipment

The forces acting between tractor and drawn trailer can be measured with a measuring device (Fig. 1, left) in x-, y- and z-direction. [3]

An inertia measuring unit (Fig. 1, right) is fixed behind the tractor cabin and records the vehicle dynamics (in general linear and rotational accelerations in all three axes). [4]

Fig. 1: Device to measuring the forces between tractor and trailer (left image) and location of the IMU-box behind the tractor cabin (right image)

Traction forces on concrete pavement

The traction forces on concrete pavement were determined with and w/o 4WD by measuring the hitch forces. The tractor (actual weight 5760 kg) was equipped with the force measuring device (348 kg), but not further ballasted. Firstly, the tractor pulled the brake-truck owned by the BLT Wieselburg, secondly the tractor was pushed by another tractor. The driving speed was 3 km/h. The highest traction forces where obtained when the tractor was pulling w/o major slip (Tab. 2).

Table 2: Traction forces of tractor during pulling and braking

traction forces	4WD		2WD	
	w/o slipping	slipping	w/o slipping	slipping
tractor tows brake-truck (tractive force)	57 kN 100 %	45,7 kN 80 %	45,4 kN 80 %	31,9 kN 56 %
tractor pushed by another (thrust force, (without service brakes)	51,4 kN 90 %	not measured	25,8 kN 45 %	not measured

Braking with old tractor and old trailer

The brake-characteristics of tractors and trailers did match before the release of the new regulations. For verification purposes a Case Luxxum 100 tractor and a Brantner

Z 18051 XXL trailer were undertaken different braking manoeuvres. Initially, thrust forces were induced in the hitch, but they decreased continuously within the next 2-2.5 seconds as a result of the trailer brake activation (Fig. 2). No dangerous driving conditions were recognised.

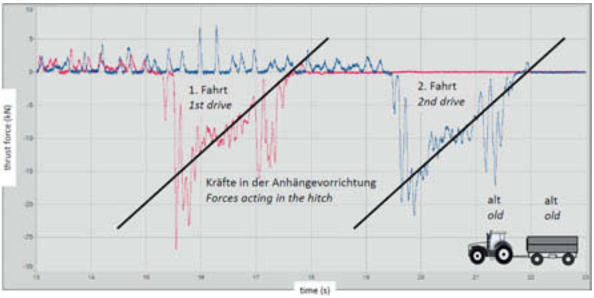

Fig. 2: Old tractor – old trailer, full braking with trailer-brake, 30 km/h empty

The test without trailer brake activation showed blocking tractor wheels. The thrust forces were rather constant until the vehicles stopped (Fig. 3).

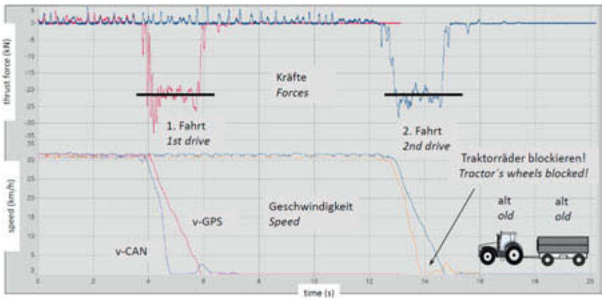

Fig. 3: Old tractor – old trailer, full braking without trailer-brake, 30 km/h empty

Braking with new tractor and old trailer

Normally, when braking the tractor, braking trailers would have to stretch the combination. But in reality it looks quite different. Why does the trailer brake react so late with a new tractor? The reason lies in the new regulation (EU) 2015/68 (TMR), where the requirements for the brakes of newly registered tractors have been regulated as of Jan. 1st, 2018 (following the truck sector). In practice, this means that you have to press the brake pedal harder than before until the full 6.5 bar nominal control pressure is applied to the yellow coupling head (empirically determined) and the trailer can also brake appropriately. This means that the braking behaviour of the tractor-trailer combination changes. The trailer brakes less, which leads to an uneven brake load distribution (trailer pushes on the tractor). As a result the tractor's brakes wear out more quickly. On slippery roads or terrain this becomes potentially dangerous because unbalanced braking load distribution between tractor and trailer can easily cause the tractor to slip, which in turn can quickly lead to accidents. This problem can be solved by using new trailers or modifications of old brake systems by an authorized workshop to meet the requirements of Regulation (EU) 176/2013.The tests with full trailer showed that the tractor´s wheels blocked with significant thrust forces in the hitch (Fig. 3).

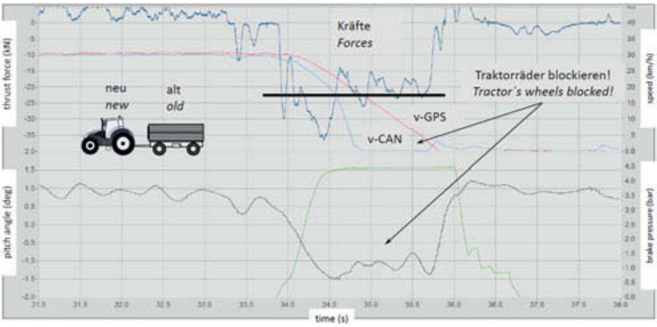

Fig. 3: New tractor – old trailer, full braking with trailer-brake, 30 km/h full

Braking with old tractor and new trailer

The trailer brakes stronger than the tractor, because the brake control of the old tractor is designed for the old trailers and a new trailer has a different brake characteristic than the old one. The trailer is always in tension (stretched) during the braking process to the tractor. When driving on the road, it will not be a problem if the trailer has ALB control (Automatic Load Dependent Brake Force Control). Due to the constant “overbraking” on the trailer, the wear of the brakes is higher, but this does not result in a safety-critical operating condition while driving on highly adhesive roads. When driving off-road, on a slope or on a slippery road, the wheels of the trailer may lock. Measurements should be performed to study the hitch-forces in different driving conditions.

Results of the stretching brake tests

When towing trailers with CVT-tractors, the drivers often reduce the speed by pulling back the throttle (driving lever) without simultaneously activating of the brake pedal. The trailer pushes onto the tractor without the driver noticing it, immediately. Especially on downhill slopes, gravel roads, slippery roads or when cornering, this can cause the combination to

buckle (jack-knife effect), get out of control and cause accidents. In order to prevent this, the tractor-trailer combination must be stretched in these driving situations. Up to now, manual stretching brakes were used for these situations. These were activated by the driver by pressing a button in the cabin, but are no longer permitted under the new regulation. Only automatic braking systems in which the pushing of the trailer onto the tractor is detected by sensors (in the transmission) are permitted. The braking of the trailer is initiated automatically, thus stretching the tractor-trailer combination. Measurements have been carried out with MF 6713S Dyna-VT and Steyr 6240 CVT both with a Stetzl 24-ton trailer.
In one system the automatic activation lasted about 6 seconds until the brakes are then released for cooling purposes and activated again (Fig. 4).

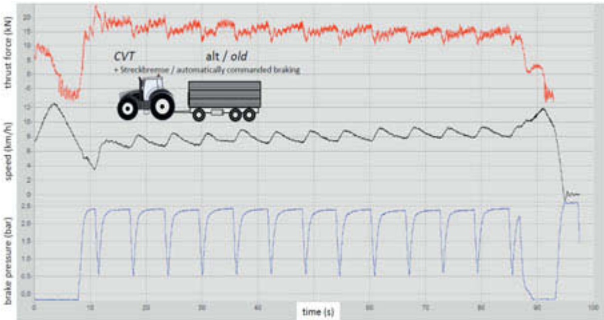

Fig. 4: CVT tractor with stretch brake, full braking with trailer-brake, 10 km/h full

Implication for practice when using automatically commanded braking systems:

- more safety when transporting trailers with CVT-tractors on the road
- fewer accidents during field work (with slurry tanker, loader wagon ...)
- more safety even for inexperienced drivers

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[2] Commission Delegated Regulation (EU) 2015/68 supplementing Regulation (EU) No 167/2013 of the European Parliament and of the Council with regard to vehicle braking requirements for the approval of agricultural and forestry vehicles
[3] Kendler, Fahrnberger (2016): Kraftmesseinrichtung für das Zugmaul und die Kugelkopfkupplung. Diplomarbeit Francisco Josephinum, 2016
[4] Automotiv-Dynamic-Motion-Analyzer (ADMA)

How to improve operator comfort in a tractor with low noise gear pump technology

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Danfoss Power Solutions, Bologna, Italy

Abstract

Currently a strategy for adding value in agricultural equipment is increasing operator comfort. One of the most common complaints among tractor operators is noise in the cabin during operation. Machine designers can decrease noise exposure in several ways; considering a hydraulic gear pump used for steering is an appreciable source of noise: after the diesel engine and the cooling system fan drive, a low noise gear pump is a solution to reduce sound level. In addition to sound level, this can improve sound quality as well as result in a cost and space claim saving compared to the use of other technologies. At the Danfoss Application Development Center in Nordborg, Denmark, a tractor from one of the market leaders has been used to investigate a more suitable solution to improve cabin comfort over the current production model with a low noise gear pump using dual-contact flank technology for steering function. The steering pump was replaced by an innovative low noise and compact gear pump with special asymmetric gear tooth profile technology. The end result was a reduction in sound pressure by up to 13 dB(A) for the second harmonic during steering, translating to higher sound quality. Additional advantages are cost reductions, improvements to sound level, and sound as well as performance consistency over time.

Introduction

Various studies [1,2,3] confirm that operator comfort is one of the most important technological innovation trends required by the tractor market. Improving the level of sound or noise at the location of the operator is a factor which helps to meet this requirement. Considering a hydraulic gear pump used for steering is an appreciable source of noise: after the diesel engine and the cooling system fan drive, replacing a standard gear pump with a low noise gear pump can help to reduce the noise percieved by an operator. In addition, considering two pumps producing the same sound level, the human perception of the sound quality heard in the cabin can vary a lot between the two pumps. When evaluating pump noise, it is important to quantify sound quality in addition to sound level. From the perspective of the operator, the cabin with the minimum sound level and maximum sound quality, in varying working conditions, becomes the preferred choice over other machines. In order to evaluate how to reach an optimum condition, a tractor at the Danfoss ADC was tested with different configurations.

Noise: sound level

Sound level in the cabin is a key factor for the final end-user. One common solution to reduce sound level in the cabin is to install an end-of-line noise reduction measure: a muffler, a damper chamber, or an accumulator, downstream of a standard gear pump. Usually these components reduce the ripple pulsation only for some specific frequency ranges, but not for the complete frequency spectrum of the pump ripple. With low noise gear pumps it is possible to reduce noise in the cabin eliminating mufflers or other noise reduction measures, with even a much better effect, since applying a low noise design of the gears reshapes the complete frequency spectrum. This allows the space claim and costs to be reduced, since additional components are no longer required. For this study a low noise gear pump (dual-contact flank technology) was already installed on the tractor. Dual-contact flank technology is a well-known method to reduce the noise produced by a gear pump, a method which achieves this by reducing the backlash between the gears to zero. This causes a double frequency of noise emission while reducing flow pulsations by 75%. In the asymmetric gear tooth profile, the non-loaded side of the gear is removed, allowing the addition of more teeth maintaining the same center distance and outer diameter - consequently increasing the frequency of noise emission, while reducing flow pulsations by 78%. In fig. 1 the three different designs: low noise gear pump with special asymmetric gear profile, low noise gear pump with dual-contact flank and, and standard gear pump, are shown.

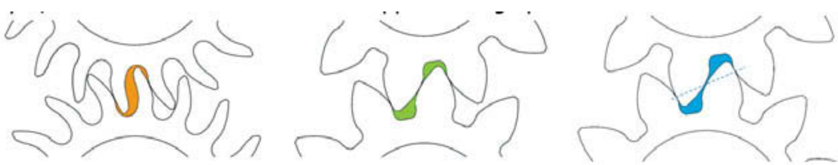

Fig. 1: Comparison of tooth profiles with the special asymmetric gear tooth profile (left), dual-contact flank (center), standard gear (right)

In the specific tractor of this study the sound pressure in the cabin has been measured in two conditions: dual contact flank gear pump and asymmetric gear tooth profile gear pump for steering. Due to a similar effect on pulsation reduction, the sound pressure measured in the cabin is comparable for the two low noise technologies (fig. 2).

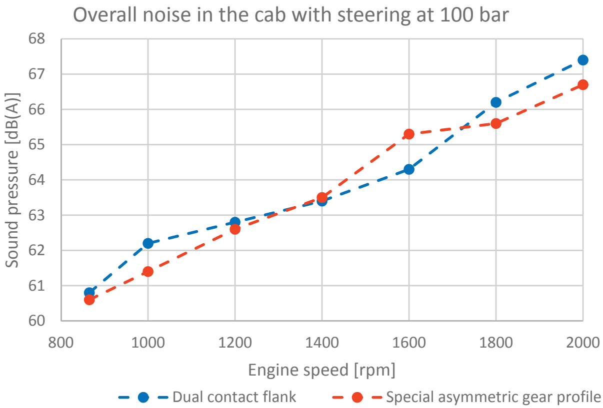

Fig: 2: Sound level comparison in the tractor cabin with a dual contact flank gear pump and special asymmetric gear tooth profile gear pump for steering.

Noise: sound quality

Hydraulic components are not always the source of a noise problem, but often receive the blame. The cause if often more a result of the quality of the sound being produced than with the level. Most readers are familiar with the annoying sound quality of a hydraulic whistle. Objectively measured, the whistle sound typically does not produce significant loudness. However it is unpleasant as the high tone makes the sound seem even louder. This is due to the fact that human perception of noise is highly sensitive to the frequency at which the noise is emitted. Specifically, in the frequency range between 20 to 20.000 Hz the lower the frequency, the lower the noise is perceived by the human ear. The frequency of noise emitted by a gear pump is highly dependent on the pressure ripple. Below is the comparison of the ripple produced by a standard gear pump, a dual-contact flank gear pump and the special gear tooth profile, in the time domain (fig. 3). Applying a Fourier transform aids in visualizing the ripple in the frequency domain (fig. 4).

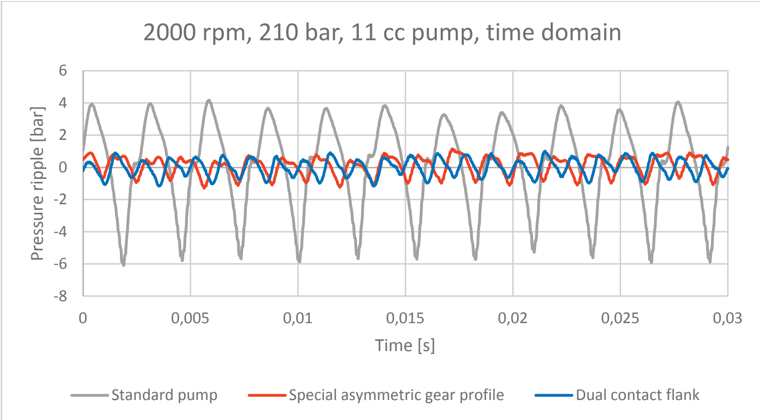

Fig. 3: Pressure ripple produced by a standard tooth gear pump, a dual-contact flank gear pump and the special asymmetric tooth profile gear pump in time domain

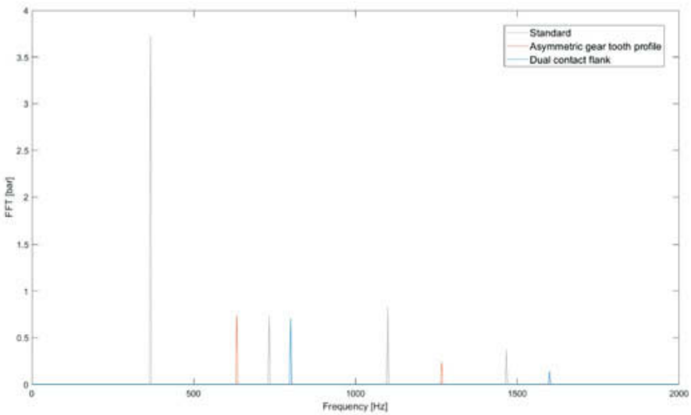

Fig. 4: Pressure ripple produced by a standard tooth gear pump, a dual-contact flank gear pump and the special asymmetric tooth profile gear pump in frequency domain

By means of equation 1, it is possible to obtain the frequency of the main harmonic as well as the second harmonic (second order) and so on.

$$f_i = i * \frac{N * v}{60} \qquad \text{Eq. 1}$$

In equation 1, N is number of teeth per gear, v is speed in rpm, an i is the harmonic order (1,2,3,etc.). In this case the standard gear pump has 12 teeth, the dual-contact flank has 11 teeth: although due to the dual-contact flank effect the formula must be multiplied by two, and the special asymmetric gear tooth profile has 19 teeth, so it is possible to identify the main and second order harmonic frequencies in fig. 4. In it the low noise gear pumps have a consistently lower amplitude of pulsation in both harmonic orders versus a standard gear pump. In addition, the special asymmetric gear tooth profile, by design, has a lower frequency of pulsation than the dual-contact flank technology. To verify the relation between fig. 3 and fig. 4, it is possible to see that for example the amplitude of the ripple in fig. 3 of the standard gear pump is 4+6 = 10 bar, while the sum of the amplitude of the FFT of the standard gear pump is 3.6+0.6+0.8+0.2=5.2, which is around half of 10 bar, so it is correct. The same logic can be applied for the curve of the special asymmetric gear profile and the dual contact flank. In order to evaluate the sound quality, in the tractor of this study the sound pressure in the cabin related to the different frequencies produced by the pumps have been measured. The analysis revealed that the special asymmetric gear tooth profile sound pressure measured due to the second harmonic is up to 13 dB(A) less than the second harmonic of the dual-contact flank technology, as seen in fig. 5. Note that to obtain the overall noise in fig. 2 a logarithmic sum of the noise emitted by the specific curves must be applied.

Fig. 5: Noise emission measured in the tractor cabin during steering operation using a dual-contact flank gear pump and using a special asymmetric gear tooth profile pump of the second order curve

From the operator perspective, a much lower sound pressure at high frequency means no perception of any "annoying whistle" in the cabin. With the dual-contact flank technology the "whistle" is up to 13 dB(A) higher, which is perceivable and is an annoyance in the cabin. The conclusion is: since the special asymmetric gear tooth profile produces less noise at the second order versus the dual-contact flank technology, the special asymmetric gear tooth profile is the better choice in terms of sound quality.

Noise: sound consistency and durability

Dual-contact flank technology has been for decades and is the most common solution to hydraulic borne noise reduction in a gear pump. The zero backlash concept entails "zero" clearance between two mating teeth. A gear pump might ideally achieve "zero clearance" when new, but due to normal degredation (e.g. oil contamination, wear, etc.) during a unit's lifecycle, a non negligible backlash is progressively generated. Eventually, a dual-contact pump behaves as a standard pump after ~500/1000h of heavy duty operation; with a higher amplitude ripple resulting in more noise, greater pulsations in the hydraulic system, and a reduction in durability. Conversely, the special asymmetric gear tooth design has the advantage against other technologies as it maintains this performance feature throughout the machine life, representing a cost saving for the machine producer [3].

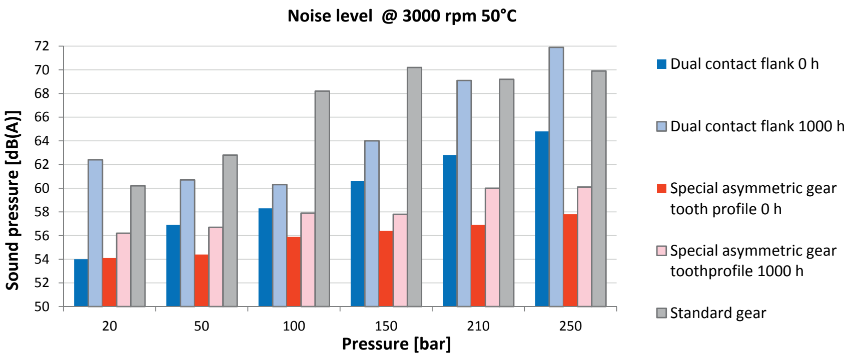

Fig. 6: Sound pressure measure at 1 m at 0 h and after 1000 h at 230 bar, 80°C, 3000 rpm

In figure 6 it is possible to see that after 1000 h of operation the dual contact flank gear pump at 3000 rpm has an even worst noise performance than a standard gear pump, while the gear pump with a special asymmetric gear tooth profile maintains a low noise performance.

Vibration

Due to reductions in pulsation of 78% between the special asymmetric gear tooth design compared to a standard gear tooth design, it is possible to obtain a consistent reduction of vibration through the steering column.

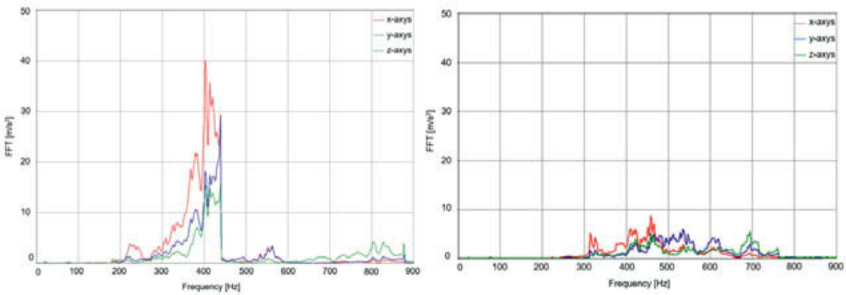

Fig. 7: Comparison of tri-axial accelerometer measurements of vibration between a standard gear profile (left) and the special asymmetric gear tooth profile (right)

With the special asymmetric gear tooth profile, several advantages are: more operator comfort, as well as better health for the operator [4] and increased hydraulic components durability.

Efficiency

The pump utilizing the special asymmetric gear profile has always at least 3 “sealing” teeth during operation, while a standard gear pump as well as a dual-contact flank gear pump has only two “sealing” teeth (fig.8), or sometimes even just one. Due to that, the special asymmetric gear tooth profile pump may perform slightly better than the other technologies in terms of volumetric efficiency.

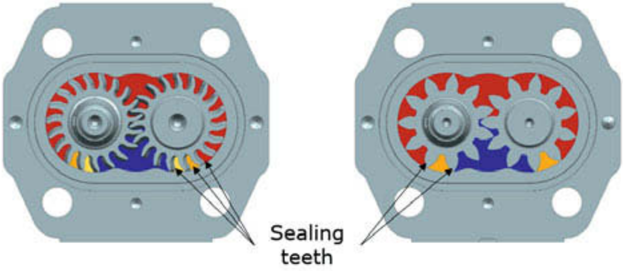

Fig. 8: Comparison of the number of sealing teeth between the special asymmetric gear profile pump and standard gear tooth pump design.

Conclusion

Machine designers can improve operator comfort, driven by clear market requirements, by adopting a low-noise gear pump for steering. The advantages of this solution are:

- Noise emitted at low frequency and low intensity, resulting in high sound quality and low sound level → Operator comfort
- Helps meet legal NVH (noise, vibration, harshness) requirements → Noise regulations compliance
- Elimination of end-of-line noise reduction measures → Cost saving and space claim saving
- Ideal for hybrid and full electric machines for which the hydraulic pump is the most significant source of noise together with a fan drive system

Among the low noise technologies in the market, applying an asymmetric gear tooth profile for the steering pump it is possible to have the best sound quality, low-noise consistency over time and efficiency available in the market for off-highway mobile machine.

Please refer to the extended version of this paper on danfoss.com for more details.

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3D Colour vision for machine automation and safety

AI Sensor Fusion

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Abstract

As farm machines become more automated, and eventually autonomous, the safety case becomes more important. However, there is not yet a simple, low cost way to detect obstacles and people in the path of a large agricultural machine. The automotive industry has solutions for on-road vehicles such as lidar, radar and conventional cameras. However, their spatial resolution is fundamentally limited by eye-safe power levels and the speed of light. Our technique promises to overturn that fact.

We show how high resolution, high integrity depth data for path planning, autonomy and safety can be produced by fusing conventional RGB and low resolution lidar data. This is achieved with a neural network which is trained on simulated scenes. The net is able to assign the correct distance to objects and pedestrians at much higher resolution than the lidar input data. It is also able to fill in areas where no lidar beams have landed, using the RGB image to discern objects from the background. Examples are shown where objects which aren't clearly visible in one image become clear in the fused image at enhanced resolution.

The need for 3D sensing

2020 has shown that agriculture is facing new pressures – not just from weather and economics, but from an acute labour shortage. Recent travel restrictions have shown how vulnerable the food supply chain is to disruption. The hope is that automation can reduce the manual input required – for instance autonomous driving of orchard tractors, automated picking and driver assistance for large machines to reduce the skill level required.

Key to all of these tasks is the need for 3D vision – depth perception. Although a range of depth capable sensors exist they all have limitations. For instance, LIDAR has good resolution horizontally, but has a limited scan rate vertically. Equally, 2D (RGB) camera sensors have obvious limitations – they only work in daylight, and then only with a small dynamic range as direct sunlight can blind them. For safety critical applications this would not be acceptable – a range of sensors with different characteristics is typically required. Also, for a high precision application such as vegetable harvesting, high resolution data, ideally with mm-size voxels will be required at low cost.

Although agriculture is a critical industry, these problems have not seen the same level of investment as the automotive industry. This is because road vehicles are often a consumer product which is heavily regulated in terms of safety and efficiency. The fact that most automotive OEM's sell their product worldwide means that research into advanced driver assistance (ADAS) and autonomy can be spread over many product sales. Agricultural machines sell in much smaller quantities, meaning research costs are proportionally greater.

Fortunately, although agriculture is regulated for safety, the standards are less stringent and the typical environment they work in is less complex than a city street. This could mean that a simplified, repurposed version of existing automotive technology could be suitable for farm automation tasks.

The automotive industry has invested heavily in the tools, software and algorithms for sensor fusion, machine vision and object classification. This paper shows how these tools and techniques can be applied to this problem – generating high resolution, high quality 3D data by fusing sensor inputs.

This technology isn't just for navigation and driving safety – it can also be applied to other automation tasks, such as picking or weed detection, where high resolution depth data is required.

Sensor fusion

Sensor fusion has been 'known' since the 1960's, with the advent of the Kalman filter, and its application to multivariable control systems. For instance, the Apollo missions relied on fusing inertial sensor data (continuously available but with an inherent drift) with star sightings (taken manually but gives angles not distances). The situation here is similar – the RGB camera has very high resolution but is unable to measure depth. Lidar sensors measure depth accurately but have limited resolution .Other depth sensors such as time of flight (flash Lidar), radar and stereo pairs can also have limits, such as vulnerability to sunlight or the reflectivity of the target.

