Feldschwarm[1] - Modular and Scalable Tillage Systems with Shared Autonomy

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Abstract

Current concepts of agriculture equipment are characterized by a high level of productivity and mechanization. At present, dimensions and weight of tractor – implement systems are the most important limitations for growing productivity. Modular and scalable systems with a high and variable degree of autonomy try to address the abovementioned challenges with the goal to deliver configuration capability regarding actual task and field conditions providing greatly increased scalability of peak performance, productivity and economy. Possible machine concepts can consist of a tractor with an intelligent and modular (tillage) unit and/or autonomous self-propelled systems working as single unit or in a swarm. Swarm operation requires an adaptive and multimodal frontend to manage and lead a heterogeneous swarm of smart implements. The modularization of the tillage system requires defined spaces for a large variety of tools, component parts and storage capacities. In addition, the interfaces for mechanical connection, power transmission and data transfer need to be developed. The conceptual idea and prototype modules are explained and potential and challenges of the idea is evaluated.

Current Situation

Agricultural mechanization is characterized by an enormous growth rate in productivity, which is probably unprecedented compared to other areas of industrialization during the last century. This growth has been triggered from the availability of combustion engines in the beginning and always benefited from incorporation of technological advances primarily developed for other industries. Introduction of synthesized fertilizers and chemicals for crop care gave another boost to the growing output per area, which drove the implementation of self-propelled specialized machines breaking with the traditional tractor – implement configuration supported by growing power density of engines and higher strength materials. However, the processes of tillage and seeding have not moved towards self-propelled concepts yet, which is going to drive the question if there is a conceptual change to be expected or even inevitable.

The challenge for agriculture is to develop systems that produce high quality and safe food and feedstuffs while also being efficient, environmentally acceptable and sustainable. Today genetic engineering and automation of machinery systems have started the next level of productivity growth leading to different variations of precision agriculture and smart farming.

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

Awareness of limited resources and reduction of greenhouse gas relevant emissions is starting to put pressure on farm businesses and machine manufacturers to re-organize the machine systems towards sustainable low-input and high-efficiency agriculture. At present, high-tech agriculture in industrialized countries faces the following fundamental problems for which substantial solutions need to be found in the near future:

- The growth paradigm of the last century "Bigger, Faster, Wider", has become a trap since machine dimensions and weights are more and more reaching and exceeding acceptable limits.
- Sustainable production of healthy goods becomes a new requirement, which is a new trend and widely expressed from consumers, while price still remains the major buying decision.
- Everywhere 4.0, digitization technologies open up new opportunities (and risks) that will transform agricultural production and the food value chains and business models.

A specific challenge in today's industrialized and highly productive environment is to maintain soil fertility. Soil compaction due to high axle loads and contact pressure is one factor that deteriorates soil quality [1]. With the continuing increase of weight of farm machinery, the problem of soil compaction is aggravated causing increased power and energy requirements, increased CO_2 emissions, difficulties in seedbed preparation, plant emergence and depending on water availability depressed growth and eventually reduced yields [2].

History of tillage and seeding tools & technologies

Usage of ploughs has been known since the beginning of civilization as the primary cultivation process, featuring the ability to turn around and mix topsoil to control weeds, prepare a suitable seed bed and bury surface crop residues. As tractor power became available in the 1930s, implements started to grow in width and operating speed – a tendency that still characterizes implement development today. Starting in the 1970s, combination of tillage and seeding without ploughs evolved into conservation tillage where mechanical crop care has been mainly substituted by pesticides. In certain conditions, some cropping systems even manage direct seeding with no-tillage, which delivers a maximum decrease of machine cost, fuel consumption and the amount of required labour. At the same time, no-tillage increases the campaign performance, resulting in a very powerful cultivation system [3] but also depend on fertilizers and chemicals. The 1990s brought increased power density of electronically controlled tractor engines, power shift gearboxes and CVT technology, which allowed new growth rates of implement operating speed and width. As a result, foldable implement concepts were created with the result that greater structural loads required higher strength material in combination with a much better understanding of load cases, which drove sophisticated solutions for structural components. However, the continuous weight increase of all machines and implements and the tendency to use machinery in critical soil conditions to increase usage hours have raised the risk of soil compaction. The weight of tractors increased as well and on top of that tractors need even additional ballast to be capable to transfer their available engine power into draw bar force [4].