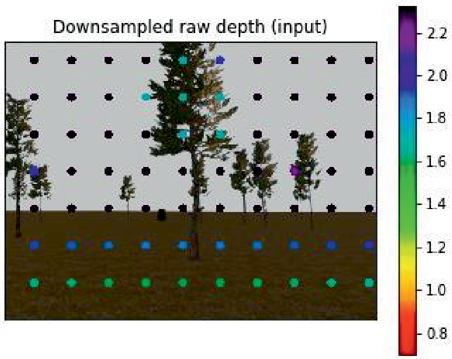


Fig. 1: Example scene showing low resolution depth data points

So, it is natural to try to fuse conventional image and depth data to form something which is higher resolution and more reliable than either sensor taken by itself. This problem will require modern techniques such as deep convolutional neural networks (DCNN). These techniques have changed machine vision in the last 3-5 years, with new capabilities such as object detection, image classification and image segmentation becoming common. The growth in the applications for these networks has also provided the mathematical understanding, software tools and pre-trained solutions which allows them to be applied to new problems in a reasonable time.

However, the main problem with all these AI or Deep Learning techniques is that they require a huge, high quality dataset for training. Although autonomous car companies are currently collecting this data, it seems unlikely it will ever exist for agriculture. This is not just down to the need to instrument vehicles and then drive for thousands of km, but that the data all has to be carefully labelled by humans.

Fortunately – the need for automotive companies to have a large enough dataset to show safety means that they have also developed powerful simulation techniques. These are based on game technology, and can render arbitrary, almost photo-realistic scenes. They can also, with adaptation generate other data which we can use for training:

- Depth data, which is subsampled, quantised or warped to the error characteristics of a given depth sensor.
- Semantic data – what is this this object (ground, tree, person, obstacle etc)
- Deliberately inserted errors, such as areas with no depth information.

- Velocity data and possibly radar cross sections.

As part of our work for automotive groups, we have developed a range of tools and simulation environments for cars and city scenes. These can be easily adapted to agricultural settings.

System Workflow

So, this approach gives us a workflow to develop an algorithm which can fuse the data. The typical approach is

- Generate scenes representing farm tasks such as driving through an orchard, manoeuvring a large vehicle, or collecting grain from a combine harvester.
- Generate simulated data from sensors – RGB camera, lidar scanner, time of flight camera. Also generate semantic data to aid training and help the network learn 'higher order' concepts about objects and structure. Also generate 'true' depth data.
- Define the loss function – the metric for how well the candidate network is performing. For instance, this could be RMS error in depth or a more sophisticated metric.
- Select a suitable network and weights. For this work we used a pre-trained image classification network: since it was already trained to perform segmentation this reduced the training time significantly (transfer learning).
- Train to minimise the loss function (improve fit between predicted and true depth).

This trained network can now be tested and developed in a variety of ways. The first step is to establish performance, particularly in a range of settings such as day or night, with a range of objects present. The number of scenes available, and the fact that the 'ground truth' is known means that statistical metrics for accuracy can eventually be calculated.

The neural networks

Although many classifiers, detectors and other types of network exist for familiar RGB images, it is not as simple as adding another channel to process depth. This is because depth is not a property of an object in the way colour is. For this reason, the architecture used processes RGB and a combination of visual and depth information separately. These separate chains of convolution are combined at each layer, finally being upsampled to give a full resolution depth image:

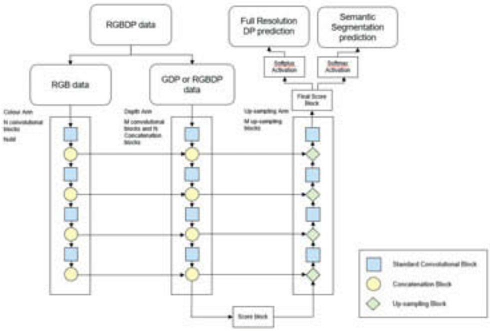


Fig. 2: Overview of the neural network used.

This is a reasonably complex network, which has around 1.3M weights, meaning full training will be expensive. Fortunately, the weights can be started from an existing standard classifier (such as Mobilenet V2), this transfer learning will reduce the time needed and also help to guide the learning in early epochs.

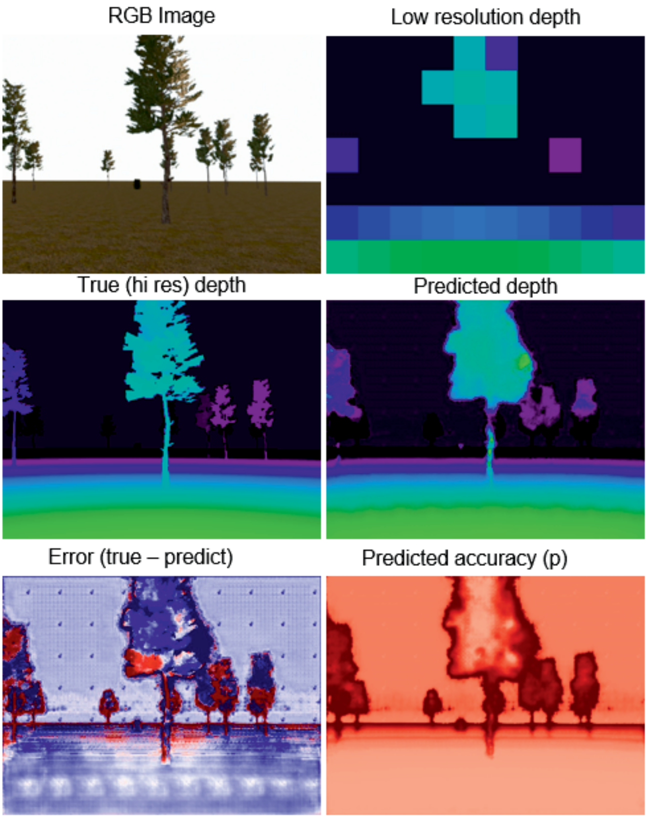
Quality and uncertainty

A key feature is that the network both accepts quality information (denoted P above, = $1/\sigma^2$) from the depth and re-generates it at full resolution at the output.

As an input, this allows the network to be adaptable a range of sensors. Also, 3D sensors can have complex error models, for instance which change with working range, background illumination and geometry. At the output, this information is effectively a degree of confidence that the predicted (upsampled) depth is correct. This is critical when giving a warning or intervening on behalf of the driver – the *probability* that an object has been detected needs to be considered. Equally, finding degraded quality at a distance which could represent an imminent collision is also grounds to raise an alarm or intervene.

The network has two major outputs, the upsampled (reconstructed) depth and quality information, and semantic segmentation (how objects are connected). The loss function has to allow the optimiser to train the weights to improve both of these, so it must carefully balance the errors in each. The loss function itself needs to tolerate outliers, this was achieved by using an L1 rather than an L2 norm. This gave greater consistency and allowed model improvement.

Example Results



1 Fig. 3: Example results

These results show how features which are visible in the RGB image, but not in the low resolution depth map can be indentified. For instance, the trunk of the tree is not visible in the depth, but appears at the right depth in the output. Also, the net is able to give a higher uncertainty to the trunk, which matches the error which is actually observed.

Conclusions

This work has shown how modern simulation techniques can enable high quality data fusion of visual and LIDAR data. We expect to be able to extend this approach to cover radar and other types of range information.

A review on plant and soil properties estimation using ground-based computer vision techniques in the visible spectrum

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Abstract

The estimation of plant and soil properties is the basis for sustainable cultivation of arable land. The use of ground based measurement techniques have the potential of not only mapping parameters but also controlling agricultural machines in real time.

This paper presents an overview of proposed methods for estimating visible soil and plant properties. Soil properties include the soil type, soil roughness and soil cover. Computer vision techniques can also be used to estimate plant characteristics such as species, biological morphology, visual textures, spatial contexts, dimensions and reflectance of visible radiation.

Methods can be divided into the estimated properties, the employed algorithms, the data used and the proposed use case. In addition, environmental influences on the respective methods, like lighting conditions, occlusions or dust are discussed. All methods are also assessed with regard to their hardware requirements, especially the necessary camera properties.

Finally, open challenges, solutions and trends for the estimation of soil and plant properties are discussed.

Introduction

Research for computer vision applications in agriculture has been strongly increasing in recent years. Reasons for this are improvements in hardware and algorithms such as machine learning, that make computer vision applications feasible. Historically, sensor technologies and image analysis in agriculture have a strong focus on spectral analysis, however multi and hyperspectral cameras are still expensive, which limits its spread. Not only through the widespread use of smartphones, RGB cameras are getting cheaper and are

more common on agricultural machines. This opens a wide area of vision applications in the visible spectrum in agriculture.
This paper focuses on outdoor vision applications which can be used on mobile machines with low ground clearance, as shown in Figure 1. The works are investigated depending on the proposed measurement parameters and applications, the methods used, and external influences on the system. In the last section, we discuss the state of the art and open challenges.

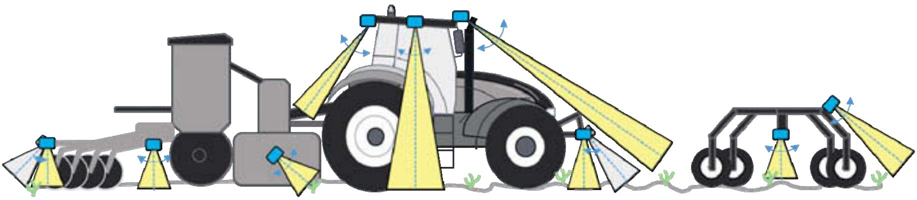

Fig. 1: Common mounting positions and field of views of cameras on mobile agricultural machines.

Measurement parameters and applications

One of the most common uses for computer vision on machines is plant species classification [1], [2]. Various applications can be solved with plant classification. It forms the basis for spot spraying, mechanical weeding, plant phenotyping and yield estimation. The detection rates of the different approaches depend on the number of classes to be differentiated. For weeding it is common to detect two classes (crop and weed).
The estimation and classification of plant parts like leafs [3], stem, seeds [4], ears [5], panicle [6] are used for phenotyping and special applications like yield estimation. Plant row detection [7] is already widely-used in practice for inter row weeding and automated steering. In contrast plant pest detection, [8] and [9], is still a field of research and no widespread applications are known. Especially, full-area real-time detection of pests in the field is due to high requirements on imaging resolution not yet practical. The same challenge concerns the detection of plant diseases, [10] and [11]. RGB vision for soil parameters is mostly limited to soil roughness and soil clod size estimation [12], [13], [14]. The transition between the estimation of the plant and soil parameters leads to the estimation of the soil cover with living organic matter such as plants, dead organic matter, like straws or residues, and stones [15], [16], [17]. Especially, distinguishing between soil and dead organic matter is, due to inherent ambiguity, afflicted with recognition errors [15].

Methods used and hardware requirements

Different computer vision tasks are solved depending on the parameter estimated or on the agronomic task to be solved. Most of the methods are based on machine learning. Within recent years a strong trend towards deep neural network based machine learning methods, especially convolutional neural networks (CNNs), can be observed.

A very common task, solved by CNNs, is semantic segmentation of images. It is often used for plant related tasks [5] as well as for soil cover estimation [15]. With semantic segmentation, pixels of an image are classified into predefined classes. This allows to estimate the extent of the projected area of an object. Object instance segmentation is related to semantic segmentation, were objects are classified and segmented [3]. However, different objects of the same class are segmented separately. CNNs for semantic segmentation are based on encoder and decoder blocks. The encoder tries to extract semantic information, whereas the decoder reconstructs the detailed image mask. The bottleneck between encoder and decoder causes information loss which reduces the accuracy of the output mask. Different methods to bypass information past the bottleneck have been proposed.

The goal of object detection is to locate the object in the image, to represent it with a mostly rectangular bounding box, and to classify it. Approaches for object detection are used for plant species classification [2], pest detection [8] or plant part detection [6], [4]. In contrast to segmentation the exact outline of the objects is not reconstructed. Image classification is used when a user can control the image section, e.g. for smartphone applications. For this task, a label is given for the entire image [1], [18], [9].

For datasets with a large number of classes and few training samples, so called few shot learning methods [19] are used. These methods are trained to estimate object similarity measures within a group of objects. The similarity measures are used to compare images to a database of reference images, where the image with the best similarity is selected.

The problem of 3D reconstruction with stereo cameras, commonly used for soil surface reconstruction [12] and plant row detection [7] is solved. Normally, for stereo reconstruction there is no need to use machine learning algorithms, hence large datasets are not required. Camera hardware, which performs the correspondence matching of the stereo images with a dedicated chip is already available. Therefore, no additional resources for stereo matching are needed in the subsequent processing unit. Optionally, 3D sensors such as TOF Cameras or laser scanners are used. There are also methods proposed which use combinations of RGB and stereo data as input for CNNs.

All machine learning based methods depend on large diverse datasets, however different approaches have been proposed to get along with smaller datasets. Transfer learning, for example, pursues the approach of transferring model weights from similar problems [9]. This allows to reuse low level features and reduce the training effort. Alternative to transfer learning, the training dataset can be expanded or interpolated. Approaches to generate synthetic data are data augmentation, generation of 2D image mosaics [20], 3D image rendering or generative adversarial networks (GANs [10]). Data augmentation is very common for CNNs and consist of geometrical and intensity transformations, like rotating and scaling of images and noise, brightness and gamma changes, etc.
Hardware requirements vary for different use cases. In general large chip sizes and high quantum efficiency is preferred to be able to reduce the exposure time at higher motion velocities, as well as high dynamic range for capturing images during strong sunlight with shadows. Plant classification, plant row detection and soil cover estimation already work with image resolutions of about 1 Pixel/mm (depending on the plant size). Especially, for plant pest and plant disease detection, higher image resolutions, more than 1 Pixel/mm are needed.

External Influences on a the vision systems

In general, environmental influences on the vision systems are discussed less. If possible, they are bypassed by additional lighting or dust shields [2]. The main issue discussed in the literature is shadows and lighting [2]. Different approaches have been proposed to circumvent the issue like active lighting, also synchronized pulsed lighting, active shadowing, log exposure and exposure on pixel level (Interleave-HDR) [7]. An approach for speed adaptive exposure has been proposed in [12], where the exposure time is increased with decreased driving speeds. Most of the public available data sets, like [21], [22] and [23], do not include images with strong illumination variance or dust and therefore limit the development of robust methods. When selecting the mounting position of cameras a certain distance or mechanical shielding from vibrating and dust producing working tools have to be taken into account [12]. Cameras are not suitable for all agricultural applications, mainly due to the formation of dust. Depending on the application, intense dust formation can occur, as for example during tillage or harvesting. However, active dust reduction systems with controlled air flow or lens wipers have been proposed.

Conclusions

This paper gives an overview of computer vision techniques for plant and soil properties estimation, with focus on application on mobile machines. The trend towards CNNs for different vision tasks also in agriculture is ongoing. However data driven approaches are dependent on labelled data. In addition to existing plant data sets, open data sets with images of challenging scenarios, like strong illumination variance and dust, are needed. Plant pest and disease detection are still open challenges in agricultural computer vision and further research is needed. Trends in the general field of computer vision should be applied for agricultural computer vision, like active vision on robots, depth estimation with CNNs, etc. It can be observed that future applications will increasingly deal with yield and yield quality estimation and will use image transfer via high speed mobile networks (5G) for training data capturing and inference. The ongoing trend of dedicated AI edge hardware for inference will further increase.

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A novel approach to determine the soil aggregate size distribution from high-resolution 3D point clouds

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Abstract

The soil aggregate size distribution is an important parameter for determining the success of soil tillage. However, existing methods are intermittent procedures or measure only secondary variables and not the distribution itself. A novel approach, applying machine learning methods, allows the non-invasive determination of the size distribution while driving in the field. The developed algorithm identifies individual aggregates in high-resolution 3D point clouds and then determines the corresponding aggregate size and distribution.

Introduction

As objectives of the joint research project "EKoTech" (Efficient fuel use in agricultural technology), measures to increase the efficiency and reduce the fuel consumption in agricultural process chains were defined and investigated. However, only the inclusion of the work quality of individual process steps enables an objective assessment of efficiency-increasing measures. For this reason, a generally applicable evaluation method has been developed, which evaluates efficiency-enhancing measures while taking into account energy demand and work quality. The aim is not the absolute evaluation of process steps, but to evaluate the relative changes due to efficiency increasing measures within a given process chain. To test the methodology, a mobile sensor unit was developed to determine parameters defining the quality of work during soil tillage. An important parameter of this example application is the aggregate size distribution. Many previous investigation methods are associated with high personnel efforts [1], can only be used in intermittent procedures [2] or measure only secondary variables and not the real distribution [3]. For this reason, a new method was developed to determine the aggregate size distribution at the soil surface while driving in the field. [4], [5]

Determine the soil aggregate size distribution from high-resolution 3D point clouds

A modular stereo camera system is taken for data collection. The system consists of two greyscale cameras and a pattern projector. With the use of the method *structured-light*, it is possible to increase the number and accuracy of disparities. Within the field of view of 600 x 500 mm, the system is capable of delivering a resolution of 5 million 3D points with a mean accuracy of 0.2 mm per captured image pair. All sensor raw data are stored georeferenced by using the *Robot Operating System* (ROS).

Then the 3D point clouds of the soil surface are calculated from the gathered greyscale image pairs. The approach for determining the aggregate size distribution is based on the segmentation and measurement of individual aggregates. The sensor provide approximately equidistant height information. Smaller aggregates therefore consist of fewer data points than large ones. Every aggregate size distribution also has a fine sand content. The aggregates of this proportion cannot be clearly differentiated and determined because not enough data points are available per aggregate.

These points must be removed from the respective point cloud. The Cloth-Simulation-Filtering algorithm is used for this. This algorithm was invented by [6] to remove buildings and vegetation from airborne 3D point clouds and to generate digital terrain models. The approach of the algorithm is shown in figure 1. It simulates a flexible cloth (red points) over the inverted point cloud (black points) influenced by a gravitational field. The cloth can be parameterized via resolution, stiffness and mass. The cloth is placed iteratively on the data points. It cannot get through the points. Then the internal forces are calculated and the expansion is determined. When the simulation is complete, the point cloud is divided into two segments. One segment contains the points (green points) that are in contact with the cloth (blue points) and the remaining points represent the second one. By adjusting the cloth parameters, it is possible that all points of the small aggregates are in contact with the cloth. They are deleted from the point cloud for further evaluation.

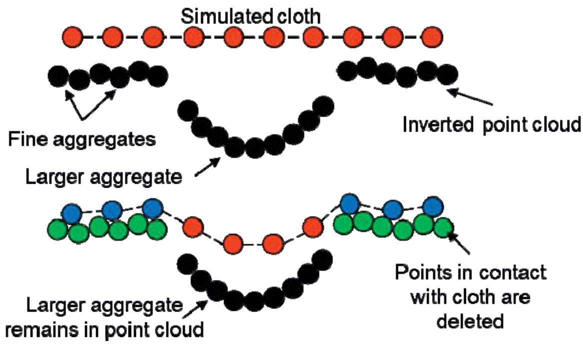

Fig. 1: Cloth-Simulation-Filtering to remove unwanted small aggregates from each point cloud (modified according to [6]). The figure shows a two-dimensional section through a larger aggregate.

As the next step, the points are segmented into individual aggregates. The DBSCAN (Density-Based Spatial Clustering of Applications with Noise) algorithm is used for this purpose. The method developed by [7] from the field of unsupervised learning in machine learning is based on different spatial densities of the points. As shown in figure 2, the algorithm searches for each point within a given point cloud the nearest points around. If the number of points inside the radius ε from the selected point is equal or greater than the parameter *minPts*, these points are forming a new cluster (blue points). If a point is reachable from the cluster, but has not enough neighbours, it is also added to the cluster as a border point (green point). This procedure is repeated with the new points until no more new neighbours are found. Then this cluster is completed and the procedure is continued at a new random location. If a point does not meet the requirements for any cluster, it is classified as noise (red point). Because of the data undercuts and the former removal of the smallest aggregates, the algorithm is capable of clustering the point cloud into individual aggregates.

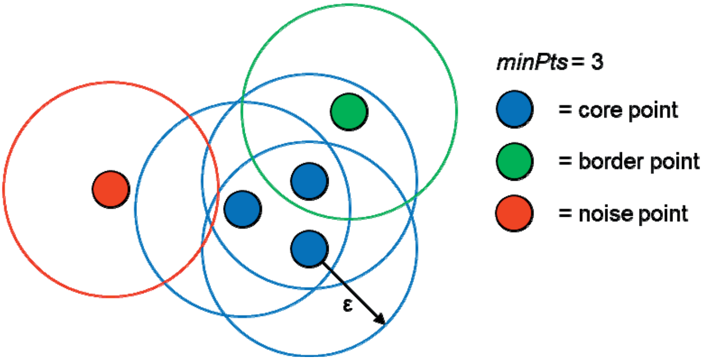

Fig. 2: 2D variant of the DBSCAN to cluster the aggregates (modified according to [7]). The blue and green points forming a cluster in this example.

The next step is to determine the size of each aggregate. According to [8] a soil aggregate can be approximated by a sphere. With a fixed point iteration of a nonlinear system of equations, every cluster is fitted with a sphere. From this the diameter of the aggregates can be determined for each case. If the degree of determination is too low, the corresponding cluster is deleted from the data. This is necessary because the point cloud can also contain organic residues. The aggregate sizes are divides into the geometric gradation by [8].
If the known mean weight diameter (MWD) [9] is calculated from the determined distribution as proposed by [8], the value is too high in comparison with literature values and visual inspection. The problem is that the proportion of the smallest aggregates is not taken into account. After [8], soil disintegrates during tillage according to the RRSB (Rosin-Rammler-Sperling-Bennett) distribution function [10]. This function can be displayed in the RRSB-grid *(DIN 66145:1976-04)* as a straight line (see figure 3). It is assumed that all unclassified and removed points are the smallest aggregates. An additional size group is formed from these values. Since the size of the aggregates in this group cannot be clearly determined, the linear relationship of the RRSB distribution is utilized. By means of an iterative linear regression, the corresponding sieve passing value is calculated using the best fit. From this, the missing parts of the smallest aggregates can be computed. This method achieves very high coefficient of determination and the mean weighted diameter shows a high degree of agreement with previous values and methods.

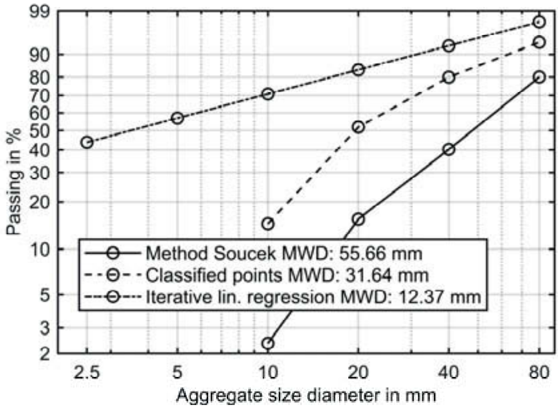

Fig. 3: RRSB-grid (modified according to [10] and *DIN 66145:1976-04*). A real distribution is a straight line in this grid. For the results from the algorithm this is not the case because the smallest aggregates are missing. With the equation of [10] these parts can be calculated and the results forming a straight line.

Results

The stereo camera is mounted in a mobile sensor unit for measuring the quality-determining parameters of soil tillage. By enclosing the sensor it is possible to eliminate the variable sunlight and create constant conditions for data recording and processing. In addition to the aggregate size distribution, a LiDAR sensor is used to determine the soil levelling and a colour camera to determine the degree of soil coverage by organic residue. The sensor unit is mounted on the front three-point linkage of a tractor. The data is recorded while driving, which enables high area coverage. The system has been used for 3 years in different applications of soil tillage and so far 120 test series have been carried out.

As an example, the results of the individual steps of the algorithm are shown in the following point cloud. The data set is taken directly after the primary soil tillage with a cultivator and a working depth of 30 cm. Figure 4 shows on the left the high-resolution 3D point cloud calculated from the greyscale image pair. Individual aggregates can already be identified by eye. The missing data points within the field of view are mainly caused by undercuts of large aggregates. On the right the result from the Cloth-Simulation-Filtering is displayed. Here many aggregates are already visible more clearly. The proportion of fine grains has been significantly reduced. In addition, the number of points has been notably reduced in order to speed up the calculation time of the further steps.

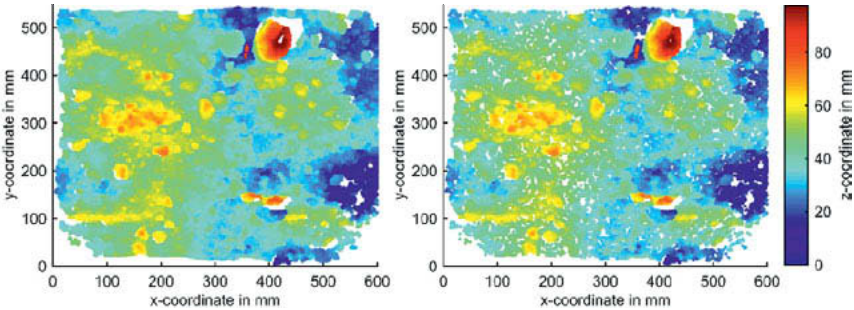

Fig. 4: Original point cloud (left, 4.225 mil. 3d points) and reduced point cloud after the Cloth-Simulation-Filtering (right, 250,000 3d points)

The point cloud clustered with DBSCAN is shown in figure 5. Every colour represents an individual cluster and therefore an aggregate. The undercuts in the original point cloud and the filtering before improve the performance of the clustering. In this case a total 1128 clusters were determined. On the right side the results of the sphere fitting and aggregate size determination are shown. The clusters are colour coded according to their size. The total number of clusters can be minor. If the degree of determination of the sphere fit is too low, then the cluster is excluded. The aggregate size distribution and the mean weighed diameter can be found in figure 3.

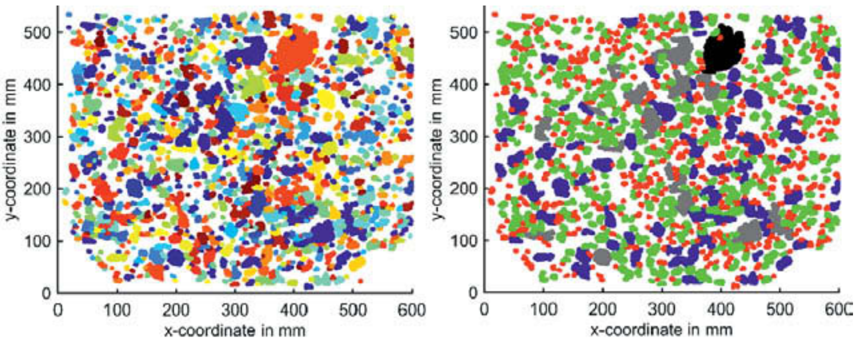

Fig. 5: With DBSCAN clustered point cloud (left, 1128 clusters found) and fitted aggregate sizes (right, red = below 10 mm diameter, green = below 20 mm diameter, blue = below 40 mm diameter, grey = below 80 mm diameter, black = over 80 mm diameter)

For development and verification, defined sizes and size distribution were investigated under laboratory conditions. Artificial spheres and individual soil aggregates of known size were used. Above an aggregate diameter of 10 mm the method shows a high accuracy for the determination of the individual aggregate sizes. This was also confirmed on a random basis in the field tests.

Conclusion and outlook

The novel approach to determine the soil aggregate size distribution shows great results. The method enables large-area data acquisition with a high spatial density and this with a low personnel input. This opens up new opportunities in the field of research and development. The method only determines the distribution at the surface. In further research work, it is therefore necessary to investigate how this parameter behaves over the working depth for different agricultural processes. In addition, it should be reviewed whether an application with more accessible and applicable sensors directly on the implement is possible. This would be of fundamental importance for a holistic view on precision farming and could open up new possibilities with methods such as Big Data approaches.

Funding authority

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Modular driveline solutions for a new generation of combine harvesters

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1. Abstract

When developing a new combine harvester product range, three of the most important targets are to achieve a higher level of performance with respect to the crop flow throughput, to increase the reliability of the complete machine and to improve the comfort for the customer. Additional targets are set by cross-product architectures and modularity restrictions. All targets need to be elaborated individually and then merged to a homogeneous overall machine concept including a corresponding driveline concept.

2. Motivation

The driveline of the LEXION combine, which was introduced into the market in 1995, has been almost kept the same since the last nearly 25 years. Only some modifications were done, when new requirements, either from the customers, like more engine power, or from governmental site, like emission legislations, needed to be fulfilled. Keeping the driveline nearly the same over years was possible, because the core aggregates of the successful LEXION combine, the threshing, separation and cleaning system was also kept almost the same. In 2019 the successor of the 1996 LEXION generation was presented. This machine needed to be modified in every assembly group to fulfil the requirements.

3. Requirements to a new driveline concept

The new generation of combine harvesters has generally two types of machines, a twin rotor machine and a straw walker machine. Both are equipped with a new APS threshing system.
For both combine types, the threshing and the impeller diameter was increased by 25% and exclusive for the straw walker machine, an additional separation drum was introduced. This was done to increase the throughput for both types, especially for the walker machines. To handle the increased throughput, the grain elevator size was increased by 16%
Compared with the top model of the old LEXION generation, the engine load for the new generation was increased by 27%.

The grain tank is 33% bigger and the unloading speed is 38% higher than before. Also the standard fuel tank size was increased by 18%.

All these changes over complete machine have a huge impact on the driveline. Also some cross-product architecture restrictions needed to be fulfilled, like the lower position of the main drive intermediate shaft to gain more grain tank volume, and the restriction, that it is not allowed to design drive components on the right hand machine side, behind the elevator, to gain fuel tank volume.

Additional to the requirements for the capacity and the restrictions from the cross-product architecture, the requirements for reliability, like increasing the MTBF and ease of use features, like better accessibility and less greasing points or a fast change between two crops, soy beans and corn for example, were added to the list of requirements.

All the given requirements and the demand to secure that the new generation combine harvester will also be 25 years successfully in the field made it necessary to develop a complete new driveline.

4. Modularity

The concept of modularity is used primarily to reduce complexity by breaking a system into varying degrees of interdependence and independence and "to hide the complexity of each part behind an abstraction and interface."[1]

Also a big effect of modularity is the reduction of R&D effort. Initially, more time is needed to develop a modular system, but then a lower amount of components needs to be designed. As a result of that, the validation effort is also lower especially for the strength tests. Only a functional test is needed, if one modular system is used in different applications.

Another important advantage of modularity is, that by reducing the complexity of a system by multiple use of single parts, the quantity of the single parts is increasing, which has a positive purchasing effect.

5. New modular driveline concept

5.1. The current driveline

When a new driveline concept needs to be developed, it is important to understand the existing driveline concept with all advantages to carry over and all disadvantages to improve.

The existing driveline, which is shown in figure 1, shows the transmission gearbox which is attached to the engine (1). From this gearbox, three coupling drives are assembled to engage the aggregates, the main drive (2), the three step straw discharge drive (5) and the grain tank unloading drive (6). The main drive runs the intermediate shaft from which the

header (3), cleaning and grain handling (4) are driven on the left hand machine side. On the right hand machine side (figure 2) the intermediate shaft runs the threshing mechanism (7), the cleaning fan (8) and the two step twin-rotor drive (9).
On a straw walker machine, the rotor drive is replaced with the walker drive which is situated on the left, respectively on the right hand machine side, where the multi finger separation drum is driven, behind the fuel tank (10).

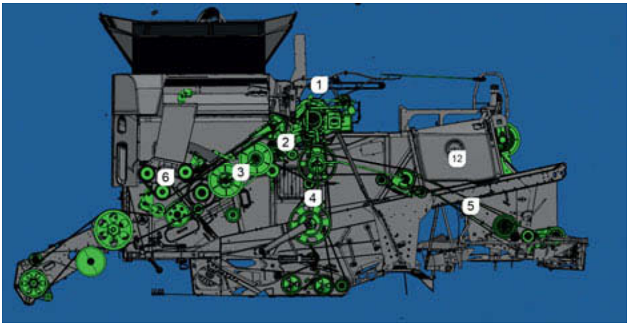

Fig. 1: Driveline left hand side of the current LEXION

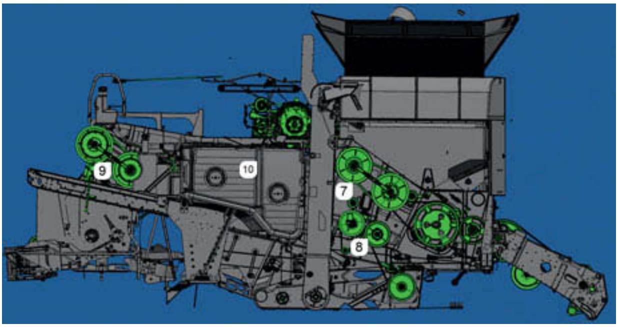

Fig. 2: Driveline right hand side of the current LEXION

5.2. The new modular driveline

The most important difference between the current driveline and the new driveline is the main drive (shown in fig. 3). Both concepts have a Power transmission gearbox which is assembled to the engine (1). But the current concept has one powerband (2), connecting and engaging the process drives, which runs all aggregates.

The new driveline has a friction disc clutch as an engagement device, integrated into the power transmission gearbox. The concept uses two powerbands to transmit the power. One for the intermediate shaft (2.1) which runs the right hand side of the machine, and one to distribute the power over the left hand side of the machine (2.2).

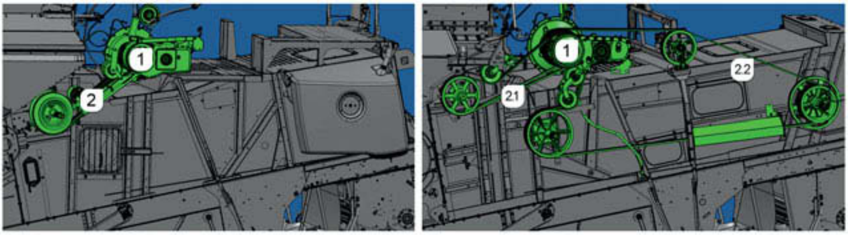

Fig. 3: Main Drive comparison (left current main drive, right new main drive)

The new main drive concept was required, because it was not possible to increase the performance of the current belt (2) to the requested power increase of 27%. Also, the friction clutch has a huge positive impact on the lifetime of the belt and the comfort of the machine. The engagement of the drives is smooth and gentle and it feels very comfortable for the customer. With the new belt (2.2) it was possible to realize all drives on the left hand machine side, except the threshing and cleaning fan drive. This was a requirement from the architecture to gain fuel tank size.

The complete driveline concept is given on figures 4 and 5. The pictures are showing, that the driveline of the twin rotor (fig. 4) is very modular to the driveline of the walker machine (fig. 5). Both concepts have the same main drive belts 2.1 and 2.2. The belt 2.2 runs the twin rotor drive (9), the chopper drive (5), the header (3) and the cleaning / grain handling drive (4).

Fig. 4: Driveline left hand side of new generation combine (twin rotor)

On a walker machine, the rotor drive is replaced by the walker drive, which is driven by the cleaning / grain handling drive (4).

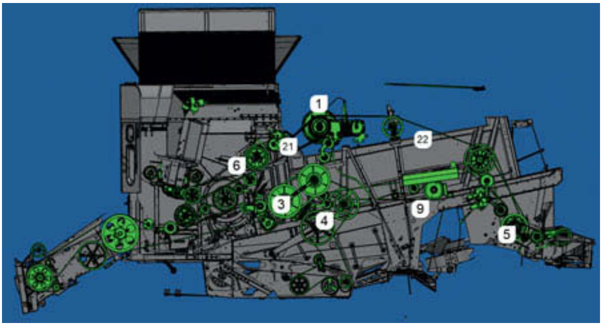

Fig. 5: Driveline left hand side of new generation combine (walker)

The right hand machine side gets the power from the main drive (2.1) which runs the intermediate shaft. There, the threshing drum drive, inclusive the variator and an optional available reduction gearbox and the cleaning fan drive is operated (shown in fig. 6).

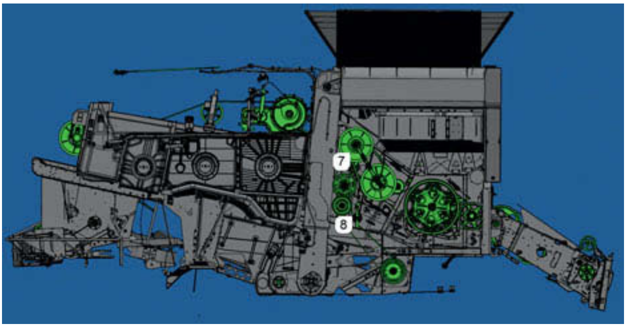

Fig. 6: Driveline left hand side of new generation combine

5.3. Modularity and comfort in the new driveline

The new driveline concept shows a significant amount of modularity over the complete product range of the new LEXION and a lot of comfort improvements. With the new driveline, there are no greasing points at all belt tensioners, the tensioners are maintenance free and only need to be used to re-tension the belts. Also the accessibility of the tensioners was improved.

The complexity of the cleaning fan drive (8) could be reduced from three different driveline to one driveline. The cleaning fan variator is using the same manufacturing technologies as the larger variators, which are used in the rotor, header or threshing drum drive. All variators (3, 7, 8, 9) are completely maintenance free, no greasing is necessary by the customer. The large variators (3,7,9) have a common part rate of 95%.

The technology which is used for the main drive clutch (1) is also used for the clutches of the header drive (3) and the grain tank unloading drive (6), which is available as an option. In this unloading drive (6), the customer is able to reduce the unloading speed halfway and to run only the unloading pipe, at the end of the unloading process, to reduce grain losses. The chopper drive (5) complexity was reduced to a modular kit, which is available in three comfort levels. The highest level allows the customer to change the chopper speed from the cabin.

The cleaning / grain handling drive was reduced from two drivelines to one driveline over the complete product range.

The reduction gearbox in the threshing drum drive (7) is also available as an option and it is possible to shift it from the cabin.

6. Summary

With the new driveline for the new LEXION generation, the demands from the customers regarding comfort and reliability and the requirements from the engine power increase and from the process technology, were realized with respect to the complete machine and production concept. It is now possible to produce a low specified walker machine next to a high end twin rotor machine, because the same, scaled modular parts are used in the same production step.

Also, in the future it is possible to scale the new driveline concept, further to the existing product range. A larger twin rotor machine with more engine load can easily be set up and even for a smaller range of combines, the new driveline can be used, because of its modularity. The driveline of the LEXION 1996 lasted nearly 25 years, the new driveline is ready for the next 25 years.

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Development of a header-prototype in order to increase combine throughput in grain harvest

Showing the upcoming problems of the development by analysing advantages and disadvantages of grain strippers

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Abstract

Nowadays the way of farming is driven by the need of affordable and high-quality food. As the prosperity of society rises, people have more choice to decide how food will be produced. Political influenced decisions in order to fulfill ecological targets are already part of today's farming structure and will be even more extensive through social demands.

Over a long period of time the way of farming will change. This does not only include methods of planting, cultivating or crop protection, it also includes grown fruits and their way of harvesting.

While larger farms are in the ability of producing high-quality food at high yields, especially smaller farms are in the need of finding methods to economical sustainable farming.

On the one hand the need of high throughput machinery is necessary to withstand price fights and save the future of farming in Middle Europe. While on the other hand flexible and small harvesting technologies are necessary to exploit new methods of farming.

Therefore, a rethinking of the way how harvesting works is necessary, including reducing actual problems caused by modern combines.

Those problems mostly refer to existing machinery dimensions and weights. Axle loads are an overall problem. The technical product development of tomorrow is responsible for protecting the soil and keeping soil compaction to a minimum. Whereby existing limits of the StVZO shall not be exceeded.

Heavy farming machinery do not only damage the soil, moreover, lead larger working widths to an imprecise distribution of the remaining straw. This implicates disadvantages for all following working steps. Especially in the case of tillage reduced farming principles like no or strip-till, the state of harvesting machines processing cereals and stubbles should be also questioned. [1]

All mentioned aspects are the basis for the development of a header-prototype. It builds the most significant part of a new harvesting concept. To fulfill today’s harvesting claims a lot of tests are necessary.

Optimization

One way to increase combine throughput without extending existing dimensions is to keep the straw movement at a minimum while separating the ear from the straw before the actual threshing process. Therefore, only inflorescences were led through the combine which reduces the workload of the whole machinery, especially the residual grain separation. [1]

Like the Shelbourne Reynolds Stripper (see [2]) the new solution separates the ear from the straw before the actual threshing process. Furthermore, some major changes were made to the crop flow. The patented operating principle is shown in the following image, figure 1.

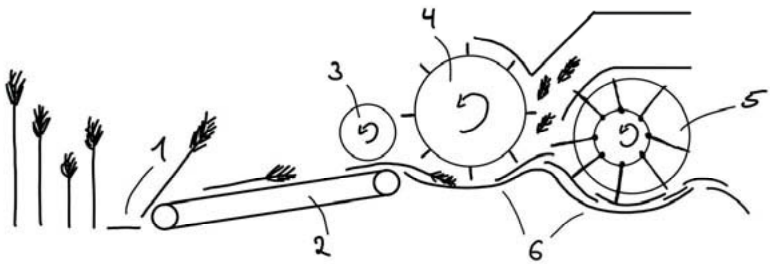

Fig. 1: Patented operating principle

It is characterized by the actual stripping drum (4) a following rotor (5) and a transport unit (2) with a feeding drum (3) to ensure active feeding. Plants are cut (1) at the beginning of the header and are moved by the transport unit to the stripping drum. In order to realize the stripping effect, the feeding drum presses the crops down. This induces a friction force and ears can be stripped efficiently from the straw. Through the force of centrifugal acceleration, the ears will be automatically separated from the straw. To ensure this separation process a rotor obtains the crop flow and leads the straw out of the machine. Moreover, the rotor makes it possible that stripping losses are separated by the concaves underneath (6). [3]

The concept has not only been developed to harvest cereals like wheat. Moreover, it is usable for all established cash crops and is suitable for Middle European arable farms. Meaning that losses through the stripper can be separated while the remaining straw is immediately swathed. A tremendous increase in combine throughput is been also given by the fact of enhanced concave area around 160%.

Advantages and disadvantages of strippers

Besides the given advantages the following part focuses on the advantages and disadvantages of the process itself. Because plants are mostly “chaotic” material, stripping can cause mainly three negative aspects which lead to high stripping losses.

Case 1) Ears can burst by the rotating stripping drum

According to the moisture of the fruit, it’s ripeness and the crop itself the stripping velocity can vary from around 13 m/s to 21 m/s. The higher the velocity the easier the ears can be stripped. But higher stripping velocities can also cause higher stripping losses, which means that single grains can be hit out of the ears. While too low stripping velocities can lead to effects like a threshing process.

Case 2) Ears are not barely touched and won’t be stripped

Because the plants are fed to the stripping drum on its downside it is much harder to ensure that all crops are evenly stripped. Therefore, the stripping quality is dependent by the thickness of the crop flow and the gap between the stripping fingers and the concave.

Case 3) Ears are stripped but can’t be separated

Especially under high crop flow volumes stripped ears can’t be hurled by the stripping drum because of loose straw preventing ears to hit their target.

According to the disadvantages of the given principle a reliable statement about how much percentage of the incoming plants can be efficiently stripped is currently not possible. Although stripping losses can be caught by the following rotor, all over grain losses under 2 % are hard to achieve.

Therefore, the development of a header in order to allow an intelligent pre-separation by a stripping unit is a long improving way and does not only include the header itself. Through regarding the following advantages of the concept, the whole harvesting process and associated machinery needs to be redefined.

The idea of stripping describes a process to separate inflorescences from the rest of the plant. This makes the concept usable for more processes than just threshing. Stripping drums can be used in all crops with mostly big inflorescences or blossoms as they are already used during hemp harvest. Using several harvesting components through all kinds of crops over a larger period can make farming more profitable and sustainable especially for smaller farms.

Overall, the energy of rotating stripping drums is also comparable to threshing drums. This makes it possible to use those headers as a pre-separation unit for crops which need to be more beaten than threshed. The combination of thinner crop layers and larger concave areas bring a high profit for those crops like canola or soy. Finally, the good accessibility is useful under tough conditions and for complex crops.

Testing and Results

In order to assure that stripping reaches at least 60 – 80 % efficiency the process needs to be observed through small units. Understanding the way how stripping works leads to an optimal development by optimizing all relevant components at early stages. Therefore, multiple series of tests were performed with different crops from different years:

- Barley-17 (B-17)
- Triticale-17 (T-17)
- Wheat-17 (W-17)
- Barley-20 (B-20)
- Triticale-20 (T-20)
- Wheat-20 (W-20)

The series of experiments are about single plants which are fed through the unit by hand. The unit is shown in figure 2 and has four major parts.

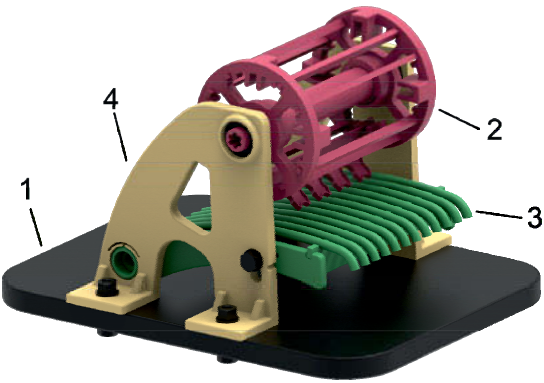

Fig. 2: Test unit

The stripping drum (2) and the concave (3) underneath are mounted on two frame parts (4) which are fixed on a plate (1). All rotating parts are driven by an electric drill, which makes it possible to switch between two rotational speeds at 1500 rpm and 2400 rpm.

The focus is about finding out how good stripping works in combination with a concave underneath. While analyzing the video material a better insight is conveyed why stripping is successful or not.

All test series lead to the following results, table 1. Results between 0.6 to 1 are rated good while results between 0 and 0.59 are rated bad. Good results are marked green while bad results are marked red.

Table 1: Test scores

SPEED	B-17	T-17	W-17	B-20	T-20	W-20
1500 RPM	0.57	0.28	0.73	0.66	0.63	0.54
2400 RPM	0.40	0.65	0.66	0.41	0.65	0.70

All test series are rated through the given table to compare several settings, table 2.

Table 2: Evaluation matrix

Class	Value	Category
none	1	stripping losses (Sl)
small	1	stripping losses (Sl)
medium	0.8	stripping losses (Sl)
high	0.6	stripping losses (Sl)
1	1	separation (Sep)
2	0.8	separation (Sep)
3	0.6	separation (Sep)
x	0	separation (Sep)
successful	1	assessment (A)
failed	0	assessment (A)
Wheat-17	1	factor of fruits (Fof)
Barley-17	0.5	factor of fruits (Fof)
Triticale-17	1	factor of fruits (Fof)
Barley-20	0.7	factor of fruits (Fof)
Triticale-20	1	factor of fruits (Fof)
Wheat-20	1	factor of fruits (Fof)
incomplete	0	segregation (Seg)
complete	1	Segregation (Seg)

In order to understand how the results in table 1 are computed all categories are explained below. Furthermore, the result is computed through the following formula which ensures a consistent evaluation.

Result = IF(@seperation>1;Sl*Sep*A*Seg*Fof;Sl*Sep*A*Seg)

A test fails (zero) if the “segregation” is “incomplete” or the ear burst which means that the “separation” is equal to “x”. Therefore, negative tests have a bad influence on the whole series what is necessary in order to ensure that stripping is evaluated correctly. Next to the stripping losses pieces of ears also will be counted through the category “separation”. Because some crops lead to higher stripping losses and ears may burst more easily the “factor of fruits” rates sensible crops more strict. For example, because Barley-17 is a very dry skinny crop hard to strip, it gets rated worse under suboptimal stripping conditions in order to match up with Triticale-20 which is way more easily to strip. The “factor of fruits” makes it therefore possible to compare multiple fruits. While it is only active if the class “separation” is bigger than 1.

The results in table 1 show the already addressed differences in stripping all kinds of crops. While it is hard to say exactly when stripping works best it is much easier to describe when stripping doesn’t work at all. Stripping is especially influenced by the following parameters:

- Stripping velocity
- Ripeness
- Dimensions of the ear
- Fingergeometry

Thererfore, stripping fails when either the stripping velocity is too low like in Wheat-20 and Triticale-17, too high like in Barley-20 or the fruit is non-strippable which means ears are too small and burst while the stripping drum hits it like in Barley-17.

By the following selected videos problems of stripping are pointed out more clearly and information about stripping are summed up. While black arrows mark the ears, white ones tag single grains (stripping losses).

According to the necessary stripping force stripping losses can extremely vary. While barley is the fruit with the least stripping force, its ears can burst very easy. Therefore, single stripping pictures as shown in figure 3 can look way different from the following.

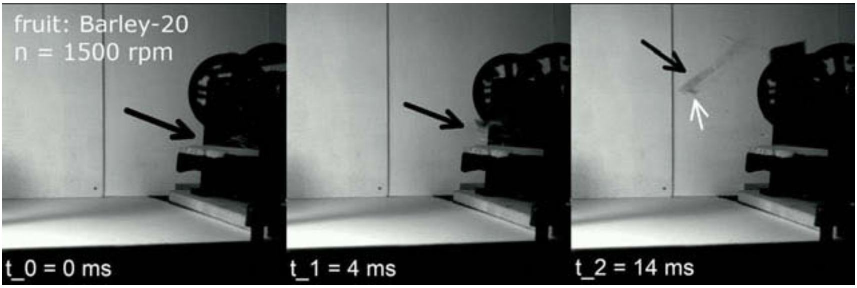

Fig. 3: Sequence of images for Barley-20

Depending on the local hit of the fingers ears can totally burst or be perfectly stripped. The picture shows instead a perfect stripping with one single grain.

Another case for suboptimal stripping velocities is shown in figure 4.

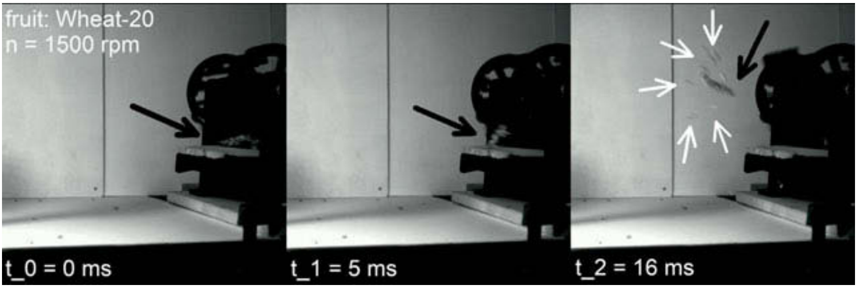

Fig. 4: Sequence of images for Wheat-20

As already mentioned, stripping losses can also extremely vary if the relative velocity of the stripping drum is inadequate to the fruit. Higher stripping losses can either be an indicator for too low or too high velocities. If the stripping velocity is too low, like in figure 4, ears are more threshed than stripped. Whereby too high velocities lead to single grain losses which means that grains are hit out of the ears through the impact of the rotor, like in figure 5.
The shown pictures do not only refer to the ripeness of the fruits. The size of the ear also has a major impact on the stripping efficiency. Thus, it is much easier to strip big ears like Triticale.
Eventhough drum rpm are too high, figure 5 shows stripping losses which stay to a minimum.

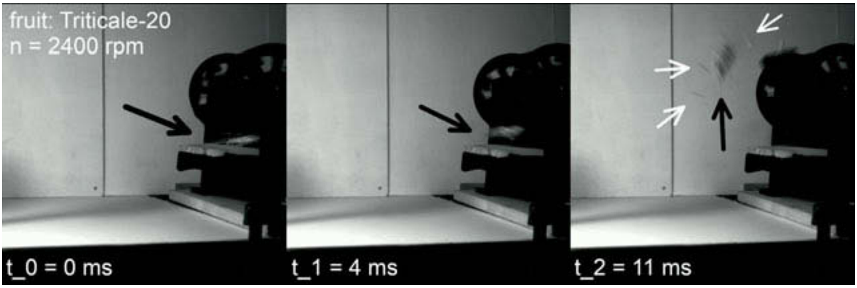

Fig. 5: Sequence of images for Triticale-20

Conclusion

The development of a header-prototype in order to increase combine throughput in grain harvest is not only about technical issues. It is more about handling simple crop flows in order to understand the scheme of stripping and find possibilities to realize an intelligent pre-separation. Although the development requires a lot of testing, the given advantages can lead the way of harvesting to another level of farming. This does not only include increasing combine throughput but also reducing fuel consumption. While area performance should be held at the status quo machinery dimensions should be reduced and prepared for automation processes.

Further steps in order to prove the concept under real life conditions will be taken by a real test-unit for the tractor front hitch.

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Development of an advanced grain handling system for a new combine range

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Introduction

After almost 25 years of Lexion with continuous minor or major improvements, a completely new generation of machines was launched on the market for last year's harvesting season. At first glance, the changes may not be immediately apparent, the whole machine setup looks similar, but the vast majority of parts and components have been newly developed.

Motivation

One of the targets of this new combine range was to achieve the next level of throughput performance. Within the general machine concept, also the design of the grain handling system had to be adapted to answer the ever-rising customer requirements. Especially grain tank capacity and unloading rate had to be significantly increased to meet the overall machine capacity.

For the new grain handling system, the following requirements were considered in the design phase:

- Conveying capacity for higher throughputs
- Functional reliability in all crops and all crop conditions
- Modular integration into existing machine concept
- Low specific power requirement
- High wear resistance of conveying components
- Gentle grain conveying
- Compliance with legal requirements

With regard to the North American markets, the grain tank had to fulfill the customer requirement of being able to harvest the length of a quarter section of high yielding corn without unloading. As a consequence of this increased storage volume, the performance of the unloading system had to be adapted to stay within the required time limits of the unloading process.