Limits of current concepts and concept objectives

Productivity of machines is directly coupled to the process area of the specific function. In the past productivity increases have been mainly achieved by an increase in process area in terms of working width, machine internal process channel width, storage volume or operational speed. The high-end products of Ag-machinery manufacturers have reached and exceeded legal limits in physical dimensions and axle weights today, which creates the new requirement to deliver further productivity increases while maintaining weight and maximum dimensions. Two seemingly mutual exclusive paths to cope with axle loads and dimensional limits become visible (Figure 1):

- current machine concepts need further increased functional performance density and utilization of fiber composite material to reduce specific weight, either one resulting in progressive cost to value relation or
- known agricultural concepts shifting towards highly automated, flexible operating machine systems with hybrid power sources and distributed drive architectures, which would start a paradigm shift from large machines towards smaller, more intelligent and highly automated systems.

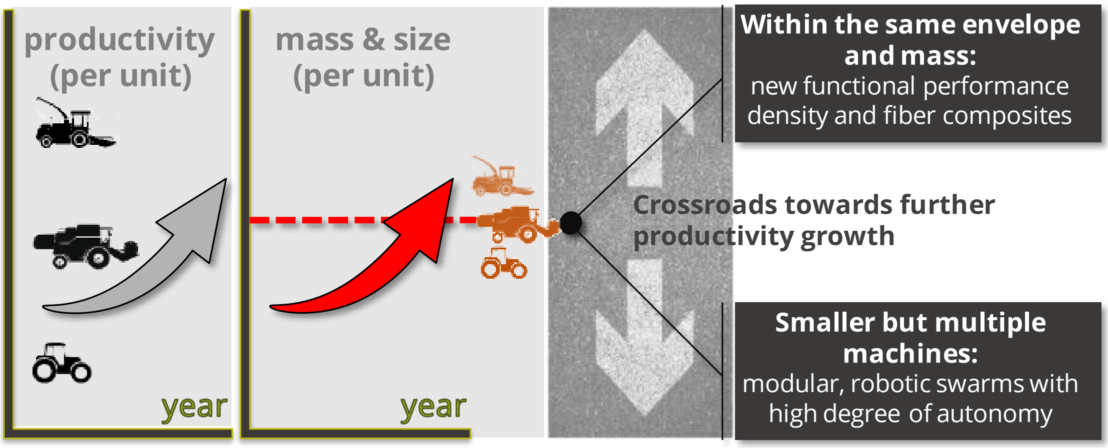


Figure 1 Alternatives for future productivity growth considering the weight and dimensional limitation of mobile machines

Technology enablers like multi axle navigation control, electrification of drive trains, composite and function integrated materials, plant and soil sensing with its respective mapping technologies or cloud computing-based process management and processing of big data have affected and will change the nature of field operations towards more automation with the objective of better utilization of all given resources. Specifically, with electrification, it becomes possible to completely rethink the tractor – implement domain to

- reduce the required traction force of tractors by using distributed drives on implements allowing speed variable active tools or single driven wheels up to a level where an implement does not create any force requirements at its connection points for traction and navigation anymore and becomes virtually self-propelled,
- have modular power sources based on tractor power or auxiliary power modules, where power sources can be external electric supply by wire [5, 6] or combustion engines with mechanical to electrical energy transformation,

- significantly increase the degree of automation of implement navigation and their functional processes fully acknowledging the requirement that the resulting increase in productivity and resource protection is fully amortizing the additional system cost for such modular systems.