Parameters

The big challenge in achieving the set goals was to comply with the limited design space. Due to the larger threshing unit, the new machines have increased in length, which was a positive effect for increasing the grain tank volume. However, the remaining design restrictions of 3 m in width and 4 m in height of the overall machine could not be exceeded. Therefore, alternative conveying principles and drive concepts were considered and evaluated.

Grain tank

Based on described restrictions, the necessary additional grain tank volume could mainly only be achieved by increasing the height. This means that especially to reach the new maximum size of 18.000l, the grain tank covers (extension) had to be significantly larger. Nevertheless, it had to be ensured that the covers, when folded, still maintain a flat surface within the 4m overall height limit. Therefore, a cover concept was developed in which all four cover elements each have a hinged additional cover. This ensures that the side, front and rear covers do not overlap when folded. For the actuation of the folding process this means a controlled successive opening and closing of the individual cover elements is necessary. When the grain tank is opened, first the lower large covers are mechanically unfolded by an electric actuator via a linkage, followed by the upper additional covers via a hydraulically operated mechanism. The four corner elements of this cover concept are each formed by two-part tarps.
Altogether, about 60% of the total volume of the described 18.000l grain tank is stored in the cover area, i.e. above 4m height. Nevertheless, it is a self-supporting lightweight concept without a supporting frame design.

Grain tank filling system

The main requirement of the filling system for the new Lexion was a higher conveying capacity in order to compensate for the increased machine output.
Special attention was paid to the clean grain elevator. Due to the limited design space, a higher conveying capacity was difficult to achieve here. Therefore, other vertical conveying principles were also considered at the beginning of the development. After all the advantages and disadvantages of the alternative concepts considered, such as a bucket elevator or vertical auger, the use of a conventional elevator has remained the best option for our application. The deciding factors here were again the limited design space, the integration of the new yield sensing system, but also the more complex drive concepts for these alternatives. To achieve the

throughput targets, the elevator dimensions were enlarged as far as possible within the available design space. Together with a moderately increased chain speed, the desired conveying capacity was successfully reached.

The next critical component was the actual filling system in the grain tank. The conveying line from the elevator and into the grain tank had to be designed in such a way that the increased throughputs were conveyed reliably at a higher filling height. This resulted in the first solution: a pivoting filling auger with an enlarged diameter. As a one-piece version, the length of the auger was limited by the size of the grain tank, which resulted in a high degree of 'underwater conveying' during operation. An additional requirement was to ensure a trouble-free crop flow on the new yield measuring system positioned between elevator and filling auger. Altogether the limits of a single conventional filling auger seemed to be too critical for a reliable crop flow. Again, alternative conveying principles and means were examined and evaluated. Finally, due to the requirement of an in-cab foldable grain tank cover concept, a dual step grain tank filling system was implemented. It consists of a somewhat shorter conventional filling auger, which is driven by the grain elevator. The second stage is a vertical hydraulically driven second filling auger. Both augers fold in with the covers when the grain tank is closed.

Grain tank unloading

For the unloading system, due to the substantially larger maximum grain tank volume, a significant step was also necessary to increase the unloading rate. It quickly became clear that a noticeably larger diameter of the conveying elements would be required compared to the existing system. This always means a major change in the overall machine concept. Therefore, it had to be examined whether alternative overloading concepts could be advantageous here as well. Especially a belt conveyor system promised advantages by a higher and adjustable conveying speed, but also with a possibility in principle for a variable overloading distance. When evaluating the advantages and disadvantages, the main aspects were crop flow reliability and the allocated design space. So power density (potential unload rate in the given design space) and a leak-proof conveying concept were decisive. The result was, to maintain the conventional auger unloading concept for the new combine generation. To meet the required unloading performance the diameter of all respective conveying components was significantly increased.

Returns system

As with the other components of the grain handling system, the conveying capacity of the returns system had to be increased. This was achieved by enlarging the auger diameters and the elevator cross section and by increasing the rotational speeds.

Validation

After the functional design of the components had been largely determined and verified in the tests, the suitability of the components for practical use was ensured by intensive trials on the test bench and in the field. Strength tests were carried out using FEM calculations and corresponding test rigs. In various regions around the world, a multi-crop test was carried out in various small grain varieties as well as in corn and grass. At the same time, the new grain handling system was subjected to durability testing in endurance machines in Europe and North America to take into account wear and fatigue experience.

Results

After two harvests after the market launch, it is evident that the grain recovery system introduced with the new Lexion series meets the demands placed on it. Of course, not everything worked at first go, different and difficult crop conditions had to be taken into account through modifications. There were also some points that required improvements in strength. Overall, however, the goals set were achieved, which is also confirmed by our customers.

Concept development of a traction management system using the example of a pipe laying machine

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Abstract

This article presents a concept for a traction management system using the example of a specialized pipe laying machine. The developed system is based on the adjustment of the tool parameters, respectively the resulting tool forces, to manipulate the transferable tensile force of the track undercarriage. Furthermore, the system architecture is described and the general behaviour is analysed using simulation models. The limits of use as well as the possible cost reduction are shown using modelled reference soils.

Introduction

In the field of renewable energies, the usage of near surface geothermal energy is described by the innovative procedure called Agrothermie, which is preferably used below arable areas. The usage of this thermal energy requires, that collector pipes are laid in a depth of two meters. This technology was prototyped in the system of thermal and energy supply along with the project “EnVisaGe” in the municipality of “Wüstenrot” for the first time. The feasibility and functional reliability of the system could be demonstrated for a couple years of operation by now. Based on the experience and the results of former projects, the large-scale trenchless laying of collector pipes using tillage similar technology was identified as the economical and technical optimal solution. Known trench cutting processes have no relevance in agricultural used fields, because of the undesirable vertical exchange of soil. Due to the experience gained and the analysis of the obtained data, the requirements for future special laying tools and base machines could be specified. The further development in the context of Agrothermie focused on the development of new laying tools. After the first field tests with these tools, the limits of available tractors and dozers became obvious. Especially the lack of controllability of the draft force, insufficient possibilities to react to soil disturbances, unavailable pipe logistics and inadequate documentation possibilities have to be addressed. Based on this discrepancy of the state of development between the laying tools and the base machines, current research is focusing the development of a functional demonstrator of such a pipe laying machine system (Fig. 1).

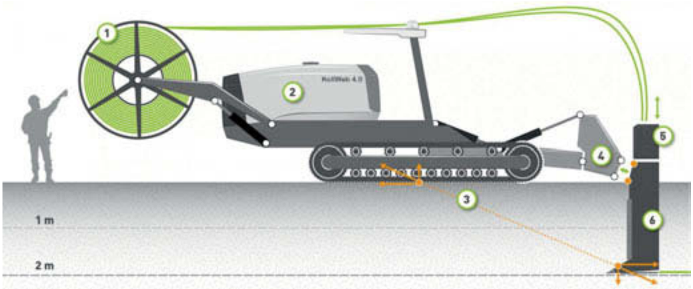

Fig. 1: Laying machine concept

Machine development

For meeting the requirements of the laying process the functional demonstrator is currently being developed. A concept was designed based on machines used for long distance laying of cables, pipes or drainage systems. With the exception of the track undercarriage and it's hydraulic drive, all systems have been completely new developed. The concept is shown in in Fig. 1. The base machine consists of the upper and lower section (2) with engine compartment, operator's place and track undercarriage. A completely new kinematic system (4) was developed for coupling the special laying tools (6). It was designed to optimize the insertion and lifting process of the tool. During the laying process, the hydraulic cylinders of the kinematics are hydraulically locked with check valves. The line of the resulting tool force (3) describes the dynamic load transfer from the laying tool to the crawler track. The positive effect of this load transfer on the traction behaviour of trench cutters and trenchless working ploughs was first described by Kalbheim [1]. In the context of pipe logistics, the laying machine carries its own pipe reel (1). The pipes are fed to the laying tool via the pipe driver unit (5). Inside the tool, they are guided to a depth of two metres below ground and leave the tool at the lower rear end.

Traction management system

The results of previous projects and the experiences with trenchless working machines have shown that the transferable tensile force of the track undercarriage is one of the most limiting factors. The soil resisting forces can require 200 kN draft force or more. Depending on the traction properties very high slip values are possible. In the worst case, the laying process must be interrupted. In this case a smaller laying tool has to be used. This means that a smaller number of pipes can be laid in parallel at the same time and the productivity of the process decreases. The approach to be developed considers an adaptation of the transferable tensile force to the laying resistance of the tool. The idea is based on manipulating the vertical force transferred from the tool to the track undercarriage by adjusting the tool. Consequently, the slip of the track undercarriage is the controlled variable of the system. The block diagram of the system is shown in Fig. 2. For further investigations a two-point controller is exemplary used. Similar to Fig. 1, the controlled system can be divided into four subsystems and the two-point controller actuates the tool. Due to the mechanical limitation, the control variable is restricted (w_R).

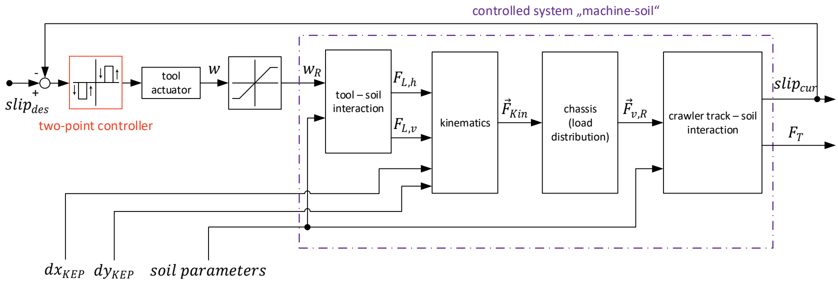

Fig. 2: Block diagram of the slip control

Modelling the controlled system

Within the controlled system, the tool-soil interaction describes the relationship between the soil properties and the tool parameters. This results in vertical ($F_{L,v}$) and horizontal ($F_{L,h}$) tool loads. For further investigations of the behaviour of the system, these relationships are modelled using a mathematical-physical approach according to *Balaton* [2]. This theory is based on considerations for subsoilers and differs significantly from normal ploughs. That means the working depth is much larger than the tool width. Furthermore, the tool compresses the soil at working depth and the soil cracks and loosens at maximum stress. In this approach the crack surface is modelled as a cone. The usage of this theory was described in [3]. The control of the tool width W, in the form of extendable wings, serves as an example for the investigations in this paper (Fig. 3). The cutting angle of the wings λ is significantly smaller than that of the foot β. Within the model the tool behaviour for specific soil parameters is described through the superposition of constant (foot) and variable (wings) parts. For further investigations an exemplary set of soil parameters is used (resulting forces acc. to Fig. 3). The loads due to the geometry of the foot ($F_{L,H0}$, $F_{L,V0}$) are calculated according to *Balatons* approach. In order to take the influence of the wings into account a separate calculation is carried out. In this context a foot with a cutting angle set to λ = 2,5° is considered. The resulting change in force due to the wing width corresponds to the increase of the forces in the diagram (Fig. 3) and is added to the values of $F_{L,h0}$ and $F_{L,v0}$.

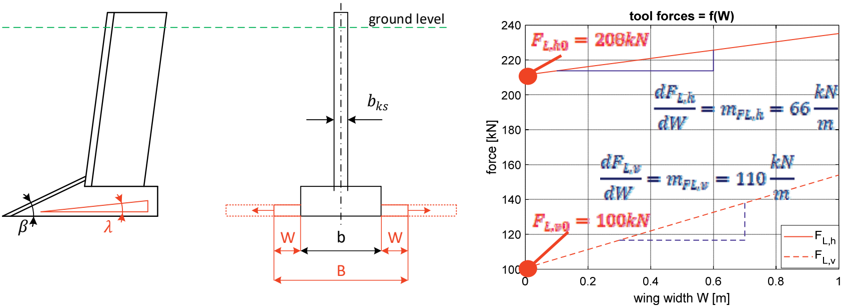

Fig. 3: Force changes due to wing adjustment

The resulting tool forces are transferred to the coupling points between the base machine and the kinematics and are summarized in the vector F_{Kin}. For describing this behaviour, the kinematics is modelled as a rigid, zero mass beam. The real mass of the kinematics is considered within the machines centre of gravity (COG). Thus, only the differential forces due to external loads are determined. This procedure is possible because the absolute values of the forces in the coupling points are of no interest. The calculations for determining the roller loads on the crawler track are carried out using a 2D mechanical simulation (see [3]). Accordingly, the roller loads are determined depending on the forces in the coupling points, the machine mass and the COG. The contact point of the drive wheel (last roll in the rear of the machine) describes the centre of rotation of the whole machine. For the modelling of the interaction between the crawler track and the soil a semi-empiric approach according to *Becker* [4] is used. The complete description of the adaptation and the usage of this theory is part of the content of [3]. For the further investigations, reference soils with different traction properties are modelled based on measurements made by Wong [5].

Simulation studies

The two-point controller (see Fig. 2) is used as an example to investigate the general behaviour of the controlled system for the reference soil C1 (see **Fig. 4**-A). The tool behaviour is modelled analogously to Fig. 3. **Fig. 4**-A shows the adjustment process by reaching an upper threshold value. The reference force-slip curve without considering the wing setting is represented by W = 0. At point 1 the current slip is within the threshold values, so the controller is inactive. The control becomes active when the upper threshold value is reached (2). Due to the wing adjustment, the slip and the resulting tensile force change according to a characteristic curve until the desired value is reached. There is a separate traction slip function for each value of W.

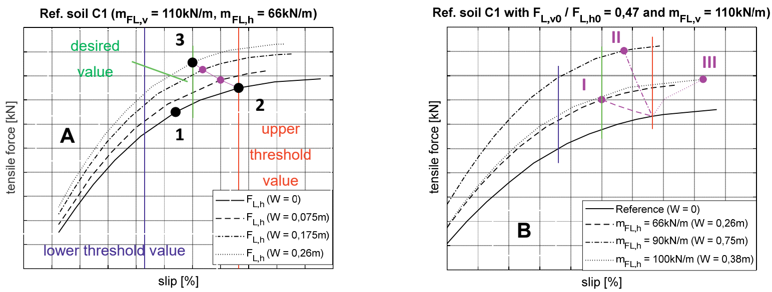

Fig. 4: System behaviour and limitation of control for a reference soil C1

The behaviour of the whole system is mainly defined by the tool-soil interaction (**Fig. 4**-B). The effect of a larger influence of the wing adjustment on the horizontal force, described by $m_{FL,h}$, is shown as an example. Case "I" is analogous to **Fig. 4**-A. Example "II" with an increased value of $m_{FL,h}$ = 90 kN/m shows that the desired value cannot be reached. The further enlargement up to $m_{FL,h}$ = 100 kN/m leads to a non-controllable system.
This also applies to a possible reduced influence of the wing width on the vertical force. In summary, the described parameters limit the operating range of the system. The wing adjustment for the reference soil (A) is visualized in **Fig. 5**. In contrast to **Fig. 4**, it can be seen that significantly higher slip values are reached. **Fig. 5**-A and B show how different threshold values and desired values affect the system behaviour. If the values are defined too small, traction potential remains unused (**Fig. 5**-A). Furthermore, the horizontal force is unnecessarily increased due to the adjustment, although the slip is not yet very high. On the other hand, the possible slip from **Fig. 4** is not as high as in **Fig. 5**. That could be a problem during a change of soil properties. Consequently, it must be summarized that each soil requires specific control parameters. This would be practical to examine. The controller gain would also have to be set on the basis of the measured values.

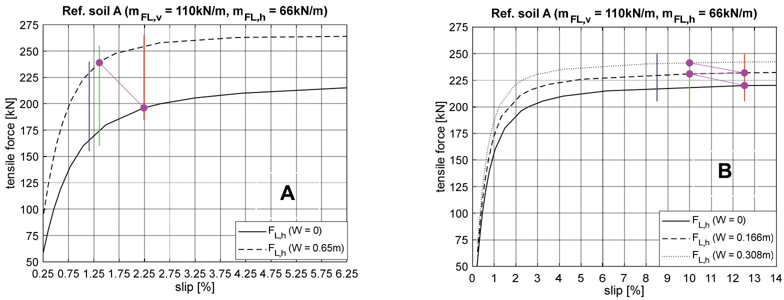

Fig. 5: System behaviour - reference soil

Conclusion and outlook

The presented control system enables the machine to be optimally adapted to the traction properties and the required tensile force. In addition, soil compression could be reduced by minimizing vertical load to a value necessary to ensure traction. The studies have shown that the applicability of the system significantly depends on the adjustment behaviour of the tool and the traction properties. Further research should focus on determining real soil behaviour and optimizing the simulation models based on field measurements with the functional demonstrator. In this context, the real operating areas and the positive effects in different soils have to be quantified to define an optimal tool design.

The following cost considerations should serve as an outlook. **Fig. 6** shows possible cost reductions for two cases by using the traction management. The calculation bases on a virtual laying scenario and the costs consists of costs for depreciation, accommodation, repairing, interest charges, insurances, fees, costs for auxiliary and operating materials as well as labour costs. In **Fig. 6**-A the required wing width for the reference soils A, C1 and C2 is visualized for a foot resistance of $F_{L,h0}$ = 190 kN. While C2 requires a minimum value of W = 0,54 m, no adjustment would be necessary for A and C1. This is due to the poor traction properties of C2. In this example (constant pipe laying distance), the traction management system enables a maximum cost reduction of up to 125 €/ha (-12,5%) for a certain foot resistance $F_{L,h0}$ compared to a tool with constant wings of W = 0,54 m. **Fig. 6**-B shows the cost reductions for the reference soil C1 by varying the foot resistance. The reference tool, a system with uncontrolled wings with W = 0,65 m and the traction management system are analysed. Compared to a tool with constant wings, it can be seen that significant savings can be expected, especially in the partial load range. In this example, the control system enables even higher tool foot forces in comparison to the reference. This would to be investigated in different soils conditions.

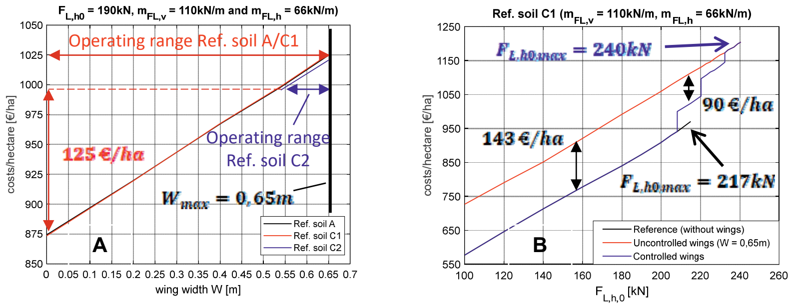

Fig. 6: Analysis of process costs

Further information

This measure is co-financed by tax funds on the basis of the budget approved by the Saxon State Parliament.

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New approach for an innovative straw management with the ”Kombi-Mulcher“

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Abstract

Climatic changes are causing increasingly extreme weather conditions, which are making the demands on crop production in the agricultural sector ever more challenging. These changes result in shorter periods for grain harvesting, higher demands on sustainable agriculture and leads to more incalculable economic developments.

The classic method of straw management is either the complete straw incorporation or straw removal from the field. To remove and remain the straw variably would be desirable depending on location and crop rotation for optimal control of the nutrient balance and further more. In addition, a high cutting combine harvester in particular can be used more efficiently and productively due to a lower straw content in the crop flow. The straw remaining in the field have to chopped but will have advantages for incorporation into the soil. The even distribution of straw in the field in longitudinal and transverse direction significantly improves the preparation of the seedbed and ensures uniform conditions for the following plant. With this concept it is possible to recover the straw remaining on the field after the high cut in variable quantities and optional to shred the remaining stubble.

This contribution to the conference provides the requirements analysis for the design of a so-called ”Kombi Mulcher”. This consideration is carried out holistically, taking into account the mechanical engineering, crop production and economical aspects. The advantages of improved field hygiene, the decoupling of the moisture content of grain and stalk as well as the increased efficiency of the combine harvester during high cut are the main focus here. The analysis is based on practical studies and interviews with various experts from different areas in this topic. The methodical procedure for creating, conducting and evaluating the surveys for an effective result is described. This makes it possible to answer various questions in the field of process technology in order to find an optimal solution for the overall concept. A classification and optimisation of the concept in agricultural process chains is a particular focus. The article presents the results of these investigations and provides an inside in innovative and new possibilities of straw management.

1. Introduction and motivation

Climate change and the associated weather extremes pose new challenges for agriculture, also in Europe. In addition, ever shorter time windows for harvesting are being created by weather extremes with rapidly rising precipitation at harvest time. One possible way of increasing the working speed and making use of these shorter time windows is to harvest grain in high cut. This method is known from Australia or the US but also under discussion in Europe. A major part of the straw remains on the field for the time being. Further processing of the straw is necessary. Long periods of drought in the summer are also posing increasing problems for farmers in terms of the soil quality to be preserved over long time periods [1]. Furthermore, the awareness for sustainable and resource-saving agriculture is becoming more and more established. Consequently, changes in the law are also reflected in the fertilization ordinance, which places a special focus on the control of soil parameters. This also includes the humus balance [2] which can be influenced by the amount of straw material. In Germany, between 33 and 38 million tons of this fresh mass are produced annually [3]. Current process chains usually provide for either a complete straw incorporation or straw salvage. It is not possible to extract or supply straw in a manner appropriate to the location and crop rotation. This is where the process concept of the so called "Kombi-Mulcher" can claim its benefit. The innovative straw management system starts after the combine threshing in the high cut. It enables the further processing of the straw after the high-cut as well as the targeted straw management.

2. Innovative process for extended straw management

With the conventional method, the straw is either completely taken from or left in the field. Irrespective of this, the combine harvester cuts and processes all the grain with a certain residual stubble height. The main focus is on grain harvesting. The straw passes through the entire combine harvester. If straw is to be harvested, the straw of the entire working width is deposited in a swath. In the following work step the straw is completely taken up usually by a baler, knives or choppers are used for short cutting lengths. If the straw should not be extracted and remain on the field, it is chopped and distributed evenly over the working width of the machine. Subsequent stubble cultivation is used to mix the straw with the soil and to initialize the decomposition of the straw. This conventional method has some disadvantages. [4] The entire straw always passes through the combine harvester, regardless of its further use. This inevitably leads to a higher power requirement of the combine harvester and a deterioration of the cleaning device for grain separation. Due to the higher power requirement, more and more motorized machines are necessary or result in lower working speeds. With shorter time frames for harvesting due to increasing weather extremes, this leads to problems during harvesting. In addition, there is a problem with the straw remaining on the field. To achieve a good rotting process and a homogeneous humus balance, it is necessary to ensure that the straw is evenly distributed over the working width of the combine harvester. This is often difficult with working widths of more than 9 or 12 m on current combine harvesters, especially when the influence of wind is taken into account [5]. This is where the concept of the "Kombi-Mulcher" comes in. In this method, the "cutting and threshing" and the "straw management" operations are decoupled. The grain is harvested with a conventional combine harvester using the high-cut method. In order to avoid damage to the grains, the optimum straw content in the combine harvester can be determined via the cutting height. After this threshing process, the individual stalks of straw remain standing on the field. The straw management with the “Kombi-Mulcher” is then carried out. With this it is possible to recover a variable part of the straw and the other part remains on the field. Figure 1 shows a functional approach to the way the machine works.

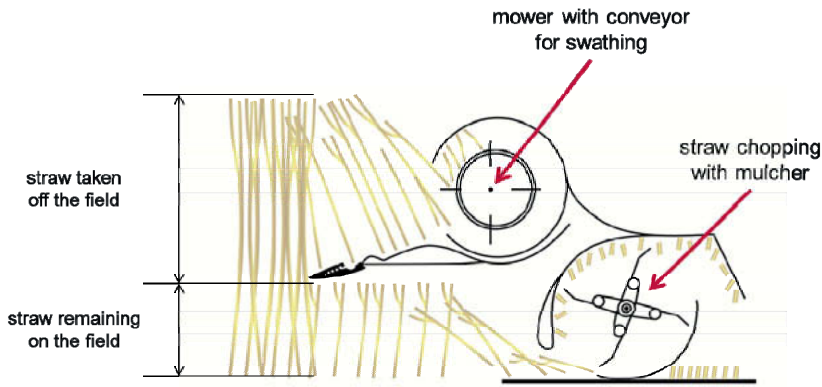

Fig. 1: Schematic illustration of functionality of “Kombi-Mulcher” [6]

A mowing unit cuts a variable part of the straw in the upper part and transports it with a header auger. It is deposited in a swath and is collected by a baling press in a subsequent operation. The remaining part of the straw that is to remain on the field is chopped up by a mulcher. The height of the cutterbar and mulcher can be adjusted variably. Thus it is also possible to recover all the straw or leave it on the field. The presented method of straw management has several advantages. Less straw passes through the combine harvester due to threshing in high-cut. This means that the cleaning system works more efficiently and the power requirement is reduced or the working speed is increased. This means that even short time frames due to the weather during the harvest can be used. In addition, the straw is much better chopped and distributed, which significantly improves the decomposition process. Due to the variably controllable amount of straw, the humus balance can be optimally controlled, for example depending on the conditions in the field or the crop rotation.

3. Methodical approach to finding a solution in holistic

The combined conception of the "Kombi-Mulcher" combines different sub-processes such as cutting, mulching and transporting, resulting in various challenges. It is important that both the sub-processes are optimally designed for themselves, as well as the combination and mutual influence of the processes. To solve this challenge, a methodical approach to finding a solution can be applied. The procedure of this methodology is shown in figure 2 and explained in the following.

The development process starts with the identification of the requirements of the individual sub-processes and the overall system. For initial clarification, an extensive literature research is carried out. Expert interviews and practical field tests are available as additional tools. These three tools run in parallel and influence each other. Certain problems can be clarified right at the beginning exclusively by a literature research. Other problems cannot be clarified directly due to the completely new approach to a machine concept. This is where the two other aids of expert consultation and field trials come into play. In the expert survey, candidates are first identified and categorized. For example, experts from the fields of research and development, industry or farmers are available. Furthermore, a categorization can be carried out based on their areas of expertise. A discussion guide is developed from the open questions. It is important to keep the questions as open as possible and to initiate a discussion during the survey. This promotes the creative process of finding ideas. The discussion guidelines will be adapted to the categorization of the experts. For example, it may not be effective to ask a mechanical engineer questions about plant production. Parallel to this, practical experiments in the field are planned and carried out. Following the expert survey, this is evaluated and analysed in the same way as the field trials. An evaluation of the results of the survey and the trials is made by comparing them with each other and with the results of the literature research. In this first step various problems can be clarified and evaluated as valid. The problem is considered to be solved if the solutions to the problem from all three tools are largely identical.

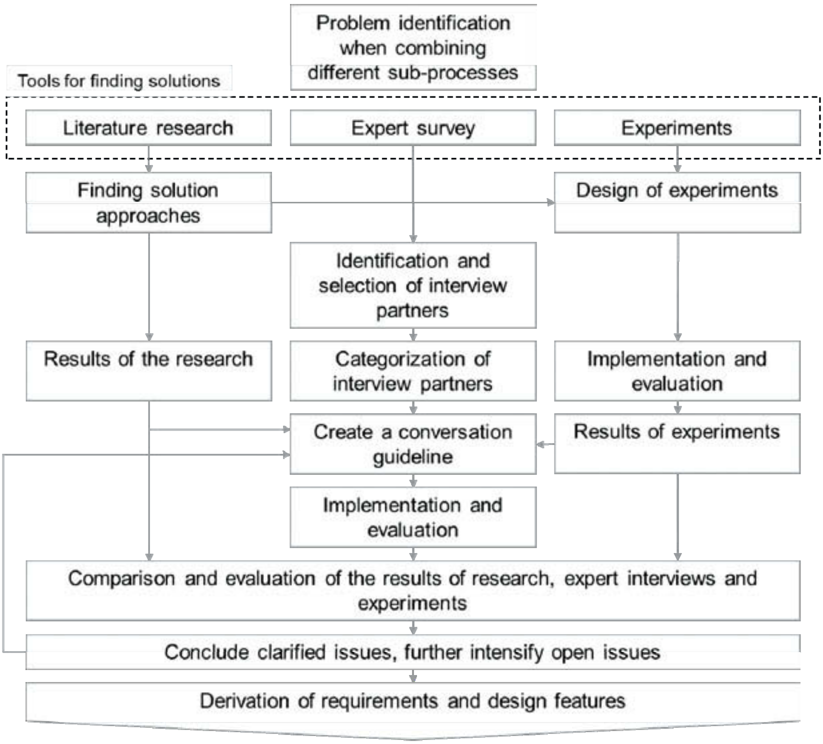

Fig. 2: Flow chart for methodical solution finding

Unresolved problems are concretized in a further iteration loop. For this purpose, the discussion guide is adapted to the knowledge gained and new surveys are conducted. The same applies to the field tests. The design of the experiments is adapted and carried out. The evaluation process takes place again as described above. At the end of this methodical procedure, the requirements and design features of the "Kombi-Mulcher" are derived.

4. Research results of the methodical procedure on selected examples

In this chapter the method described above shall be demonstrated by means of two abstracted examples. One of the most fundamental challenges in the development process is the selection of the individual specifications of the subsystems. For example, a large number of different cutting systems are available. In the first step of the literature research, the possible combinations for the subprocesses cutting, mulching and transporting of straw could be identified. Furthermore, first indications for advantages and disadvantages of the individual systems were found. As an example, a double-knife cutter bar, a disc mower, a drum mower, a flail-type mower or a sickle-type mower could be used as a cutting system. Basic points to consider for each type of mower can be found in the literature. In particular, the pros and cons with regard to current developments could be clarified here within the framework of the expert survey. Experts from the category development in the industry provided important aspects for selection. These surveys have the advantage that a large amount of knowledge from many different subject areas can be gathered in a short time. The willingness of the selected experts from all areas to take part in a survey of about 45 minutes can be evaluated as extremely positive. Such a survey requires much less time than extensive experiments in the field or extensive research in the literature. Furthermore, the interviews revealed interesting information that was not taken into consideration when the challenges were first identified. The example of the selection of the cutting unit also showed that not all problems can be clarified directly. Thus, the evaluation did not show any concrete result regarding the question whether a single culm in the upper area provides sufficient resistance for a cut without counter blade. Usually cutting units work according to the principle of a cut without counter blade in the lower part of the plant. It was questionable whether it is also possible to cut in the upper area with this cutting principle, which is a basic requirement for the "Kombi-Mulcher". Based on this, this question was clarified with the third aid, the field trials. It was questionable whether even at high working heights and speeds all stalks would still be cut completely and not kink in front of the cutting unit. Furthermore, the straw quality should not be affected by the cutting process. A corresponding test was planned and carried out. The test evaluation confirmed that a cut in the upper part of the stalks with the cut without counter blade is also possible. After this procedure all sub-processes were examined and evaluated individually and in their entirety. A simplified representation of a morphological box is shown in figure 3.

Element	Realization					
Cutting unit	Double-knife Cutter	Finger Cutter	Disc Mower	Drum mower	Flail-type mower	Sickle mower
Mulcher	Hammer flails	Y-knifes	Swing mower			
Straw transport system	Auger	Belt				

Fig. 3: Morphological box of the sub-processes

The overall evaluation of the morphological box shows a rough overview of the one design feature of the subprocesses. A simplified description shows that a disc mower is particularly suitable as a cutting device. It allows high driving speeds, low maintenance and does not tend to clog. A machine with hammer flails is used as a mulcher. This has a high suction effect even when the straw is lying down, ensures an even straw distribution and offers advantages in maintenance. A header auger is recommended for conveying the straw in transverse direction. It is a simple design, requires little space, is resistant to clogging and, with throwing plates, also allows longitudinal conveying for depositing the swath.

Another example is the problem of the swath. The straw to be recovered with the "Kombi-Mulcher" must be deposited in swaths. A possible consideration is the direct overloading of the straw from the "Kombi-Mulcher" into a baler. Two problems arise here. Firstly, it cannot be guaranteed that the moisture content of the straw after high-cutting is low enough directly for baling in the baler. This could be clarified both by questioning the experts and by tests on the field. On the other hand, the combination of "Kombi-Mulcher" and baler results in a high power requirement. This approach should therefore be rejected. Consequently, the straw to be harvested must be deposited in the swath. This is inevitably done on already mulched ground. The problem of straw recovery after using the "Kombi-Mulcher" is shown in Figure 4.

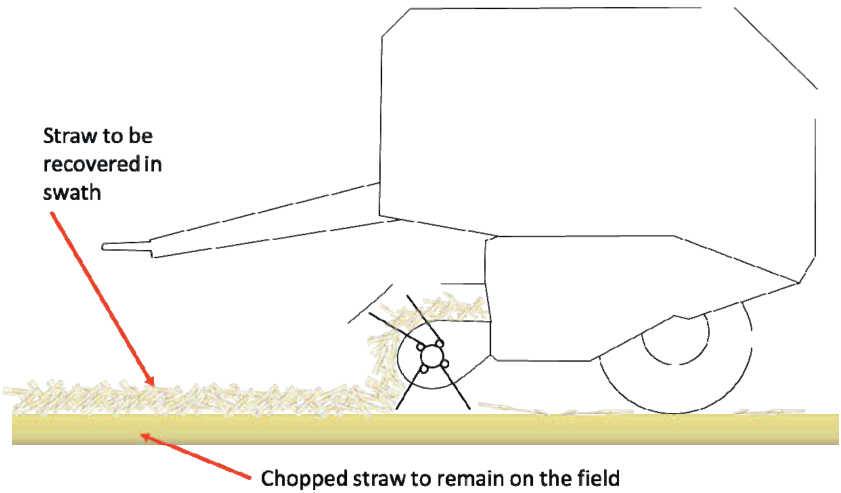

Fig. 4: Principle illustration Problem of swath recovery

It was questionable whether a subsequent recovery of the straw would be possible with the baler's pickup without contaminating the straw and impairing the even straw coverage of the ground. It is important that the pick-up tines do not work so deep that they pick up the mulched straw, but also not so high that part of the straw to be recovered remains in the field.

This question could not be clarified in the final analysis either by questioning experts or by researching the literature. The final clarification was achieved by field tests. Figure 5 shows the test setup with the swath on the straw distributed and chopped by the mulcher.

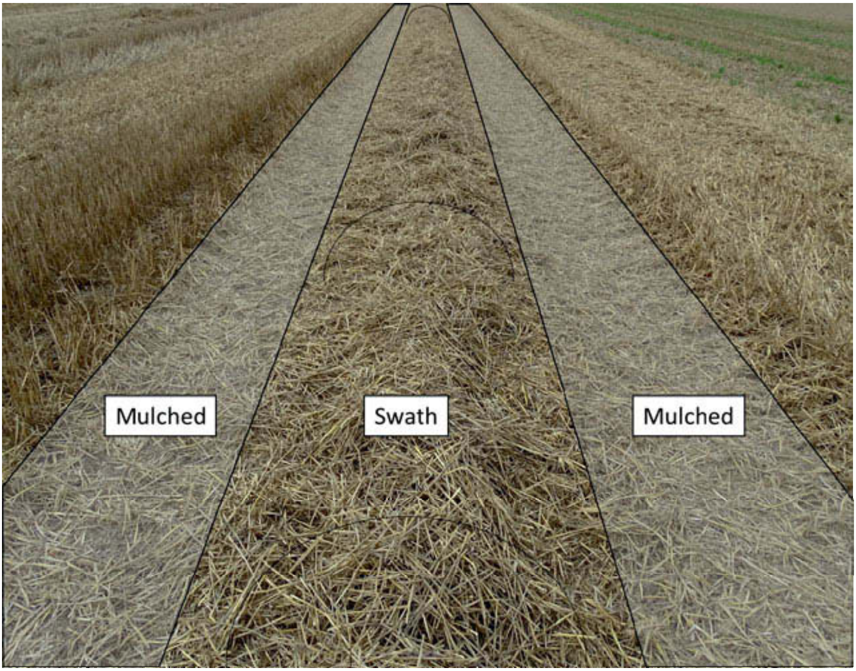

Fig. 5: Test setup for the pickup of the swath

The swath was then picked up by a baler. The setting of the pickup was varied. An evaluation clearly showed that with the correct setting, picking up the swath was unproblematic. No impurities were found in the recovered straw. A complete pickup was possible. An examination of the straw remaining on the field showed that the homogeneous distribution was not affected and was not picked up by the baler. Thus, the problem could be finally clarified with the presented methodology.

5. Conclusion and outlook

The developed methodology, which is presented here with two examples, has created a time and cost saving possibility for the development of a "Kombi-Mulcher". The methodology shows great success in the various aspects necessary for the design and fulfillment of the requirements. Furthermore, it was confirmed that the presented method for an innovative extended straw management brings great advantages. This concerns ecological, agronomical and finally also economical aspects. Thus scientifically an innovative and holistically considered way of using straw, which has an increasing role in agriculture, is being investigated.

After application of the presented methodology, the construction characteristics for a prototype machine can be derived from this. After the final design and dimensioning, a first prototype can be built for the next harvest season. Extensive field testing will investigate the envisaged benefits and identify the final potential for improvement.

6. Acknowledgement

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Alternative drives for agricultural machines

Legal frame, meaning, concepts, validation, conclusion

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Abstract

The interaction of respective agreements and regulations on global, European and national level with relevance for agricultural machinery will be presented. The contribution of agricultural machinery to greenhouse gas emissions from combustion processes in Europe and Germany will be quantified to capture the importance of alternatively driven agricultural machinery on national economic level. Already realized concepts on alternative drives for agricultural machinery will be presented. Those examples will be validated regards their CO_2 prevention potential respectively other chances for realization and market success.

1 Agreements and regulations for climate protection

A legal framework of interacting and interdependent agreements and regulations has been established on UN, EU and on German national level, which continues to be extended. Their task is to regulate how consequences on world climate caused by undamped fossil energy usage must be embanked. Basing on United Nations Framework Convention on Climate Change [1], the major of such items to call are the Kyoto Protocol [2] and the Paris Agreement [3/. Whereas [2] was targeting until 2020 to shrink down the yearly global CO_2 emissions onto the level of 1990, it is captured in [3] to limit the global warming by greenhouse gas emissions to 1.5 °K until the end of this century.

Corresponding EU measures to these agreements are e.g. defined in [4] und [5], with [5] setting CO_2 emissions reduction targets for individual EU member states, which are related to their respective state in 1990. Thus, for entire EU until to year 2030, the CO_2 prevention target of 40 % is legally fixed. Germany as one of the biggest emitters within EU has to carry a major portion on CO_2 prevention and must reduce its yearly emission till 2030 by 55 %.

In Climate Protection Plan from November 2016 [6], German Federal Cabinet did outline how the assigned target must be achieved. Its legally binding transition is the Climate Protection Law [7] entering into force in December 2019, which was supplemented by Climate Protection Program [8], which contains respective measures for each sector of this way split up German economy. For achieving the climate targets in German regulations, two essential steering elements of either regulative [7] or market-oriented nature have been implemented. If the sector Agriculture – for which CO_2 emissions from internal combustion engines in agricultural machines are explicitly included – fails to meet its target, affected German Federal Ministry for Nutrition and Agriculture may decide actions to get back into foreseen corridor of tolerable CO_2 emission assigned for each year. As last resort, German Federal Government can compensate breach of regulations of one or more sectors by buying EU emission certificates out of only a few industry sectors covering EU emission trading system.

For developing national emission trade to other sectors and to foster market-oriented principles, German Federal Government enacted a regulation [9], which realizes CO_2 emissions from fossil fuels and prescribes trade yearly declining, free saleable energy volumes of fuels recorded beginning in 2021. For volumes beyond, national certificates must be bought, which increase fuel prices to motivate energy savings resp. to give way to alternatives.

The Climate Protection Program may be superimposed respectively significantly revised by potential impacts of recently announced EU Green Deal [10] of new EU Commission. This term stands for a new orientation of current EU climate policy, according to which the entire EU must prevent until 2030 - instead of 40 % - already up to 55 % CO_2 emissions. Since at editorial deadline no further details - about new guidelines for member states in particular – were available, the upcoming development can just be pointed out.

2 Contribution of agricultural machines to CO_2 emissions

The path of energy to consumer [11] consists of sections energy emergence, primary and final energy consumption. The last section is formed by industry, transport, households and a domain for commerce, trade and services. The biggest deduction when transiting from German primary to final energy consumption is marked by energy transition losses, which are almost as high as the biggest final energy consumer and which clearly exceed the volume of produced renewable energy.

When looking on the development of CO_2 emissions out of fossil combustion since 1990 up to today, a clear decline of emitted quantities must be noticed. Today, the energy production holds with more than 41 % the majority portion of these emissions. It is obvious, that the public electricity and heat production, refineries as well as solid fuel production out of predominantly fossil sources ensure energy production this top ranking. These processes are responsible for the very high transition losses in primary energy section as well. Transport sector – which normally includes agricultural machinery – has increased since 2010 [11].

Agricultural machinery cannot be made responsible for the stated increase of CO_2 emissions in transport, since the available agricultural area in Germany is declining [12] and the stock of such machinery in the market is stagnating due to the trend towards bigger, more effective machines [13]. Based on documented subsidy for agricultural Diesel fuel, the CO_2 emissions of agricultural machinery in Germany can easily be predicted [14]. Their volume is roughly 3.6 % of transport sector's CO_2 emissions [11, 14]. This is in alignment with related figures for entire Europe [15]. Thus, it can be noted both for Germany and Europe, that Non-Road Mobile Machinery cause round about 5 % of fuel consumption resp. of CO_2 emissions from transport sector. This is equivalent to a portion of roughly 1.1 % of CO_2 emissions from combustion of fossil energy sources in total. Approximately 0.8 % are emitted by agricultural machinery alone, the rest is caused by construction equipment.

3 Sustainable powertrain concepts for agricultural machines

Although the contribution of agricultural machines to greenhouse gas emergence out of fossil combustion in total is straightforward, this group of machines has been used since a long time to investigate several different alternative powertrain concepts. Some of them are cloth before start of series production resp. could have been acquired by customers already. Such already realized concepts can be grouped into liquid fuels (Compression ignited engines operated with alternative fuels), gaseous fuels **(**Compression or spark ignited engines operated with regular fuel plus a gaseous portion or purely with compressed natural gas (or biomethane) as fuel), electric powertrains **(**Various hybridizations, battery or fuel cell electric vehicles) and new machine forms (New vehicle concepts with different electric powertrains)

Representants of first group are e. g. machines from John Deere, which are operated with pure plant oil according to DIN 51605 or DIN 51623 carrying engines with actual emission technology. Despite Mannheim tractors of all sizes [16, 17], very large and powerful machinery such as forest harvester [18] and combine [19] have been evaluated successfully in the field over a longer period of time without penalties in functionality, durability or productivity.

The most advanced model out of machines powered with gaseous fuels is the New Holland T6.180 Methane Power [20]. In this tractor with market entry in 2021 a spark ignited gas engine is used, which comes in terms of torque and speed with Diesel-identical performance. With range extender this tractor achieves round about 48 % of onboard energy quantity of his Diesel driven pendant with related consequences for cruising range and/or productivity.

Despite the very first commercial offer of a micro hybrid tractor by John Deere (2007) [21], his successor and from this one derived experimental hybridization variants [22] plus a high-power battery electric tractor prototype [23], the Fendt e100 Vario [24] is the most up-to-date battery electric tractor. An electric motor with a power of 50 kW replaces the Diesel engine. With a battery capacity of 100 kWh an operation in range of 4 – 5 h becomes feasible, due to CCS quick charge 80 % of battery capacity can be recharged within 40 minutes.

The very first fuel cell driven vehicle at all was a tractor! Already in 1959, Allis-Chalmers presented in the US such a tractor with a power of 15 kW in a short field operation [25]. Next in 2009, New Holland displayed another tractor operated with a fuel cell – which was already invented in 1838 - now with a power of 100 kW, obtaining its energy out of hydrogen high pressure tank with a capacity of 283 kWh and showing up with two electric motors of a 100 kW each for propulsion and for power take off as well as for auxiliary drives [26]. After extensive field investigation, any further development of this concept was stopped for the sake of New Holland's methane gas powered tractor.

In 2018, John Deere introduced in project GridCon [27] with a strongly modified tractor concept a purely electrically operated new machine form. The man less and cab-free tractor receives out of the grid a maximum power of 300 kW through a 1000 m long electric cable at a voltage level of 2500 V. The cable is onboard carried on a cable drum. In the field the machine can be operated autonomously, supported by a robot arm managing cable routing on the ground and cable on and off spooling. A different approach representing another machine form too, was chosen by Fendt with the robot swarm concept Xaver [28]. Various small, battery propelled vehicles machine the field in a swarm, actually with seeding operation exemplarily in focus. By the multitude of robots, a high operational safety shall be achieved. The low soil compaction shall favor realization of a variety of precision farming ideas.

4 Concept validation

The prime target of alternative drives for tractors is to replace Diesel fuel by another, more environmentally friendly energy source. By this, CO_2 emissions shall be prevented and/or costs of operation shall be reduced. The general conceptional target of alternative drives should be to achieve similar level and duration of performance as on conventionally propelled pendant, such that they can enter to the latter in comprehensive competition and may become for customers truly an alternative. The concept maturity correlates necessarily with degree in which existing components of vehicle infrastructure can be carried over – despite a completely mature new machine form can convince customers right away.

For validation of introduced concepts, the relative potential for CO_2 emission prevention and the relative onboard energy capacity of actual concepts with highest maturity according to above definition were compared. As reference for intended relation, a conventionally powered tractor was chosen, which has an energy capacity of 100 % and a CO_2 prevention potential of 0 %. Competitive products with partially unknown technical parameters have been made comparable with data from close Deere models. Thus, in this comparison differences in power and other brand dependent discrepancies could get levelled.

Into this comparison went the John Deere pure plant oil tractors, the New Holland biomethane tractor and the battery electric Fendt e100 Vario. Due to varying data in literature, always the maximum potentials have been included as e. g. to be found in [29]. In the nomenclature energy capacity / CO_2 prevention the John Deere pure plant oil tractors score up to 93 % / 91 %, the New Holland Methane Power with range extender achieves 48 % / 89 % and the Fendt e100 Vario captures 14 % / 100 %. These numbers are not absolute figures due to deviation margin in literature, divergences are feasible! However, from qualitatively clear differing onboard energy capacity follow as well clear constrains regarding traditional tractor usage pattern, which are dependent from chosen kind of alternative drive. In return, all alternative drives compared can convince with a very high potential to prevent CO_2.

5 Conclusion

Today's alternative drives for agricultural machines with highest maturity are such with liquid or gaseous fuels as well as battery electric driven concepts. The kind of propulsion dictates the bandwidth of potential application and available power, because the concept dependent onboard energy capacity is the overarching key parameter for an operation in a manner the individual machine form is known for. Similarly, the decision on drive technology impacts achievable CO_2 and operation cost reductions. The kind of alternative drive with its individual pros and cons is not dominating the buy decision alone. The latter is significantly impacted by available or affordable infrastructure on the individual farm the alternatively driven agricultural machine goes to. The national economic contribution of such machines to climate protection is objectively small. However, for perception of agriculture in public, alternative drives of agricultural machines have a big, positive meaning.

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From driver to automated driving – Proposal for a holistic step by step approach

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1 Introduction

A higher degree of automation up to fully autonomous mobile machines in many industries generates a large number of advantages starting from a higher efficiency, safety, precision up to performing autonomous missions which cannot be performed with driver operated machines. Two important questions arise in this context:

1. What is the right degree of automation for a particular machine to meet future market demands?
2. In the future most, added value will be created by software-based solutions, which even have to meet functional safety demands. At the same time the required software gets more complex finally conforming the major part of cost for a new machine development.

This paper provides an overview of different degrees of automation and mobile machine autonomy and outlines how the demands on the different levels can be met by a modular and holistic approach to efficiently implement related systems. This concept also takes into account the functional safety considerations as required by law to fulfill CE certification needs.

It is important that in this concept an easy upgrade is possible from one step to the next level of automation without the need to redevelop the system or parts of it. This also applies to the integration of newly upcoming sensors as well as to enable a product concept where different levels of autonomy can be offered as product options by the OEM.

The scope of this paper covers mobile machinery mainly operated in off-highway applications like e.g. agricultural machines, construction and mining machines as well as harbor machinery. Despite the fact that these machines have very different tasks and thus different designs they typically share major commonalities. They work on designated areas with restricted or no public access, driving on public roads is not the main purpose, the environmental conditions during working operation can be comprehensively described and maximum speed is limited. Furthermore, in addition to driving one or multiple working functions are part of the machine's tasks.

2 Functional safety

2.1 Philosophy

Different B-type safety standards have to be considered in terms of functional safety, namely the ISO 26262 for automobile on road vehicles which is only of relevance when mobile machines are operated in on road use cases. This standard expects the consideration of a dedicated safety function throughout the design process.

Although the goal of achieving a safe function is the same for machines, standards like the EN ISO 13849 propose and follow a modular approach. EN ISO 13849 describes how to combine pre-validated hardware components as well as safe software modules to a safe function. This approach challenges component manufactures to evaluate multiple use cases for their safe hardware and software products. Machine OEMs on the other side can utilize such a safety component as a black box just by evaluating whether the provided safety parameters suit to the calculated safety goal. What of course remains from a safety perspective is the compliant combination of safety modules and the design of these modules which are not available as pre-evaluated or pre-certified.

Beside some obvious similarities, automotive safety opposes significantly different challenges for the designer. Handling complex city scenarios, unpredictable mixed traffic situations and high-speed driving are some of them.

There are lessons that can be learned from the functional safety approach for road vehicles, but it should be kept in mind that the high variability and the low production volume situation applicable to mobile machinery in most cases does not allow to develop dedicated hardware and software just for a couple of hundred similar machines per year. Especially when taking into account the rapid technological progress in these areas.

Given the complexity of assisted or autonomous operation the utilization of functional safe software and hardware components are major enablers for mobile machine autonomy.

2.2 ISO 26262, EN 16590/ISO 25119 or EN ISO 13849, which standard to follow for agricultural machines driving on public roads?

For agricultural machines working on the field EN 16590/ISO 25119 as a harmonized standard describes the requirements for functional safety. Although not harmonized ISO 26262 due to the recent extension to vehicles above 3,5 tons has to be considered as well for agricultural machines driving on roads. Fortunately, ISO 26262 standard makers have allowed to utilize a machine safety standard when designing machines which beside their dominating working task have to drive on roads. This approach is described in ISO 26262-8 Edition 2 and specifically refers to the utilization of EN ISO 13849 instead of following the entire ISO 26262. Talking into account that the available engineering for the automation of mobile machines are significantly lower than the once for automotive this is a necessary and important exception. Thus, one lean approach to realize higher automation for particularly agricultural machines is the utilization of hardware components and software modules certified for both EN 16590/ISO 25119 and EN ISO 13849 safety functions.

Hereafter a real safe assisted and autonomous operable machine will be introduced which already has proven more 250.000 km of fault free operation on private grounds. The automation system has been designed based on EN ISO 13849 safety requirements within less than 12 months.

3 The Holistic and Modular Approach

3.1 Concept

On the way from fully manual operation to the highest level of autonomy, a number of intermediate steps are required in order to enable a customer oriented and modular setup so finally each level of automation can be purchased as a separate option.

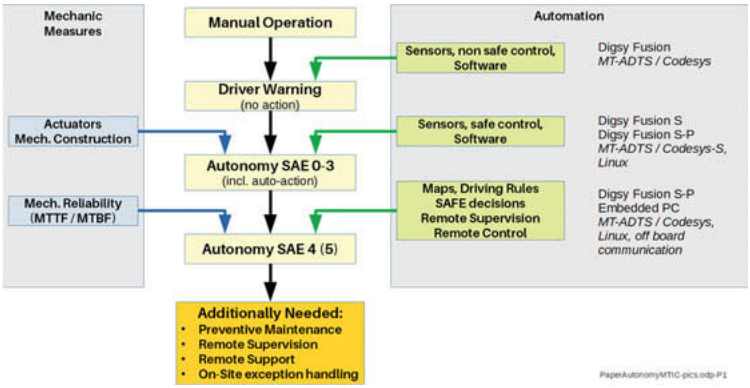

Fig. 1: Requirements of different automation levels

If these single steps are building upon each other, an easy upgrade is possible, development cost are minimized resulting in highly profitable products and services, even at lower production volume.

First and as a precondition it has to be emphasized that autonomy also may require changes in the mechanic design of a mobile machine. This may nevertheless be considered as e.g. electrically driven machine require a complete review of the drive train in terms of energy efficiency and duty cycle management. Autonomy in turn especially require the machine to be mechanically extremely reliable with highest possible MTTF as it should not be required to send a person to the machine during a regular operation duty cycle.

The automation system of an autonomous mobile machine mainly builds on two pillars:

1. Off-the-shelf mobile controller hardware for standard and functional safe control with highest possible protection level (PLd / CAT3)
2. A modular software framework with far most prefabricated – and possibly pre-certified functions for functional safe and non-safe control as well as for environment detection, navigation and guidance, remote access and an advanced Human Machine Interface for (remote) supervision and control.

A related setup basing on standard hardware and software is shown in picture 2.