The growth in installed capacity in a machine or a given combination of machines is counterproductive in regards of flexibility of the system and scalability of capacity. The idea of a modular and scalable self-propelled implement system tries to solve above mentioned challenges with the goal to deliver

- configuration capability regarding actual task, field properties / conditions and farm infrastructure by providing the ability to configure width and / or combination of implement functionality as well as the power supply related to the actual task,
- scalability of peak performance, productivity and economy using single or multiple number of units with the same or different process tool modules and
- as much as possible compatibility to the existing tractor implement world.

Concept Vision

The evolution process, which agricultural technology will face, has profound implications on the future design and functionality of tractor – implement systems and their ability to interact with soil and plants environmentally sustainable and economically efficient. The next decades will see known agricultural concepts shifting towards machine systems with a high degree of autonomy utilizing electrified and distributed drive architectures. In the long perspective, research shows that a paradigm shift from large machines to smaller and more intelligent multi-robot systems is expected [7], which can establish and nurse plants even at an individual level [8]. The additional efforts to increase productivity and performance within the limits in physical dimensions and legal restrictions while still delivering value growth is going to drive system cost of known concepts more and more progressively. This trend is currently balanced by increasing system efficiency instead of peak performance, which is mainly driven through automation. Machine systems utilizing robotic concepts are not economically viable today, however, a future break-even point is expected where the value increase is delivered by system flexibility and adjustable capacity using a certain number of modular units (swarm), which always produces a linear behaviour between cost and productivity. Focusing on future challenges and technology trends in agricultural industry, an engineering team from TU Dresden and Fraunhofer started the Feldschwarm project together with seven industrial partners in 2013. It is a process focused approach where the process tools, drives and frames are designed as modular components with standardized interfaces, which allows to connect to each other and to the supporting components like traction modules, storage of fertilizer and seeds or the automation components comprising sensors, controllers and actuators. The intent is to cover specific process requirements and typical process variability within the process modules and keep the other modules as common as possible to enable effective configuration for each process task while having tractor like high utilization of the common components. Figure 2 shows the modularity and the parallelism to known tractor models of the past. The concept of a multi equipment carrier was very prominent in the 60-s and 70-s of the last century but suffered from the very limited room for engine and drive train growth, which eventually reduced market volume and market share significantly in the 90-s.

Figure 2 Modular concept of the autonomous, self-propelled Feldschwarm unit and its design similarities to a tractor from 1960 [9]

The advantage of a multi equipment carrier is due to the four attachments areas (front, inter-axle, rear and top), which allow for high flexibility of the combination of different process tools and storage equipment. The Feldschwarm unit provides three areas for attachment and can either work passively (without energy and traction module) behind a tractor or in the self-propelled configuration using the power-generator unit or an external electrical energy source. Module relationships and unit interaction with the swarm management and the farm management level is shown in Figure 3.