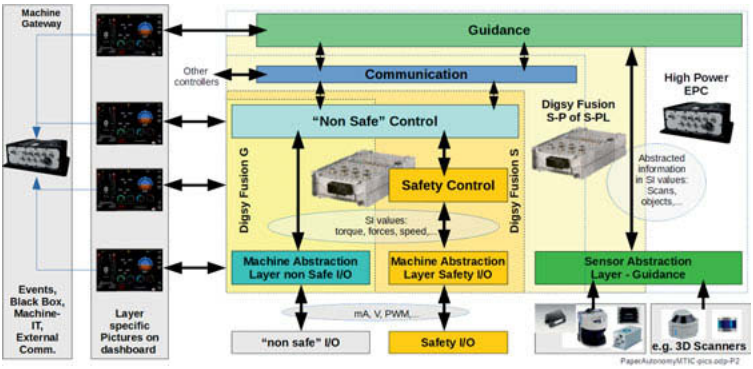

Fig. 2: Modular Hardware and MT-ADTS Software Setup

In this illustration the hardware complexity is increasing on the x-axis while the functional complexity is increasing on the y-axis:

A simple, non-functional safe machine control or operator assistance can be implemented with standard (non-safe) I/O's and the use of standard software functions. The related controller is a cost efficient digsy fusion G by Inter Control (see chapter 4). Should on the same machine – potentially later or in a more advanced version safety functions be required, the digsy fusion G is exchanged by a fully compatible digsy fusion S. This applies e.g. when the same or a more advanced version of the machine is to be equipped with e.g. brake- or steer-by-wire functions. If then more advanced sensors are needed, the next higher-level hardware is used: digsy fusion S-P, providing a Power-PC based CPU board fully integrated into the controller on the non-safe side. As with the exchange of a digsy fusion G by a safety certified digsy fusion S, the external I/O remains fully pin-compatible not requiring changes in the wiring of the machine. The digsy fusion S-P is also available as digsy fusion S-PL running LINUX as a standard operating system on the performance board allowing the integration of demanding sensors and IT level functionality.

If high end sensors are used e.g. 3-D Lidar scanners and CPU heavy algorithms have to be used for object recognition and guidance, an additional embedded PC is used as these sensors and the corresponding algorithms nevertheless do not allow functional safe processing.

3.2 Safety Control

The design of a Safety Control system for mobile machines requires to take into account some important aspects in order to save development time and effort and to assure a long term reliable legal operation. Some of these aspects are:

- Does the controller hardware architecture meet the application‘s safety requirements? For x-by-wire applications in most cases a double channel Cat. 3 layout is required or at least strongly recommended.
- Is it possible to run safe and non-safe („standard“) applications on the same controller?
- If yes, does the certificate allow to change the standard applications without the need for re-validation of the safe functions?
- Does the certified uptime of the controller allow continuous operation without reboot for the regular operation time of the machine?
- Does the certified lifetime of the controller allow operation for at least the designed lifetime of the machine (e.g. 20 years) without the need for exchange?
- Are pre-certified software libraries available for the intended functionality?

- Can tools be easily made available to assure machine parameter maintenance and diagnosis by regular service staff without access to the development system?

For the Inter Control digsy fusion S all these questions can be positively answered. Many prefabricated and partially also pre-certified software modules available, also in form of pre-certified libraries.

A lot of these functions and libraries are available for the Inter Control digsy fusion S series together with comfortable tools for online diagnosis and configuration. As the use of these tools does not require access to the programming environment it is suited for production and field service.

3.3 Autonomous Guidance and high-level functions

Originating from the long year experience in automation of mobile equipment MobileTronics has created a software and system toolbox for functional safe and autonomous mobile machine applications: This „*MobileTronics Autonomous Drive Tookit System*“ („*MT-ADTS*“) consists of standard and functional safe libraries for digsy fusion controllers as well as for scan analysis, object recognition, guidance and navigation as well as for handling basic traffic rules for mixed traffic applications on private ground.

4 Modular System example

On the way from fully manual operation to the highest level of autonomy, a number of intermediate steps are required in order to enable a cost efficient, customer oriented and modular setup so finally each level of automation can be purchased as a separate option. This example from a recently implemented project covers options from a very simple near field collision warning up to fully autonomous operation. In any case and in any of the steps below, working functions of a particular machine (like loading, unloading etc.) can be included additionally:

4.1 Simple near field Collision Warning

The very basic system equals a parking sensor system which protects the near space around a slow-moving vehicle. Depending on type and price of sensors this system is usable to a distance of between 2 and ca. 8m.

The system consists of only cheap and passive ultrasonic and optic sensors, potentially from automotive. No computer other than the general-purpose mobile controller (digsy fusion G).

The Human Machine Interface consists either of a warning column and / or of a dashboard display integration.

Communication with other CAN bus devices or the integration of a steering

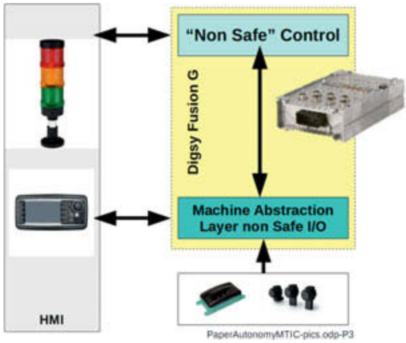

Fig. 3: Simple non-functional safe collision warning

4.2 Collision Warning and Emergency Brake

An extended collision warning is used to include an additional Emergency Brake function. For this purpose, e.g. an additional steering angle sensor is included to mask out irrelevant areas.

In addition, an electric brake valve is needed to trigger the stop from the Safety Controller.

It consists of the basic system acc. To 4.1.1, however uses a PLd CAT 3 safety controller of type digsy fusion S instead of the general-purpose unit.

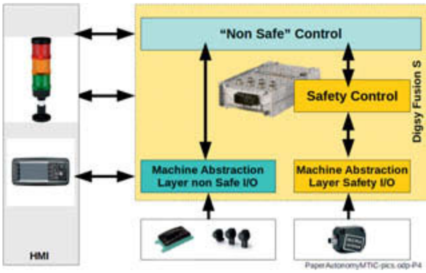

Fig 4: Collision warning and Emergency Brake with PLd CAT3 Safety Controllers

4.3 Extended Collision Warning

The extended collision warning is used to extend the coverage range into the main driving direction of the vehicle (forward and backward). The purpose is to add some pre-warning capability exceeding the coverage range of the basic near field sensors, which is of special importance when the machines are operated at higher speed.

It consists of the basic system incl. Emergency Brake acc. to 4.2 and in addition provides longer range sensors for early warning in driving direction forward – backwards as automotive radar sensors.

It is used on the same vehicles with an upgraded Safety Controller of type digsy fusion S-P to cope with the high data rates coming from the radar sensors. In addition, there

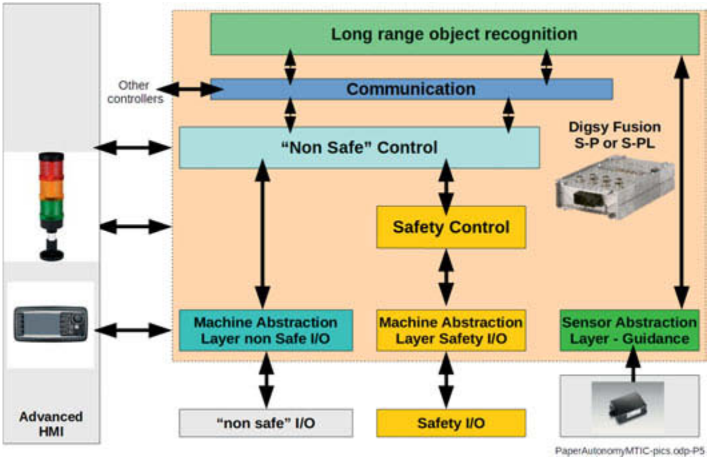

Fig. 5: Extended Collision Warning using digsy fusion S-PL

is a sensoric speed input from the vehicle. The user interface mainly remains basic as in the lower levels.

4.4 Auto-Steer / Auto Throttle Driver Assistant

The driver assistance system acts like an „*auto steering assistant*", comparable to a lane departure assistant in a car: When the machine is running in well-defined environment, the driver pushes the „Auto-Steer" button in his multifunctional joystick and the machine is steering in accordance to a predefined regime.

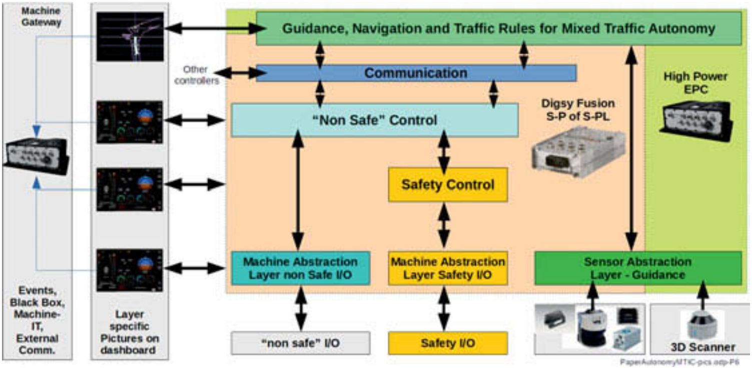

Fig. 6: Full Auto Drive System Setup

Together with other driving parameters like target speed and max speed this steering regime is set for predefined route sections. The regime switching is either performed manually by the operator or by simple external measures (RFID, GPS positions etc). It is proven to work perfectly e.g. in a tunneling operation. In narrow areas the auto-steering also allows a higher driving speed than a manual operator can achieve.

The system builds upon the system in 4.3 and adds high level sensors like 3D Lidar systems and Embedded PC level computing power to run advanced and CPU heavy navigation algorithms.

In addition, the HMI is extended by a high-level Ethernet based graphic display usable for operation and machine service.

4.5 Driverless operation – Full Level 4 Autonomy

In order to achieve the full autonomy, the system described in 4.4 does not need any hardware extension. However external communication has to be assured in order to report about status and functional problems. Additional hardware covers cameras around the machine and related data recorders to store videos synchronized with operational data. Furthermore, a permanent connectivity to a remote supervision center is needed to assure smooth operation with minimal downtime.

5 Summary

Depending on the application, a full driverless system in a defined private ground environment defined is possible today. This has been shown in applications implemented by Inter Control and MobileTronics during the past couple of years.

The modular and step-by-step philosophy including all aspects from safety control to autonomy efficiently implements related solutions and leave a maximum degree of freedom to the OEM for setup of high revenue software-based product options. At the same time development cost for safety control and autonomy can be kept at a reasonable level due to the modular system setup, prefabricated software components and Functional Safety certified application libraries.

Fig. 7: Screenshot from Mixed Traffic Autonomy video

Currently, a number of private ground mixed traffic applications as well as operation on public roads are under realization in different industries. The operation of a remote supervision center will be offered as service by MobileTronics.

Autonomous Navigation Strategy for an Orchard Robot Using Simulation Design

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Abstract

Autonomous robots are extensively appearing in agricultural domain with ranges of application, and still evolving. Navigation is one of the most important aspect in designing an autonomous robot. Therefore, the present study focuses the navigational strategy for an orchard robot using model based design. The navigational model is developed in MALTLAB/Simulink as a software development and simulation platform. This navigational unit includes motion planning, obstacle avoidance and data transmission module. The navigational model acquires planned path coordinates from path planning module required in motion planning algorithm. The pure pursuit controller is used in this study for the path tracking algorithm. Before hardware testing, the model was verified in MATLAB 2D virtual environment to visualize the robot navigation. The geo-referenced image was used for localization. This increases the reliability for navigation in GPS denied environment. The navigational control strategy for a real robot is verified using the remote controlled robotic platform named elWObot. The developed model was tested in the laboratory with operating speed of 1 m/s and was able to navigate successfully. Additionally tests were carried out to validate the model performance in outdoor environment

1. Introduction

Robotics has been increasingly utilized in agriculture for developing intelligent vehicles to enhance the productivity and to perform operations in uncertain agricultural environment. Agricultural robotics dates to mid-1980s, when research on fruit harvesting robots was initiated in Japan, Europe and USA. After that remarkable progress can be seen in the field of robot sensing, perception, navigation and actuation, etc. [1]. Accurate and robust environmental understanding is a prerequisite, which needs to be analyzed for automation process [2]. The design of mobile robots operating in outdoor environments such as agricultural applications is still a challenging subject. Navigation in agricultural environments presents difficulties due to the changes in weather conditions and variations in the nature of the terrain and vegetation. These environment characteristics must be addressed and requires the design and conception of efficient and robust sensing and control systems [3].

Nowadays auto-guided agricultural machineries are using Global Navigation Satellite Systems (GNSS)-based navigation system, but they do not provide any information about the “dynamics” of the environment [2]. Additionally, one cannot use this technique in the orchards due to the poor GPS coverage while driving between dense tree rows [5]. They also have a low level of accuracy of 4 to 5 meters that are not feasible for autonomous navigation, however, there are centimeter levels accurate GPS are available, but they are expensive and make the system cost ineffective. Anderson et al. [5] provides a navigation solution that does not rely on GPS while driving between rows in the field. They used laser scanner measurements for localization and obstacle detection. Hassan et al. [6] designed a robot to automate the seed sowing process that does the lane tracking and the path following. The robot uses ultra-sonic sensors for track following and obstacle detection. Linz et al. [7] developed a 3D simulation environment for virtually testing a robotic platform preceding to its application in real field. They have used image-based sensors (Sick outdoor laser range finder) to perform the robot navigation. The navigation algorithm was tested in Gazebo in simulation as well as in the indoor and outdoor simulation platform.

In most of the cases, integration of multiple sensors and control software in diverse platform makes system more complex and difficult for integration. This multi-level sensor fusion even makes the system cost intensive. Therefore, this work proposes developing a functional level navigation algorithm with minimum sensor integration using same software and hardware development platform that overcomes the framework integration issues and system cost intensification.

2. Robot Kinematic Model

The robot navigation is generally divided into three phases. The first one is environmental mapping that tells where the robot works. Then, next one is path planning in the mapped environment followed by the robot navigation. In the navigation phase robot follows the planned path by the path planner and generate the control actions for the robot. In navigation phase for control action generation, it often requires the robot model such as a kinematic or dynamic model. This model selection depends on the system complexity and speed of operation. Since the maximum operating speed of the robotic platform under testing is limited to 8 km/h therefore, for the simplicity a kinematic bicycle model [4] is considered to replicate the four-wheeled mobile robot. The front and rear two wheels at front and rear axle are merged into a single wheel at front and rear axle. Let's assume that the robot navigates in the configuration space ***C.*** Its configuration is given by:

$$\mathrm{C} = (\mathrm{x}, \mathrm{y}, \theta, \delta) \quad (1)$$

The robot is both the front and rear wheel steered. The following are the other equation used to model the robot motion model [3].

$$x = v cos\theta \quad (2)$$

$$y = v sin\theta \quad (3)$$

$$\dot{\theta} = \frac{V Cos\beta}{l_f + l_r}\left(tan\ \delta_f - \tan\delta_r\right) \quad (4)$$

$$\beta = tan^{-1}\left(\frac{l_f \tan\delta_r + l_r tan\delta_f}{l_f + l_r}\right) \quad (5)$$

Where, x,y represents the co-ordinates of the point located at the centre of rear axle, v is the vehicle forward velocity. ***θ*** represents the robot's orientation whereas δ_f , δ_r represents the front and rear wheel steering angle. *β* denotes the vehicle slip angle that can be neglected in case of slow-moving vehicle and it was also verified during simulation. The robot steering wheel has kinematic constraints that lies in the bound. The δ bound for the robot was $\pm 45°$.

$$\delta\_min \le \delta \le \delta\_max \quad (6)$$

The following robot parameters given in Table 1 used in the modelling.

Table 1: Robotic platform specification

Parameter	**Value/specification**
Length (m)	3.18
Width (m)	1.3
Height (m)	0.93
Wheelbase (m)	2.2
Engine power (kW)	30
Steering mode	4-Wheel Steering
Communication	CAN

3. Navigational Model Architecture

The navigational architecture gives the overview of the different subsystems module for robot navigation and their interaction with each other. The robot navigation architecture is given in Fig. 1. The algorithm is built entirely in the MATLAB and Simulink environment.

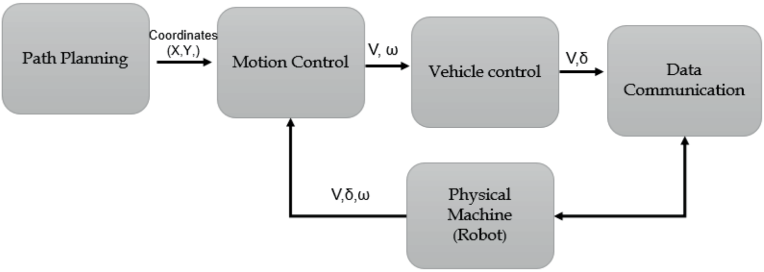

Fig. 1: Simplified robot navigational control architecture

The path planning is performed by using the image of the environment, which can also be added with the LiDAR (Light Detection and Ranging) scan map of the environment. The path planning unit gives the geo-referenced path co-ordinates for the robot to navigate. However, the path planning is entirely a different task therefore, that is not discussed here. The motion-planning module includes path tracking and obstacle avoidance block. The Pure Pursuit controller does the path tracking whereas the obstacle avoidance is done by identifying the static obstacle in the given map. The Pure Pursuit controller outputs the linear velocity and steering rate, which is transferred to the vehicle controller. The vehicle control module generates the desired control action in terms of linear velocity and steering angles for the robot. This control action is transmitted to the robot via CAN interface.

4. Navigational Control Strategies

In present research, the pure pursuit controller and vehicle odometry data, with two-dimensional referenced map is used for path tracking and localization. This makes the first layer for navigation; however, the other incoming sensor information can be used to increase the map description and dealing the dynamic obstacle in the environment. The obstacle detection is split into two-phase static and dynamic obstacle detection. The static obstacle is considered as a tree row, depression on the moving surface or any fixed landmarks whereas the dynamic obstacle involves any passing by human, animal etc. The static obstacle is taken care while building map of the environment whereas the dynamic obstacle is left for second phase since, sole focus was on navigation with minimum sensor interactions. The pure pursuit gives a high level of robustness with quick transient changes even at higher speeds [8]. Therefore, to design a robust path tracker, the pure pursuit, and a PID controller is used in combination. Fig. 2 shows the PID control structure for orientation correction adopted in navigation algorithm.

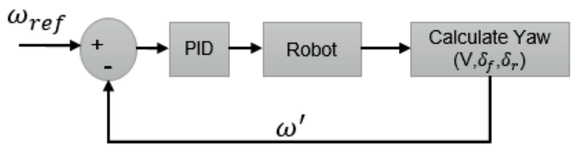

Fig. 2: PID control structure for orientation correction

5. Model Based Tuning

The PID controller was used for correcting both the steering and velocity input based on the error signal. However, in order to get the desired response from a PID block it needs to be tuned properly. Most of the time it is manually tuned which is quite challenging. Therefore, in present work a model based PID tuning is used. As the testing robot was available, an open loop robot's steering response was captured with specified step input. This captured steering response act as a base model for PID tuning. The gain value for proportional (P), integral (I) and derivative (D) value of the PID controller is derived by the signal analysis in the Simulink Control Design tool in MATLAB/Simulink. The maximum output of the PID block is set to 45° due to the mechanical constraints of the steering system. The PID tuning requires a linearize plant model to approximate the model output behavior, since the present model is nonlinear therefore another plant model is identified from the robot steering response as shown in Fig. 3. Once the plant model is identified, the PID block can be tuned with desired level of robustness and response

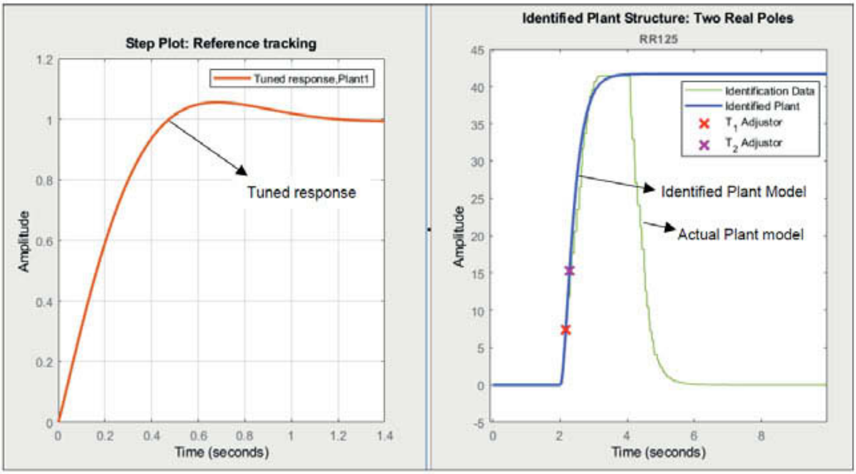

Fig. 3: Model based PID tuning for robot steering response (a) tuned PID block response (b) plant model identification with actual data

6. Testing and Results

Fig. 4: elWObot test bench

The control algorithm for the robot navigation was tested in the MATLAB 2D simulator environment that visualizes the robot moving in the planar environment. Furthermore, it was tested on the robot named elWObot [7] in the lab and in the outside environment. The elWObot is a robotic platform that runs with diesel engine and electric generator in combination. It has four individual traction motors for propulsion and four motors for individual steering control. Fig. 4 shows the robot testing in the lab environment. For setting the communication between the robot and the host machine a separate CAN module was created which sends the specified CAN messages to the robot PLC (Programmable logic controller). The data communication is done by using the Vector VN1640A [9] CAN hardware. For navigating the robot, the desired steering and velocity command was given from the controller. The velocity and steering feed-back are taken from encoder mounted on the steering and wheel motors.

6.1. Velocity Response

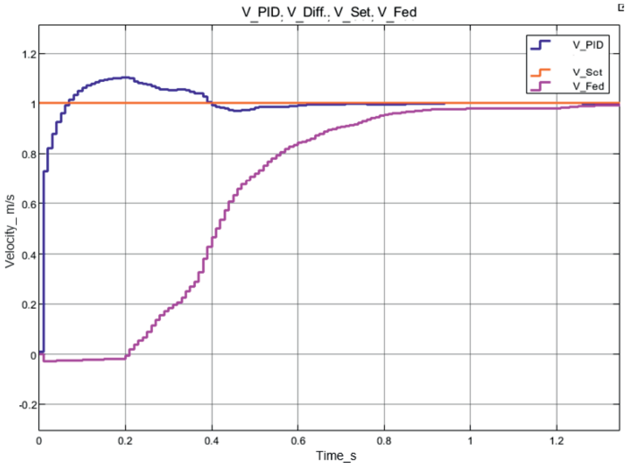

Fig. 5: Robot velocity response

The robot was tested and tuned to the input velocity response at 1m/s. The main concern during tuning was to launch the robot without jerk. Here, it can be seen in the Fig. 5 how the V_Fed velocity is synchronized with the V_Set velocity at 1 s. The V_Fed velocity is the feed-back velocity coming from robot wheels whereas the V_Set is the set velocity. Initially until 200 ms there is no response in the feedback velocity followed by a gradual increase. This is due to fact that CAN messages are transmitted periodically at 200 ms whereas the data received at 10 ms rate. As the robot receives driving input, the feedback velocity starts increasing grad-ually after 200 ms. The overshoot in the input PID velocity can be minimized, however it makes the response more sluggish. Therefore, a trade-off was made between overshoot and system response.

7. Conclusions

It is seen from the results that the system works well and is able to navigate in the given environment. The robot navigation is based entirely on simulation model and static features consideration. The model is built with the available onboard sensors and vehicle odometry data to minimize the system cost and to verify the system functionality. The robot is able to navigate without GPS and can be a solution in GPS denied environment. However, its accuracy can be increased by properly sensing the robot orientation using orientation sensor that is currently dependent on vehicle velocity and robot steering angles. To deal with the dynamic obstacles in the environment 2D LiDAR/range sensors can be used to detect obstacles in the real-time environment.

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Process model for an economic evaluation of cultivation methods on agricultural farms

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Abstract

Starting from an agent-based process model, this paper presents an approach to determine the costs of field work on arable farms and to assess holistically farm specific operational changes within complex simulations. After a short introduction to the model, the calculation of cost factors such as machine depreciation, repairs and fuel requirements are discussed and first simulation results are shown.

Introduction

The volatility of profits generated on agricultural land has been particularly marked in recent years [1]. Especially dry seasons with low yields increase the economic pressure in agriculture. In addition, farms are increasingly faced with an intensified competitive situation, both regionally and internationally, and with growing societal demands [10]. Against this background, the question of individual competitiveness is moving further into focus. Potentials for increasing efficiency can lie in the reduction of production costs. Changes in machine equipment, process steps or the entire crop rotation system offer opportunities to reduce the financial efforts for production-related work. However, especially extensive modifications, such as the inclusion of further or other crops in the crop rotation, also influence the farm's market performance. In order to evaluate adaptation strategies for future demands, various tools offer a good overview of individual cost areas. The KTBL (Association for Technology and Structures in Agriculture), for example, offers a web application to quantify the expenses incurred for the machinery. Other services provide farmers with solutions for calculating the full costs during the production. This article is intended to suggest an approach for further individualisation and a more holistic view of the farm. Within a process model, necessary working hours are determined on the basis of operational information such as field structures, machine equipment and the applied process chains with individual process steps. The simulated times are charged with respective cost rates to get the cost structure for the production on each field. Considering estimated yields and sales revenues statements regarding profitability can be made. In order to limit the scope of this work, the focus is on the use of common machinery for general European arable farms.

Model approach

The present approach determines the costs incurred for field work on farms with the aid of a process model that was developed as part of the research project "Efficient fuel use in agricultural technology" (EKoTech). In simulations, times for individual subtasks (cf. time structuring scheme KTBL) can thus be calculated during the work processes of an entire season. By adding cost factors for inputs such as seed, fertiliser, diesel and pesticides, as well as an evaluation of direct machine costs, it is also possible to indicate production expenditure on a field-specific basis. Figure 1 shows the general procedure. Information about the position of sites and fields, the machinery and the process chains within the crop rotation are the basic conditions for the representation of a farm. Developed and implemented methods and functions enable a model-like depiction of field work within the software environment. They are briefly presented in this article, further descriptions can be found in the publications [6] and [11].

At the beginning of a simulation an algorithm maps the fields divided into main field and headland on a GIS map using the coordinates of the corner points and sets field entrances and properties such as a soil class and calculates a gradient value via the height information of the corner points. Information from “OpenStreetMap” integrate the road network. Each machine is represented as an agent. Properties such as the working width, traveling speeds, purchase price and machine ages can either be taken from a database in form of machine classes or adapted in the user interface for the respective farm. Therefore individual classes are built up from data of the KTBL. After assigning process chains for each field, work orders are created based on the process steps. These jobs contain the field, the machine combinations involved and information about working methods, such as working speeds, processing depths and application rates. Depending on a scheduled date of execution, the daily working time and the availability of necessary machine combinations, the orders are continuously assigned to the respective agent. During the simulation, each machine combination uses an agent control system to process the jobs. Depending on the individual situation, represented by a state vector, a decision for the following action is made. These actions are supply or setup processes, loading and unloading or moving along pathways. Route planning functions enable the agents to calculate routes between fields and yards as well as to plan and cover lanes and paths in the field to represent fieldwork. For this purpose approaches of Dijkstra [3], Dubins [4] and Reeds [8] are used. The required partial times and used operating resources are recorded and stored after processing a job. Comparisons of simulated partial times of this process model with real records of field work have been shown by Hanke [6].