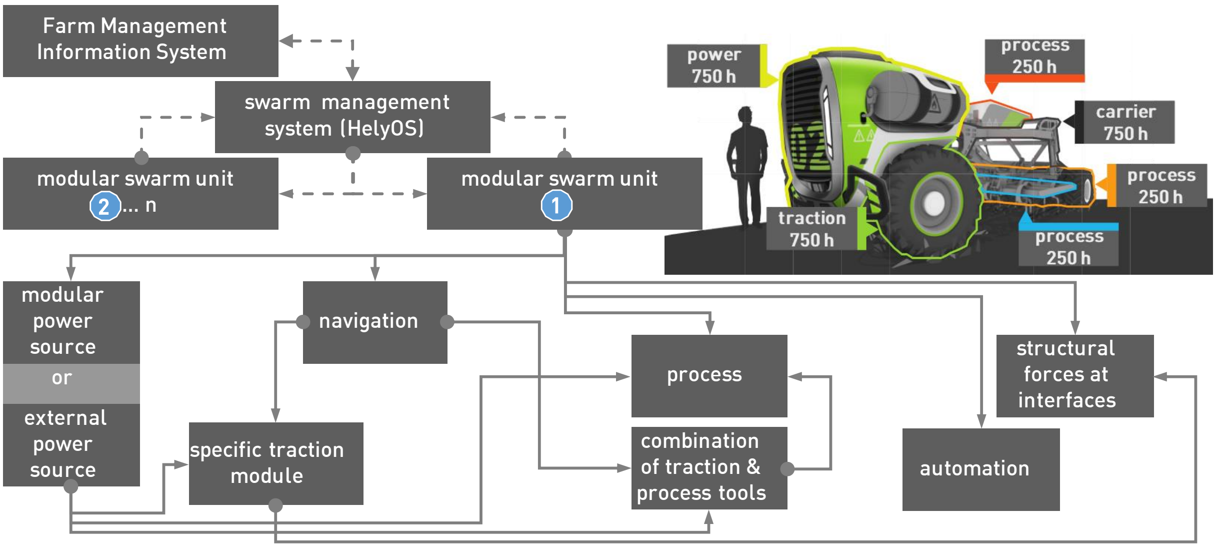


Figure 3 Tractor – implement functionality reflected in a modular system and anticipated annual usage hours for the different modules

The swarm management system HelyOS (Highly Efficient Online Yard Operating System) [10] is a Fraunhofer developed control center software for gated areas in automated truck logistics and is being modified for the Feldschwarm application. It splits the site-specific process task derived off the FMIS or other sources into navigation tasks comprising the respective site-specific information for each of the single units Every unit receives its task prior to execution. It is submitting back the operational status and any FMIS relevant data gathered from sensor signals or process internal parameters during the task execution. As long as the unit is in schedule, including tolerated deviations, the swarm management system does not intervene. New task and path planning only happens if for some reason (process implications, unit failure, new objectives, etc.) the original tasks need to be changed. The Feldschwarm user interface incorporates the operator as an important part of the system and uses his or her competencies for the ease of operation and utilizing installed technical capacity. Based on the operating paradigms of familiar terminal interfaces and logistics management applications, the HMI merges both to provide a mobile swarm control panel for autonomous agricultural machines [11]. Specifically, the new HMI strategy allows the control and monitoring of several autonomous units that can be equipped with various process tools from selectable locations.

Development objectives

The uniform working width of process modules was chosen to be 3 m. When forming a swarm, the effective working width is defined by the number of machines used for the task. Main specification parameters are as follows:

- Power source is a combustion engine with 150 kW, currently diesel engine, later using alternative fuels like Methane or Hydrogen.
- Electrical system with 600 V DC intermediate circuit.
- Traction unit based on a modified tractor front axle with 140 kW / 450 Nm electrical machine (Figure 4).
- Active electrically driven process modules: rollers 2 x 20 kW, combination of tine and rotary harrow 60 kW.
- Hydraulics: 20 l max. 180 bar steering and brake for traction module, 40 l max. 200 bar for hydraulic cylinders.
- Passive processing modules disc harrow and tine harrow designed for tillage depth of 15 cm, prototype of tine harrow module is shown in Figure 4.
- Transport position center module coupling frame 1000 mm above ground, working position 450 mm above ground with 400 mm adjustment range.
- Communication between units and swarm management system utilizes IEEE 802.11p.
- Weight of an autonomous unit is between 5 – 8 t, depending on the process equipment.