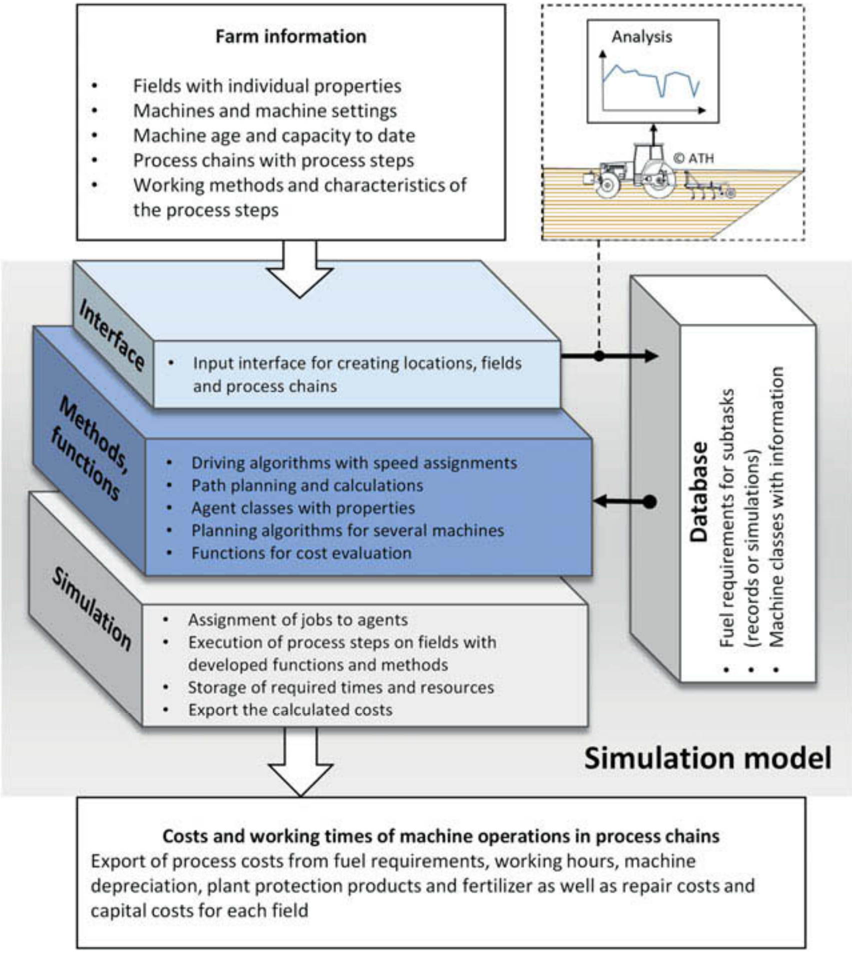

Fig 1: Structure of simulation

For an economic evaluation of cultivation methods, an extension of the model includes cost factors of operating resources (fields, fertilizer, seeds and plant care products) and fuel as well as machine costs. So it is able to show the incurred production costs for the farm and for individual fields after all working times for the entire season's process steps have been determined. The financial expenses for fertilizer, seeds and pesticides are considered on the basis

of the application rate and a mass-related price or as area-related expenses. Depreciation, interest costs, costs for repairs and maintenance as well as diesel costs and other annual expenses represent the direct costs for the use of agricultural machinery.
The literature contains various approaches to machine depreciation [2]. One variant implemented in the model is the straight-line method. Here, the difference between the purchase price and resale value is distributed equally over the years of use. The model suggests a resale value to the user according to the expected usage time and usage performance, which can be adjusted individually. Another implemented variant is the "Resale Value Method". Here, the value of a machine is estimated before and after the season. The loss in value corresponds to the annual costs. The presented model uses a KTBL approach for estimation [5], in which the reduction is derived on a linear basis according to the useful output and the period of use:

$$\mathrm{RV} = \mathrm{Q}_0 \cdot (0{,}74 - 0{,}27 \cdot \frac{t_{current}}{t_{potential}} - 0{,}27 \cdot \frac{a_{current}}{a_{potential}})$$

For this reason, each machine class is assigned a usage potential in the form of time ($t_{potential}$) and work output ($a_{potential}$), which is provided by the KTBL [7]. The resale value RV, can then be calculated using the purchase price Q_0, the machine age ($t_{current}$) and work output ($a_{current}$) at the date of valuation.
In both, the Straight-Line and the Resale value method, the cost rate results from the annual depreciation divided by the simulated annual scope of use. Depending on the machine, this is multiplied by the working time, the worked area, the transported or spread masses or volumes of the individual simulated process step and field. In a third variant, flat-rate cost rates can also be assigned, as is often the case with rented equipment. Concerning the interest costs, the monetary value of the machine in the middle of the season is valued according to the approach presented and charged with a percentage interest rate.
Repair and maintenance costs are expressed by cost rates for individual machines. The model uses a weighting function to adjust the respective cost rate depending on the previous usage performance. It is assumed that the repair costs will increase over the life of the machine. KTBL data ware also used here and two functions for machines with high and low wear were implemented [7]. In figure 2 the weighting factor is plotted over the percentage useful life of a machine with low level of wear (e.g. a tractor). The result is a progressive increase of the accumulated costs for repairs and maintenance, as the example shows for a 135 kW tractor with an assumed cost rate of 4 Euro/hour.

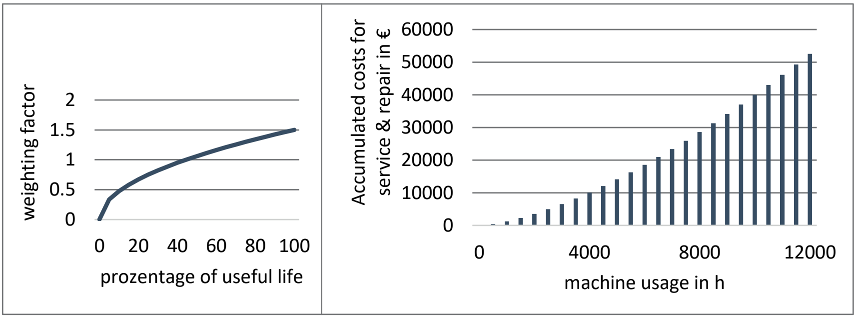

Fig. 2: Weighting factor and accumulated costs for service and repair of a 135 kW tractor

The costs for fuel are calculated on the basis of the current fuel price and the required amount. In order to determine the consumption for every job, each part-time period is multiplied by a corresponding time-related fuel requirement. Within the EKoTech project, machine models simulated this requirements for combinations under conditions of different model farms. The results are available for the process model in form of datasets in a database. Each dataset contains the identification numbers of the combined machines (vehicle, front and rear working implements), the fuel requirements during loaded and unloaded driving in speed and gradient intervals for driving on the road and on dirt roads, as well as a collection of requirement values, which are dependent on field conditions and properties of the process step. These include diesel consumption during work operations, turning and driving in the field, which are influenced by conditions such as the soil class, the previous state of tillage, the yield and individual process and machine settings.

To create new datasets for individual farm considerations the model interface contains relevant functions to evaluate records of real field works. Necessary information here are the GPS positions and engine data from the tractors CAN bus system. For this presented study these information were recorded with a frequency of 1 Hz for different machine combinations on a farm in Saxony-Anhalt to estimate characteristic values for individual part-times under current field conditions. The figure 2 shows one record during a plant care application. For the analysis a graphical selection of a representative field (red) and route sections for asphalt road (blue) and dirt road travel (pink) is important. The measuring points shown are characterized by GPS position, speed, course, engine speed, a value for the engine load and the fuel requirement.

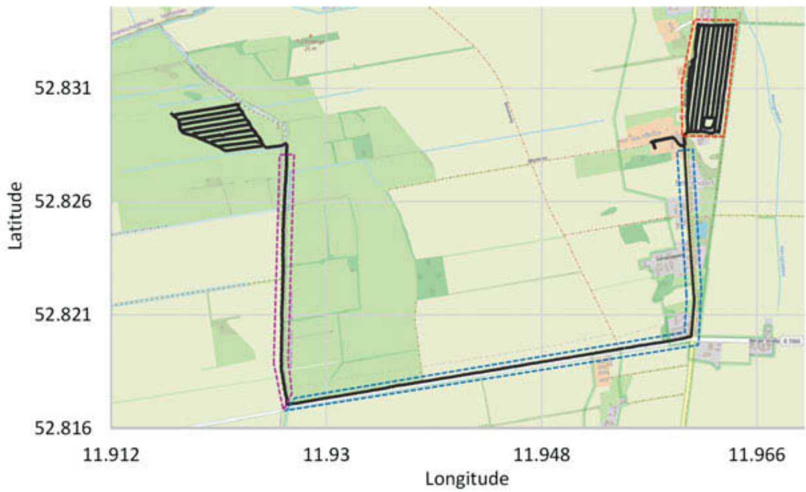

Fig 3: Record of field work with selected areas for fuel analysis (© OpenStreetMap contributors)

Within the field the system assigns each measuring point to the working process, turning manoeuvre, idle time or field travel (Figure 4). Decisive for this classification are angular deviations from previous points and from the main working directions as well as the deviation from main working speeds and the idle running of the machine. The model calculates an average fuel requirement at constant speed from at least 10 consecutive points within the working direction. For the turning, an average speed and an average fuel requirement are generated from all complete (180°) turning manoeuvres in the field.

Both, the measuring points of field travel and those of travel on dirt roads or asphalt roads are filtered according to ranges of constant velocities. With the help of this filtered data and the measuring points at idle speed, regressions for the trend of fuel consumption over speed are formed. An example of driving on a country road is shown in Figure 4. The regressions are formed under the assumption of a second-order polynomial.

One percent of fuel costs represents the costs for lubrication. Other expenditure such as insurance are includable under further annual costs. Land use costs are allocated to the fields in the form of the lease price per hectare and labour costs are calculated over the total working time of a job and a cost rate. The costs are offset by the financial returns. These returns result from sales of the cultivated products and from area-related farm subsidies. The income is expressed in the form of a field-specific yield and the revenue of the respective fruit.

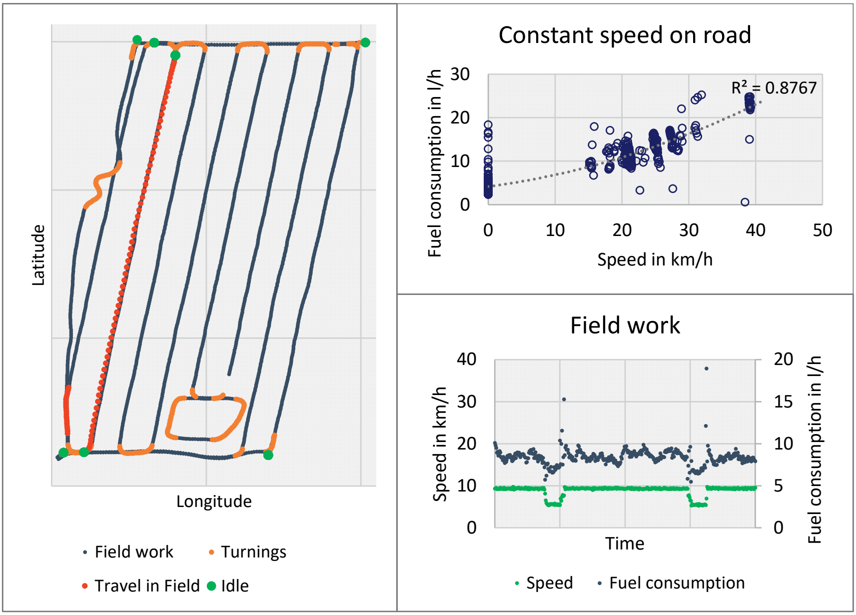

Fig 4: Analysis of field records in terms of fuel consumption

Results

Figure 5 shows the resulting operational costs for the field work of a farm in Saxony-Anhalt (Altmark). Direct costs (pesticides, fertilizers and seeds) und lease fees are not included in this diagram for sake of clarity. The three-part crop rotation system used on the farm consists of rape, wheat and barley. Variant A pictures the costs per hectare with the current machinery for different fields. In these scenario the investigated machinery equipment consists of two tractors with a power of 120 and 135 kW, a combine (225 kW) and implements in 3 m working width as well as a sprayer with 27 m boom and 4000 l tank volume.

To classify the simulation results, the average operational cost in Saxony-Anhalt from 2014 to 2018 was about 390.01 €/ha for winter wheat, 379.87 €/ha for winter barley and 418.74 €/ha for rapeseed [9].

The costs for an alternative machinery are shown in variant B. In these case a machine combination consisting of a tractor (275 kW) and a cultivator with 6 m working width replaces the previous tractor (120 kW) and the cultivator with 3 m working width for tillage. In addition, further work is taken over by the second tractor. The characteristics of the process chains are not changed and the machines were purchased at common used market prices. The hourly rates charged for labour are typical for this region. On the basis of the results it becomes clear that the change causes higher costs for depreciation especially for fields with longer distances and small sizes. However, with larger fields and short distances, there may also be financial benefits. In these example in particular, as the cost of labour can be considered as an hourly rate and not as fixed costs because of temporary employees.

Compared with all operational costs for the farm's land and previous machine equipment, variant B was just about 100 Euros more expensive under the assumed conditions, purchase prices and resale values.

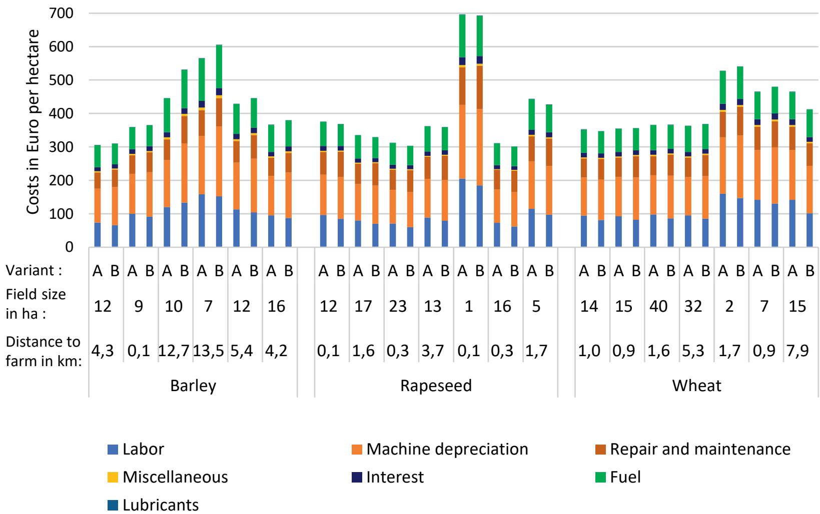

Fig. 5: Field specific operating costs as a result of the simulation. A und B represent alternative machinery.

Comparing the number of field working days required for the whole season an estimation of workload can be made. With 94 days in variant B it is 12 days less due to the higher capacity for tillage. This is an advantage that is not included in the financial evaluation, as these days can be saved, especially during peak periods, or be used for additional business. In addition, a timely and weather-adapted completion of field work is easier to manage.

In further simulations, changes in crop rotation and the process chain are compared. In this way the financial differences resulting from the extension of crop rotation can be quantified, for example to include maize together with catch crops and wheat after maize. But of cause it is difficult to quantify the benefits of greater biological diversity.

Summary and outlook

The presented extensions enable the process model to assess different cultivation methods on agricultural farms in terms of production costs. In addition to well-known approaches to cost evaluation of agricultural machinery, functions were integrated to determine characteristic values of fuel requirements of individual machine combinations from records of field work. In this way, it is possible to compare depreciation costs, fuel demand and labour costs for different farming strategies. With the help of proceeds from the sale of harvested crops and cost factors for inputs such as fertilizers, seeds or plant care products, it is also able to make statements about their profitability. In further work these results will be compared with real farm results.

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Cyber Security Management Systems for Agricultural Technology Products

A CSMS “light”

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Abstract

Recent years show an exponential increase in connectivity - also in the agricultural machinery industry. This not only brings advantages, but also brings with it the danger of increasing cyber risks. Although agricultural engineering has been little affected by such attacks so far, it is considered to be systemically relevant and therefore particularly worthy of protection. Current international regulations, such as WP.29 from UNECE, require the automotive industry to introduce and implement a certified Cyber Security Management System (CSMS) to protect the vehicles.

In this paper we give a brief introduction to CSMS and discuss their applicability to the agricultural engineering sector - initially as a “light” CSMS. Core focus is on management concepts with regard to the culture, organizational setups for a CSMS and the cyber security framework (e.g. Risk Assessment, Qualification and Communication).

Need for action

In recent years Cyber Security threats have risen steadily. In 2020 cyber-attacks rank among the top ten risks in terms of likelihood and impact in the Global Risk Report of the World Economy Forum (1). The trend to interconnect sensors and systems has created numerous potential new attack vectors. The automotive sector is already investing significantly into securing the vehicle and its surrounding ecosystem. Several data breaches and cyber-attacks have been reported and many white hacks exposed vulnerabilities in Car IT, Infotainment Systems, Vehicle Access, Sensors and even in Advanced Driver Assistance Systems (ADAS) functions. To protect these systems and the companies and people behind, several international guidelines and standards on cyber security have been newly developed in recent years (e.g. EU Cyber Security act, 2). One of the most recent is WP.29, published in June 2020 by the

UNECE, defining uniform provisions concerning the approval of vehicles with regard to Cyber Security and the need to introduce a CSMS, Cyber Security Management Systems. It is to be expected that these UN regulations will be adopted worldwide under the 54 parties to the 1958 UNECE Convention and beyond on a broad basis in the automotive industry. That means that the regulations come into force at the beginning of 2021. From July 2022, the new regulation on Cyber Security in the European Union will be mandatory for all new types of vehicles. From July 2024 they will then apply to all new vehicles.
In detail they require the implementation of various measures to manage cyber risks in the vehicle system, vehicle fleets and the value chain (3):

- A holistic "end-to-end" risk management
- A minimization of risks along the entire value chain, starting in the design phase
- Detect and respond to security incidents across the entire fleet of vehicles
- Providing "over-the-air" software updates that ensure vehicle security throughout the entire life cycle through software updates, ideally in real time

So far, agriculture has not been the focus of cyber-attacks apart from ransomware attacks which are common across different industries. And, agricultural machinery is not currently in the scope of WP.29 regulations either – but, among others, it was mentioned in earlier drafts.
The agricultural sector deploys sophisticated IT systems and uses interconnected machinery with a high degree of autonomy for efficient and sustainable production. With ISOBUS, agricultural engineering has also developed its own data bus standard (4). The connectivity and complexity of these systems opens potential attack vectors for cyber criminals with possible extreme effects on food production, farmers and the environment.
Food production, as well as energy and water supply, is one of the most sensitive areas, especially in times of crisis, and should therefore be treated with particular caution.
Security threats could be e.g. breach of privacy, social engineering, malware, ransomware, denial of services, Cyber-Espionage, Agroterrorism, Confidential Information and Intellectual Property leakage (5).
Cyber Security Management Systems (CSMS) provide the framework to mitigate cyber risks in a systematic and integrated manner. With the upcoming standard ISO 21434 (Road Vehicles Cybersecurity Engineering, 7), Cyber Security Management Systems as described in WP.29 TF-CA/OTA (Regulation on Cyber Security) will be mandatory for type approval of new vehicles in the automotive industry. While automotive companies have to deploy a certified CSMS the agricultural sector will not have to do this in the foreseeable future. Nevertheless, it should

be noted that value-added chains are so interlocked that IT software and hardware from suppliers is used across industries, not only in the automotive sector, but also, for example, in agricultural engineering. Supplier companies, like Continental, have already seen these rising trends of Cyber threats and have made corresponding investments in Cyber Security companies (e.g. Continental with ARGUS, 6).
Accordingly, the overall concept and certain best practices together with lightweight cyber management processes could be useful for product development in the agricultural engineering context. Well established in the automotive sector, a “light” version of a CSMS can be a good approach to handle cyber threats and the risks in agriculture technology products as well.

ISO/SAE 21434

The upcoming standard ISO/SAE 21434 outlines the requirements for CSMS (see Fig. 1; 7). The final adoption and publication are expected by the end of 2020. It focuses on “Road Vehicles Cybersecurity Engineering” but will also a useful base standard for agriculture machineries. It defines a Cyber Security management and risk-oriented approach for products and product development. Furthermore, it includes cyber security requirements for Electric/Electronic systems, hardware and software components. Finally, the standard defines lifecycle management procedures including incident management capabilities and response plans. ISO 21434 certification will be expected as a standard compliance activity.

The basis for a company specific CSMS implementation is an ISO 21434 based gap analysis. This definition primarily covers the following processes:

- Cyber Security Governance
- Risk Managements
- Threat Detection Monitoring and Analysis
- Incident Response
- 3rd Party Collaboration
- System/Software Development Life Cycle

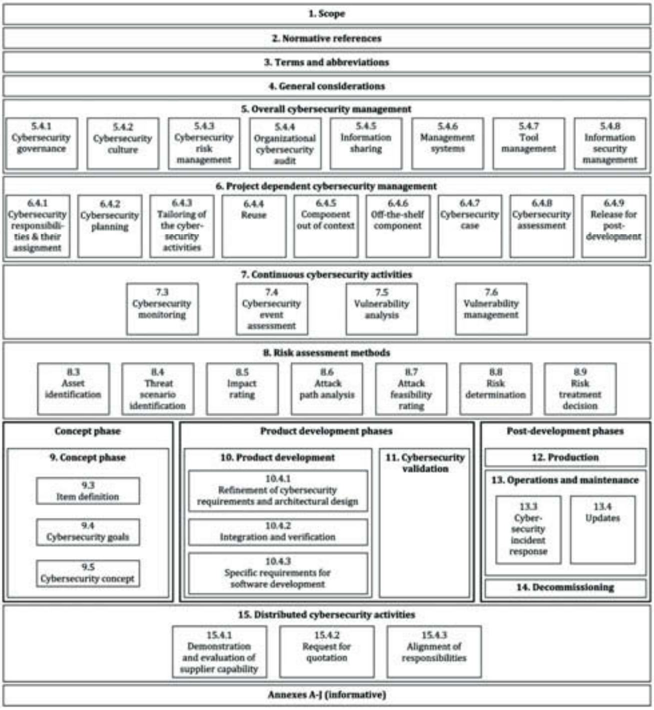

Fig. 1: Overview of ISO 21434 (7)

After the gap analysis the CSMS implementation can follow. It is based on four steps:

1. Process Gap Analysis
    - Creation of structured overview of CSMS process gaps
    - Prioritization of root causes according to impact and urgency
2. Improvement, Actions and Roadmap
    - Definition of improvement actions for the identified root causes and alignment with stakeholders
    - Approval of roadmap with project sponsor (CSMS process target state)
3. Implementation Timeline
    - Agreement of work breakdown, implementation timeline & definition of tasks
    - Assignment of task to project stakeholders
    - Implementation of status reports

4. Project Report
    - Overview of implemented improvement measures
    - Recommendations for future improvements and optimization of the CSMS process
    - Process compliance check

“Light” Cyber Security Management System – CSMS Needs: Structure, Know-How & Technology

Holistic cyber-risk management for vehicles requires well-defined organizational structure, purposeful application of holistic requirements on project level along with the targeted application of know-how and technology.

A well-defined organizational structure means the definition of processes, policies and procedures for Cyber Security management and CSMS - conformity throughout your organization, value-chain and vehicle lifecycle.

It is important to engage in the right activities at the right time (e.g. gap and harmonization analysis to the improvement/ transition project). Furthermore, processes and an organizational structure for SOC (Security Operations Center) activities are needed.

Besides technical know-how, methodological competence is mandatory to achieve compliance on a continuous basis, e.g. vehicle-specific cyber-risk catalogs, TARA (Threat analysis and Risk Assessment) evaluations, defining methods, security concept and security requirements definition.

Protect, detect and respond to cyber threats with technologies that are most relevant to the internal vehicle programs and that also serve the needs of the management systems is essential. The most important elements are definition of technology prerequisites based on regulatory requirements as well as integration, configuration and validation of proprietary security sensors.

Discussion and conclusion

Developments in other industries suggest that with increasing connectivity, there will be more cyber-attacks in agriculture as well. The final question is now whether the described requirements are also applicable and realizable for the agricultural machinery industry? On the one hand, a CSMS is currently not yet required for the agricultural machinery industry. On the other hand, the automotive and agricultural engineering industries are so closely linked via the supplier companies that the topic of CSMS will also be on the agenda in agricultural engineering in the medium term. The ISO 21434 specifies detailed activities in the context of the introduction and deployment of a CSMS. Based on the most important features and the first concepts which are currently being developed for the automobile industry, one can define lean and lightweight processes, concentrate on the core activities and define shared roles and responsibilities. Consequently, only few organizational changes have to be made. Besides a gap analysis, a catalogue of possible cyber risks has to be created.

The TARA (Threat Analysis and Risk Assessment) methodology must be implemented, and the security testing methodology has to be part of the standard development process. Further steps will be to plan the SOC and educate the personnel. Finally, all processes have to be implemented and the technology must be under control.

It is more than likely that the agricultural technology sector can benefit from the experience and lessons learned made in the automotive sector with CSMS as a holistic lifecycle approach to Cyber Security – along the value chain, along the life cycle and end to end.

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Next generation hybrid-electric power steering systems for agriculture machines

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Abstract

The Agriculture 4.0 and the Precision Farming are pushing the agricultural end user to constantly raise the demand of smart machines with higher performances, efficiency and comfort: these requirements are driving forward the advanced development of the OEM and the components manufacturers. Within this scenario the new advanced steering system under development by Ognibene, named **Intelligent Flow Digital Power Steering (DPSiQ)**, is able to fulfil all the above desired steering behaviours. The current contribution describes the DPSiQ functionalities and shows a comparison between the system and the current state of the art (SoA) in hydrostatic steering systems. An evaluation of the steering feel based on the methodology described in Chapter 7 of [1] is also addressed.

Introduction

Nowadays the farmers are constantly requiring smart vehicles to increase the performances, the efficiency with the same comfort level of a passenger car. All of these challenging requirements are driving forward the academic research and the advanced development departments of both OEM and components manufacturers to develop new solutions able to fulfil the end user requests ([2] to [7]). In terms of vehicle performances and comfort, the steering system plays a crucial role within the whole machine design; in fact, the steering system strongly affects the overall driving effort and consequently the working stress on the machine operator. Due to these reasons, and confirmed by surveys, the farmers are mainly requiring:

- the auto-guidance (GPS) system, to let end user focus on the field operations;
- smart features like the possibility to switch from reactive to non-reactive steering behaviour and the variable steering ratio, to be tuneable as a function of the driving conditions;

- the steering wheel orientation and synchronization with the vehicle wheels position (known also as “12 o’clock position” feature), to allow a multifunction steering wheel (like automotive).