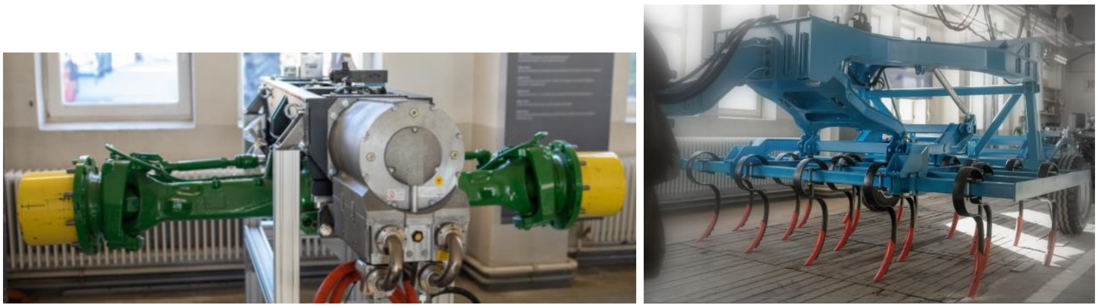
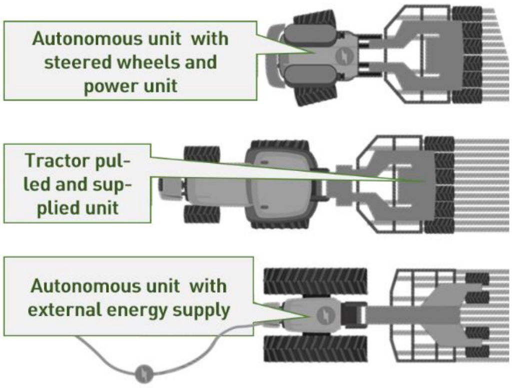


Figure 4 First prototypes of traction module (left) and tractor attached carrier with passive harrow module (right)

The compatibility to tractor attachments ensures a migration path from conventional agricultural technology, while configuration of process components and automation level already has the performance of an autonomous unit utilizing the traction and power supply capabilities of a standard tractor. In combination with active rotating tools, traction and navigation can be executed separate from the tractor, which can stay the centre for the operator. Figure 5 shows possible instances as autonomous unit or attached to a standard tractor. In case of external energy supply via a high voltage cable it is possible to deliver extremely higher power density since energy storage and conversion is done outside the field system.



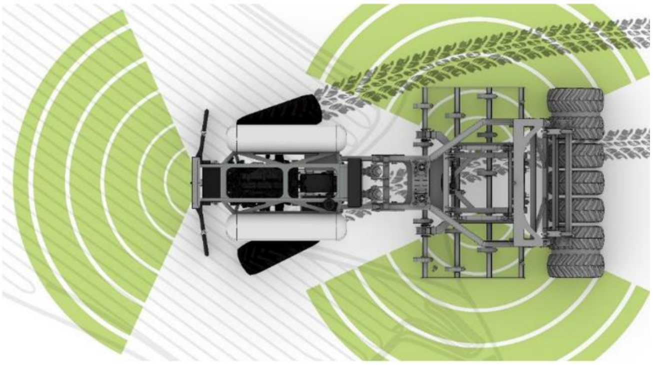


Figure 5 Basic configuration types of the Feldschwarm units

Figure 6 is evaluating degree of needed innovation versus the complexity of the main development tasks for the Feldschwarm system. Navigation task, modular and drive train design approach or machine communication are challenging but can be addressed using existing technology and design methods. However, as known from robotic vehicle approaches and the autonomous driving, the recognition of the environment regarding the process execution and in terms of functional safety is a very complex task and requires some fundamental new solutions. Fully autonomous vehicles need a “zero defect operation” robustness, which is a considerable design challenge with the risk to drive system cost up to an unacceptable level.