To guarantee the high-power density required by the agricultural steering applications and the smart features required by the vehicle end-user, a strong holistic integration between hydraulics and electronics is required.

The new advanced steering system developed by Ognibene, named **Intelligent Flow Digital Power Steering (DPSiQ)**, is able to fulfil all the above desired steering behaviours.

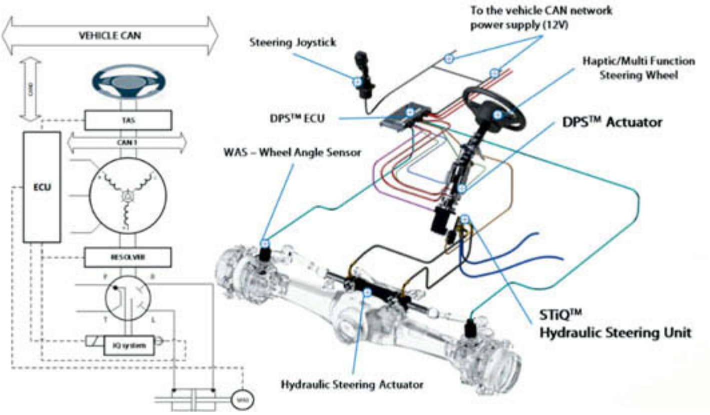

Fig. 1: DPSiQ functional scheme

DPSiQ functionalites

The DPSiQ merges the functionalities of the Ognibene Digital Power Steering (DPS) and the Ognibene Intelligent Hydrostatic Steering Unit (STiQ). To guarantee all the steering functionalities and the integration with devices like joystick and mini-wheel, the steering system has to include a Torque and Angle Sensor (TAS) which is already integrated within the DPS and a Wheel Angle Sensor (WAS) positioned on the steering axle (See Fig. 1).

The Ognibene Power Digital Power Steering (DPS) is placed over the off-highway vehicles hydrostatic steering system, improving manoeuvrability and enabling the use of GPS and auto-guidance driving systems without any additional external steering device.

The DPS is characterized by a 12V low torque brushless motor able to modify in an active way the steering wheel hardness feel, providing haptic feedbacks and controlling the hydrostatic steering unit as a function of the driving strategy: this allows the control system to implement synthetic boost curves, haptics signals in case of emergency/dangerous conditions, auto-guidance features,…

At low vehicle speed, e.g. during field operations, the steering behaviour feels completely effortless, reducing the needed steering torque in a tenable way.

At high vehicle speed, e.g. during driving on roads, a higher “breaking” torque provided by the electric motor increase the system stability, reducing the driving stress of the machine operator.

In addition, the electric motor is also able to guarantee the steering wheel complete return to zero in both forward and reverse manoeuvres due to the customizable direct action of the brushless motor on the hydrostatic steering unit.

The Ognibene Intelligent Hydrostatic Steering Unit (STiQ) is a new generation of hydrostatic steering unit able to proportionally control the flow through the steering unit from 1 up to 4 times the steering unit displacement. This flow control is carried out by means of a smart electro actuated flow regulator cartridge valve. This intelligent feature, controlled by the same DPS ECU, is also able to compensate the hydraulic leakages of the steering system allowing the OEM to introduce a multifunctional steering wheel like a passenger car.

Fig. 2 depicts the DPSiQ 12 o’clock position functionality; the active leakage compensation of the STiQ can guarantee an almost zero error between the wheel angle desired position and the real one.

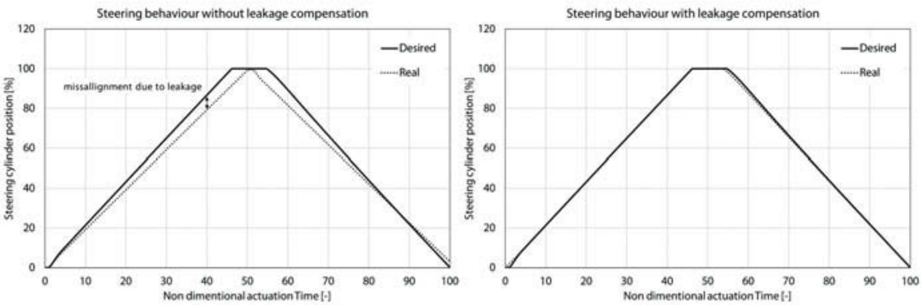

Fig. 2: DPSiQ 12 o’clock position steering behaviour.

Fig. 3 shows the STiQ behaviour simulated by a lumped and distributed parameter approach using the software Simcenter Amesim [8].

In case of misalignment error between the desired wheel position and the real one, the system increases or decrease the flow amplification ratio to reach a zero-error condition. Once the system reaches a stable zero-error condition, the DPSiQ system is able to maintain the synchronization between the steering wheel and the position of the wheels on the axle by means of a continuous leakage compensation action. The flow amplification is achieved just during the steering action when the relative deflection angle between the shaft and the sleeve of the steering unit is not zero.

In fact, the amplification feature is not carried out by means of a pure parallel path over the steering unit, but is controlled by the steering unit functionality to increase the steering system safety level.

To further increase the safety and the controllability of the system, the valve spool displacement is also continuously monitored by a displacement sensor.

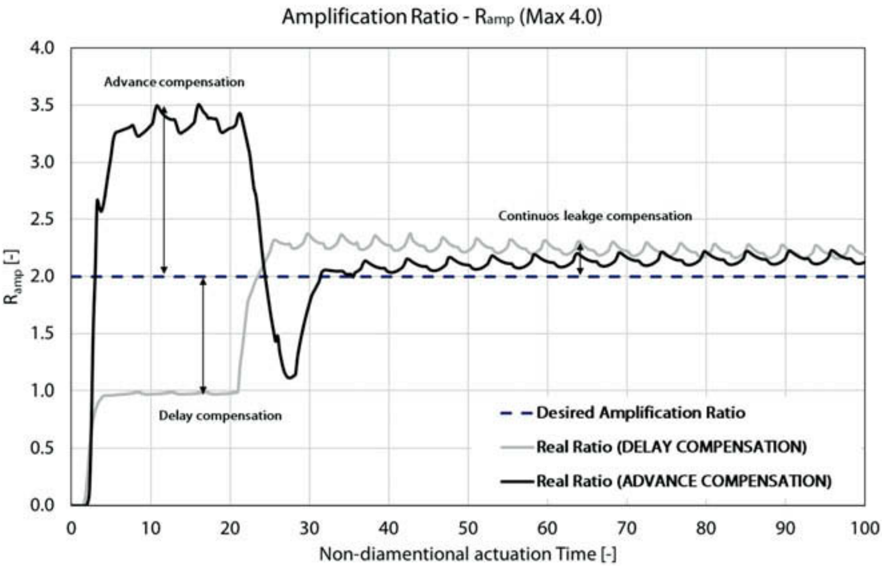

Fig. 3: STiQ simulated flow control behaviour.

Due to the combination of the DPS and the STiQ, the DPSiQ provides a parametric synthetic boost curve to the driver and variable/programmable steering ratio. Moreover, the GPS integration and the auto-guidance features are available due to the direct control of the DPS brushless motor. The DPSiQ is also improving the straight ahead driving since the system is able to apply a stability torque which tends to realign the wheels, compensating the deviations from the desired course. Therefore, the driver does not need to continuously compensate the side drift, reducing the driving effort.

The features of the “DPSiQ” system are:

- Reactive/Non-Reactive parametric Functions provided by the DPS functionality.
- Automatic realignment of the wheels and steering wheel in forward and reverse provided by the DPS functionality.
- Variable/Programmable steering ratio (Fast Steering) provided by the STiQ functionality.
- Synthetic Boost Curve provided by the DPS functionality.
- Haptic/tactile feedback on steering wheel (Machine to driver Comunication-Vibra) through the action of the DPS electric motor.
- Comfort and Agility at Low Speed – Very Low Torque
- Stability and Accuracy at High speed – Optimal Torque
- Easy interface with vehicle
- Free programmable (Smart) steering rules according with implements and jobs provided by the DPS functionality.
- Joystick or MiniWheel easy integration provided by the DPS functionality.
- Easy Auto-guidance Integration (GPS) provided by the DPS functionality.
- In GPS or Joystick steering mode, it is possible to obtain the maximum dynamics with low actuation torque on steering wheel (max 3.5 Nm, provided by the DPS functionality) combined to a low actuation steering wheel rotating speed (40rpm max, from the proportional amplification factor provided by the STiQ functionality). This feature, added to the fast detection of “hands on wheel” condition (direct steering wheel torque sensing), reduces to zero the risk of injuries during the steering wheel actuation in automatic and joystick modes.
- Multifunction steering wheel integration, due to the active motor and leakages compensation that keep the steering wheel central position: the 12 o’clock position feature is provided by the STiQ functionality.

DPSiQ vs SoA

Based on the main OEM and end user demand, the following table lists a comparison between the DPSiQ system and the current State of the Art (SoA) in hydrostatic off-highway steering systems. The table shows how the additional features, which are introduced by the brushless motor superimposed to the steering unit, can lead to a steering system potentially able to provide the same steering feel of a passenger car on an agriculture machine.

NEXT GENERATION: DPSiQ		CURRENT SoA	
0	Auto-guidance Integration (GPS) available.	0	Auto-guidance Integration (GPS) available.
0	Variable/Programmable steering ratio.	0	Variable/Programmable steering ratio.
++	12 o'clock position: multifunction steering wheel integration (**NATIVE**). Steering wheel central position due to the active motor and leakages compensation.	0	12 o'clock position: possible with additional feature.
++	Reactive/Non-Reactive **PARAMETRIC** functions available.	0	Reactive/Non-Reactive functions available. (**NOT** parametric)
+++	Automatic **FULL** realignment of the wheels and steering wheel in FORWARD and REVERSE. (Automotive manoeuvres)	0	**PARTIAL** realignment (tendency) of the wheels and steering wheel JUST in forward.
+	**Synthetic boost curve with torque shaping**. Steering rules according with implements and jobs to be implemented through electric motor torque control.	0	Steering rules according with implements and jobs to be implemented through complex control on hydraulic side.

+++	**HAPTIC/TACTILE** feedback on steering wheel (machine to Driver Communication-Vibra). Functions can be implemented to alert the driver during dangerous manoeuvres (automotive style).	0	NO haptic/tactile feedbacks are available.
++	Personal settings: comfort and agility at low speed, stability and accuracy at high speed.	0	Limited settings possibilities.
++	Easy integration in the cabin and simple interface with the vehicle.	0	Not negligible installation space required within the vehicle cabin.
0	Joystick or MiniWheel easy integration.	0	Joystick or MiniWheel easy integration.
++	Torque and angle sensor (TAS) on steering wheel available. The steering control is based on a force feedback on the steering wheel.	0	Angle sensor (SAS) on steering wheel available. The steering control is based on a displacement feedback on the steering wheel.
+++	Low torque needed (max 3.5 Nm) to override the steering wheel rotation and "Hands on Wheel" fast detection (due to TAS).	0	NO torque control available on the steering wheel since the system is control on the steering wheel angle displacement.
+	Max working pressure up to **280 bar** (High Power Density).	0	Max working pressure up to 210 bar.

Steering feel evaluation

The steering feel evaluation has been carried out on the Subjective Steering Feel Assessment (SSFA) based on the on the methodology described in Chapter 7 of [1], using the format developed by Ognibene Power and shown in Fig. 4. The assessment procedure of the steering system is composed by 34 different evaluation points related to different manoeuvres and listed in *Fig. 4*. This assessment assigns a score equal to 0 to the optimal performance, higher is the sum of the of the absolute score values, worst is the evaluation provided by the juror: the steering behaviour is far from an optimal feeling. A complementary approach is to count just the number of optimal scores. In this case, higher is the number of the of the optimal scores, better is the evaluation provided by the juror.

The driving tests have been carried out analysing the steering behaviour of a 190 hp agricultural tractor which is currently equipped by the SoA in hydrostatic steering system. Therefore, the DPSiQ system has been installed on test machine and his behaviour has been addressed. The comparative evaluation analysis has been performed by 7 Jurors selected between expert users of the same machine.

ognibene power www.ognibene.com	Subjective Steering Feel Assessment		Number SSFA__ __ __ __ Issue date: __ / __ / __ __ Page 1 of 1
	☐ DPSiQ™	☐ Competitor	☐ Others

Evaluator Name		Steering Unit Type	
Evaluator Function		Steering Unit Supplier	
Test Site		Steering Unit PN	
Field Site Type		Steering Unit SN	
Vehicle Type		Displacement	
Vehicle Power and Load		ECU PN	
Vehicle Serial Number		ECU SN	
Test Temperature		ECU SW release	
Driven Distance or Time		Max Steering Ratio	
Remarks:			

TEST TOPIC	TEST SPEC.		OPTIMAL	
STEERING WHEEL TORQUE AT THE CENTER *Cornering/sinusoidal and random steering angle input*	<15 Km/h <±20°	*too low*	☐☐☐■☐☐☐	*too high*
	>30 Km/h <±10°	*too low*	☐☐☐■☐☐☐	*too high*
STEERING WHEEL TORQUE CURVE *Cornering/sinusoidal and random steering angle input*	<15 Km/h <±50°	*too low*	☐☐☐■☐☐☐	*too high*
	>30 Km/h <±40°	*too low*	☐☐☐■☐☐☐	*too high*
STEERING WHEEL TORQUE WHEN CORNERING *Constant-radius cornering*	<15 Km/h <±50°	*too weak*	☐☐☐■☐☐☐	*too strong*
	>30 Km/h <±40°	*too weak*	☐☐☐■☐☐☐	*too strong*
CENTER FEELING *Impression of backlash or hysteresis of straight driving*	<15 Km/h <±5°	*too weak*	☐☐☐■☐☐☐	*too strong*
	>30 Km/h <±5°	*too weak*	☐☐☐■☐☐☐	*too strong*
STRAIGHT-DRIVING CORRECTION EFFORT *Directional stability to hold course*	<15 Km/h		■☐☐☐	*too high*
	>30 Km/h		■☐☐☐	*too high*
STEERING RETURNABILITY *When cornering proper righting speed of the steering wheel*	from full lock	*too slow*	☐☐☐■☐☐☐	*too fast*
	<15 Km/h	*too slow*	☐☐☐■☐☐☐	*too fast*
	>30 Km/h	*too slow*	☐☐☐■☐☐☐	*too fast*
STEERING RETURNABILITY IN REVERSE *When cornering proper righting speed of the steering wheel*	from full lock	*too slow*	☐☐☐■☐☐☐	*too fast*
	<15 Km/h	*too slow*	☐☐☐■☐☐☐	*too fast*
REMAINING ANGLE AFTER CORNERING *Angular difference between final position after cornering and central position of the steering wheel*	from full lock		■☐☐☐	*too large*
	<15 Km/h		■☐☐☐	*too large*
	>30 Km/h		■☐☐☐	*too large*
STEERING WHEEL ANGLE DEMAND *Steering wheel angle required to complete a maneuver*	field-end manoeuvre	*too small*	☐☐☐■☐☐☐	*too large*
	<15Km/h	*too small*	☐☐☐■☐☐☐	*too large*
	>30Km/h	*too small*	☐☐☐■☐☐☐	*too large*
STEERING WHEEL "12 O'CLOCK" POSITION *Steering wheel alignment with wheel in forward*	field-end manoeuvre	*imprecise*	☐☐☐■	
	<15 Km/h	*imprecise*	☐☐☐■	
	>30 Km/h	*imprecise*	☐☐☐■	
STEERING PRECISION	<15 Km/h	*imprecise*	☐☐☐■	
	>30 Km/h	*imprecise*	☐☐☐■	
STEERING FEEDBACK/DISTURBANCES *Haptic information about driving and field/road condition*	on straight drive	*inadequate*	☐☐☐■☐☐☐	*pronounced*
	under lateral acc.	*inadequate*	☐☐☐■☐☐☐	*pronounced*
SOFT END STOP AT END STROKE *Feeling on steering wheel when reach end stroke*	manual steering	*too weak*	☐☐☐■☐☐☐	*too strong*
	automatic steering	*too weak*	☐☐☐■☐☐☐	*too strong*
PARKING/FARMYARD MANEUVER *Fast cornering in repetitive cycle (load/unload)*	steering torque level	*too low*	☐☐☐■☐☐☐	*too high*
	steering progression	*too low*	☐☐☐■☐☐☐	*too high*
STEERING SYSTEM NOISE	0 Km/h		■☐☐☐	*too high*
STEERING UNIT SLIPPAGE	0 Km/h		■☐☐☐	*too high*

Fig. 4: SSFA evaluation format

Fig. 5 depicts both the average of the sum of the absolute values and the average number of the optimal scores evaluated over the 7 jurors of the DPSiQ and the SoA steering system respectively.

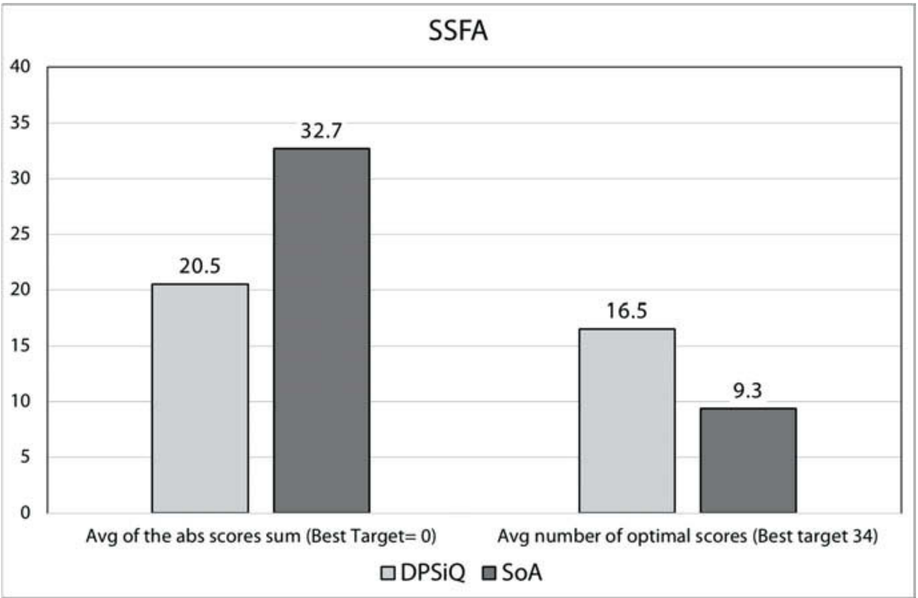

Fig. 5: SSFA result comparison – DPSiQ vs SoA

Conclusions

The working behaviour and the features of the new Intelligent Flow Digital Power Steering (DPSiQ) developed by Ognibene Power has been addressed and compared through an SSFA approach to the current state of the art (SoA) of hydrostatic steering systems on an agricultural tractor. For the first time, the driver has the possibility to get an automotive steering experience on his agriculture machine, just like a last generation car.

References

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[8] Simcenter Amesim, “User’s Guide”, Siemens Industry Software Inc.

+++	**HAPTIC/TACTILE** feedback on steering wheel (machine to Driver Communication-Vibra). Functions can be implemented to alert the driver during dangerous manoeuvres (automotive style).	0	NO haptic/tactile feedbacks are available.
++	Personal settings: comfort and agility at low speed, stability and accuracy at high speed.	0	Limited settings possibilities.
++	Easy integration in the cabin and simple interface with the vehicle.	0	Not negligible installation space required within the vehicle cabin.
0	Joystick or MiniWheel easy integration.	0	Joystick or MiniWheel easy integration.
++	Torque and angle sensor (TAS) on steering wheel available. The steering control is based on a force feedback on the steering wheel.	0	Angle sensor (SAS) on steering wheel available. The steering control is based on a displacement feedback on the steering wheel.
+++	Low torque needed (max 3.5 Nm) to override the steering wheel rotation and "Hands on Wheel" fast detection (due to TAS).	0	NO torque control available on the steering wheel since the system is control on the steering wheel angle displacement.
+	Max working pressure up to **280 bar** (High Power Density).	0	Max working pressure up to 210 bar.

Steering feel evaluation

The steering feel evaluation has been carried out on the Subjective Steering Feel Assessment (SSFA) based on the on the methodology described in Chapter 7 of [1], using the format developed by Ognibene Power and shown in Fig. 4. The assessment procedure of the steering system is composed by 34 different evaluation points related to different manoeuvres and listed in *Fig. 4*. This assessment assigns a score equal to 0 to the optimal performance, higher is the sum of the of the absolute score values, worst is the evaluation provided by the juror: the steering behaviour is far from an optimal feeling. A complementary approach is to count just the number of optimal scores. In this case, higher is the number of the of the optimal scores, better is the evaluation provided by the juror.

The driving tests have been carried out analysing the steering behaviour of a 190 hp agricultural tractor which is currently equipped by the SoA in hydrostatic steering system. Therefore, the DPSiQ system has been installed on test machine and his behaviour has been addressed. The comparative evaluation analysis has been performed by 7 Jurors selected between expert users of the same machine.

ognibene power www.ognibene.com	Subjective Steering Feel Assessment		Number: SSFA __ __ __ __ Issue date: __ / __ / __ Page 1 of 1
	☐ DPSiQ™	☐ Competitor	☐ Others

Evaluator Name		Steering Unit Type	
Evaluator Function		Steering Unit Supplier	
Test Site		Steering Unit PN	
Field Site Type		Steering Unit SN	
Vehicle Type		Displacement	
Vehicle Power and Load		ECU PN	
Vehicle Serial Number		ECU SN	
Test Temperature		ECU SW release	
Driven Distance or Time		Max Steering Ratio	
Remarks:			

TEST TOPIC	TEST SPEC.		OPTIMAL	
STEERING WHEEL TORQUE AT THE CENTER *Cornering/sinusoidal and random steering angle input*	<15 Km/h <±20°	*too low*	☐☐☐ ■ ☐☐☐	*too high*
	>30 Km/h <±10°	*too low*	☐☐☐ ■ ☐☐☐	*too high*
STEERING WHEEL TORQUE CURVE *Cornering/sinusoidal and random steering angle input*	<15 Km/h <±50°	*too low*	☐☐☐ ■ ☐☐☐	*too high*
	>30 Km/h <±40°	*too low*	☐☐☐ ■ ☐☐☐	*too high*
STEERING WHEEL TORQUE WHEN CORNERING *Constant-radius cornering*	<15 Km/h <±50°	*too weak*	☐☐☐ ■ ☐☐☐	*too strong*
	>30 Km/h <±40°	*too weak*	☐☐☐ ■ ☐☐☐	*too strong*
CENTER FEELING *Impression of backlash or hysteresis of straight driving*	<15 Km/h <±5°	*too weak*	☐☐☐ ■ ☐☐☐	*too strong*
	>30 Km/h <±5°	*too weak*	☐☐☐ ■ ☐☐☐	*too strong*
STRAIGHT-DRIVING CORRECTION EFFORT *Directional stability to hold course*	<15 Km/h		■ ☐☐☐	*too high*
	>30 Km/h		■ ☐☐☐	*too high*
STEERING RETURNABILITY *When cornering proper righting speed of the steering wheel*	from full lock	*too slow*	☐☐☐ ■ ☐☐☐	*too fast*
	<15 Km/h	*too slow*	☐☐☐ ■ ☐☐☐	*too fast*
	>30 Km/h	*too slow*	☐☐☐ ■ ☐☐☐	*too fast*
STEERING RETURNABILITY IN REVERSE *When cornering proper righting speed of the steering wheel*	from full lock	*too slow*	☐☐☐ ■ ☐☐☐	*too fast*
	<15 Km/h	*too slow*	☐☐☐ ■ ☐☐☐	*too fast*
REMAINING ANGLE AFTER CORNERING *Angular difference between final position after cornering and central position of the steering wheel*	from full lock		■ ☐☐☐	*too large*
	<15 Km/h		■ ☐☐☐	*too large*
	>30 Km/h		■ ☐☐☐	*too large*
STEERING WHEEL ANGLE DEMAND *Steering wheel angle required to complete a maneuver*	field-end manoeuvre	*too small*	☐☐☐ ■ ☐☐☐	*too large*
	<15Km/h	*too small*	☐☐☐ ■ ☐☐☐	*too large*
	>30Km/h	*too small*	☐☐☐ ■ ☐☐☐	*too large*
STEERING WHEEL "12 O'CLOCK" POSITION *Steering wheel alignment with wheel in forward*	field-end manoeuvre	*imprecise*	☐☐☐ ■	
	<15 Km/h	*imprecise*	☐☐☐ ■	
	>30 Km/h	*imprecise*	☐☐☐ ■	
STEERING PRECISION	<15 Km/h	*imprecise*	☐☐☐ ■	
	>30 Km/h	*imprecise*	☐☐☐ ■	
STEERING FEEDBACK/DISTURBANCES *Haptic information about driving and field/road condition*	on straight drive	*inadequate*	☐☐☐ ■ ☐☐☐	*pronounced*
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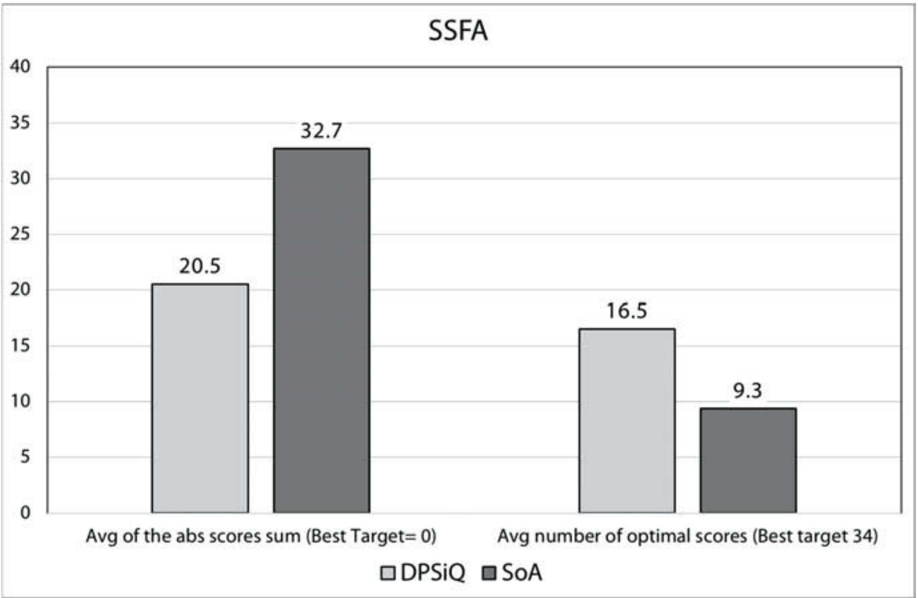

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