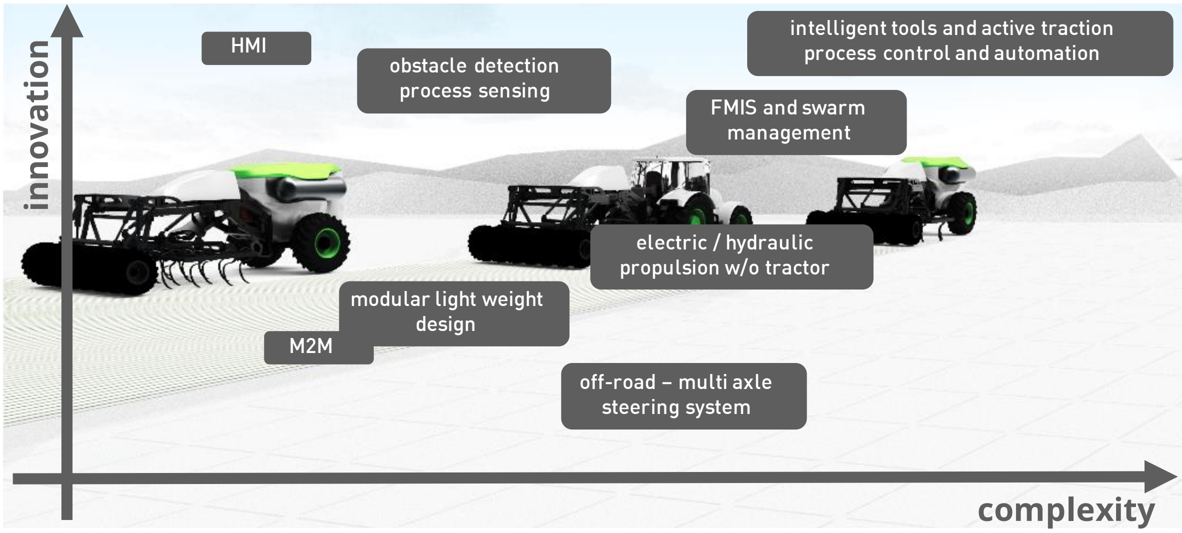


Figure 6 Development Tasks

The Feldschwarm is taking a different approach and considers the fleet operator and its practically varying capabilities as an integral part of the automation system, which allows to deal more efficient with seldom corner conditions and functional safety. A completely new and important issue in the development of future highly automated machine systems is the maintenance and improvement of operator competencies. So far, automation has helped to unload the operator from routine tasks, which has improved the efficiency of the systems and the convenience of operation but also was decoupling the human from direct process control, which consequently could lead to full automation. Under the assumption that zero defect operation as requirement for full automation [12] cannot be achieved economically "Shared Control" [13,14] between an automation system and the human is considered a valid approach to future automation solutions (see Figure 7) and is also well transferable to the process and process management in smart farming and farm management systems.

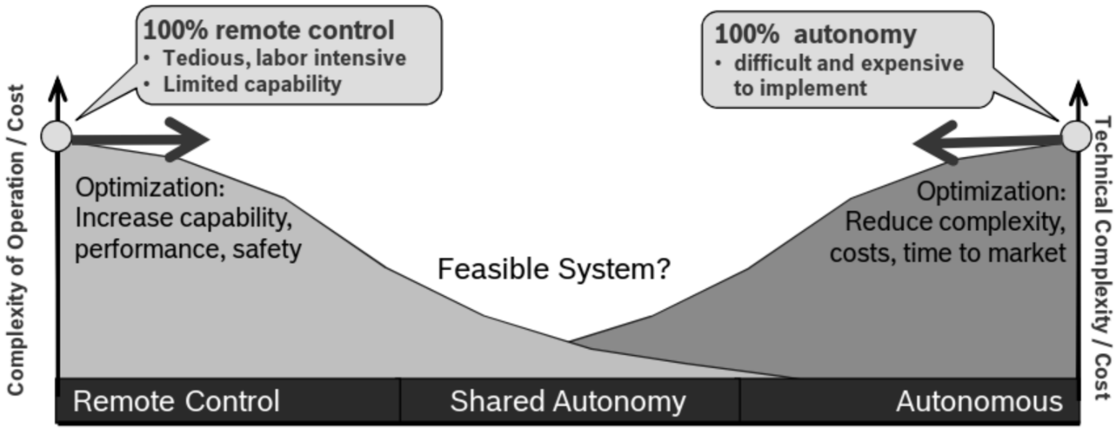


Figure 7 Shared Autonomy is an adaptable collaboration between human operation and machine control system [15]

As a result, the task of automating mobile work machines is significantly expanding into the development, implementation, and evaluation of assistance strategies that encourage the acquisition and maintenance of complex problem-solving skills for operators. It is particularly important to tackle this task in an interdisciplinary manner, including labour science, engineering psychology and media design in addition to the classical mix of mechanical engineering and computer science.

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1 P. Weisskopf, R. Reiser, J. Rek, H.R. Oberholzer: Effect of different compaction impacts and varying subsequent management practices on soil structure, air regime and microbiological parameters, Soil and Tillage Research 111 (2010) 65–74.

2 D. Bochtis, C. Sørensen, O. Green: A DSS for planning of soil-sensitive field operations, Original Research Article Decision Support Systems, Volume 53, Issue 1, April 2012, Pages 66-75

3 DERPSCH, R.: Historical review of no-tillage cultivation of crops. In: FAO International Workshop, Conservation Tillage for Sustainable Agriculture. 1998. S. 205-218.

4 Brixius, W.: Traction predictions equations for bias ply tires, ASAE paper 87-1622, 1987.

5 Spencer, J.: Electric tractor powered by a cable - machinery & implements. Farmer's Weekly, Volume 2019 Number 19013, Apr 2019, p. 52 - 52

6 Pfaffmann, S.; Tarasinski, N.; de Moraes Boos,F.: Swarm Unit – Development of a Fully Electric Agricultural Machine with External Power Supply. 77th International Conference on Agricultural Engineering, Hanover 2019

7 de Witte, T.: Wirtschaftliche Perspektiven autonomer Kleinmaschinen im Ackerbau, Journal für Kulturpflanzen, 71 (4). S. 95–100, 2019, ISSN 1867-0911, DOI: 10.5073/JfK.2019.04.04 Verlag Eugen Ulmer KG, Stuttgart

8 Blackmore, S.; Stout, B.; Wang, M.; Runov, B.: Robotic agriculture – the future of agricultural mechanization? In: Fifth European Conference on Precision Agriculture (Stafford J. V.), 2005 621–628, Wageningen Academic Publishers, Netherlands.

9 Geräteträger GT 124 mit Pflegegerät P 320 und Spurlockerer, Zentralen Prüfstelle für Landtechnik Potsdam-Bornim (ZPL) https://mediatum.ub.tum.de/

10 Nitzsche, G.; Wagner, S.; Belov, N.: helyOS - Highly Efficient Online Yard Operating System.15th International Conference Commercial Vehicles 2019 : Truck, Bus, Van, Trailer, June 4-5, 2019, Baden-Baden, Germany, Düsseldorf: VDI-Verlag, 2019 (VDI Berichte 2350), ISBN: 978-3-18-092350-5

11 Lorenz, S.; Krzywinski, J.; Schreiber, C.: Feldschwarm-HMI – a semistationary user interface for operating and monitoring highly automated systems. 77th International Conference on Agricultural Engineering, Hanover 2019

12 Pickel, P.: Insights from the corporate world - Innovation Trend "Smart Farming". 27. Hülsenberger Gespräche 2018 - Landwirtschaft und Digitalisierung, Hamburg, 2018.

13 Kalyuga, S.: Instructional designs for the development of transferable knowledge and skills: A cognitive load perspective. Computers in Human Behavior, 25(2), 332-338 (2009).

14 Kirschner, P. A.; van Merriënboer, J. J. : Do learners really know best? Urban legends in education. Educational Psychologist, 48(3), 169-183 (2013).

15 Pitzer, B.; Styer, M.; Bersch, C.; DuHadway, C. and Becker, J.: Towards Perceptual Shared Autonomy for Robotic Mobile Manipulation in Proc. IEEE International Conference on Robotics & Automation (ICRA), 2011