Autonomous Technologies in Agricultural Equipment: A Review of the State of the Art

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Abstract. *Automation and robotics for agricultural production are topics of tremendous interest and large investments. There have been significant recent advances in agricultural automation and robotics in the areas of (1) automatic vehicle guidance and steering control, (2) automatic implement guidance, (3) automatic headland sequence and turn management, (4) sensing for perception, (5) sensing for variable-rate technologies, (6) optimization of machine operation, (7) machinery coordination, and (8) machinery communication. These eight areas of progress are discussed in terms of commercially available technologies, public intellectual property, and the research literature.*

Keywords. *Automation, headland and turn management, implement guidance, precision agriculture, robotics, sensing, steering control, variable-rate technology, vehicle guidance.*

Introduction

Investment in advanced agricultural technologies has increased by 80% annually since 2012 (Walker et al., 2016). A major portion of these investments has been focused on automation, and great interest exists specifically in new robotic technologies (Tillett, 2003; Oberti and Shapiro, 2016). Many agricultural operations are suited to automation, with vehicles commonly operating in large, well-defined open areas relatively free of obstructions and personnel.

To be commercialized, automated robotic systems (ARS) must increase productivity of over current levels (Goense, 2003). Productivity and work quality must increase even for semi-automated systems, which have to respond quickly in unstructured agricultural environments (Bechar, 2010). Technical factors limiting ARS include deficiencies in detector performance and automated decision-making along with the need for low human involvement in dynamic environments (Bechar and Edan, 2003). The technology must be capable of recognizing changing conditions and spatial variability in the physical environment, potentially through incorporation of intelligent systems (Almeida Bessa et al., 2015).

Agricultural field machines have already undergone significant automation and are progressing from the common automatic guidance of today to the fully autonomous field robots of tomorrow. Major areas of advancement include the following: (1) automatic vehicle guidance and steering control, (2) automatic implement guidance, (3) automatic headland sequence and turn management, (4) sensing for perception, (5) sensing for variable-rate technologies, (6) optimization of machine operation, (7) machinery coordination, and (8) machinery communication.

The authors composed and presented a broad group of conference papers on these topics at the 2018 ASABE Annual International Meeting in Detroit, Michigan. For the sake of brevity and cohesiveness, only three of those papers (Baillie et al., 2018a,b; and Thomasson et al., 2018) are covered in this compilation. The fourth focused on sensor-based nitrogen-management technologies (Antille et al., 2018a). Thus, this article does not offer a fully comprehensive view of automation in agricultural production, which would go beyond the four articles mentioned, but it attempts to cover automation as it pertains to large agricultural machinery. Each of the covered areas of advancement includes an overview of commercially available technologies and also touches on research and uncommercialized intellectual property. Regarding commercially available technologies, the authors reviewed commercial literature and conducted discussions with corporate personnel (with varying degrees of success) from six major machinery manufacturers: John Deere, CNH, AGCO, CLAAS, SDF, and Kubota.

Automatic Vehicle Guidance and Steering Control

Automatic guidance and steering control systems for agricultural vehicles have been commercially available for about 20 years. These systems guide vehicles precisely with navigation based on global positioning systems or systems that place the vehicle relative to the crop, with minimal driver interaction (e.g., Lipiński et al., 2016; Thanpattranon et al., 2016). Such systems reduce driver fatigue (Kvíz and Kroulík, 2017) and enable the driver to better monitor implement and machine operations. They also enable more advanced agronomic techniques such as precision seeding and controlled traffic (Dijksterhuis et al., 1998; Antille et al., 2015, 2016; Seyyedhasani and Dvorak, 2018). A primary benefit of automatic guidance is the reduction in overlap during seeding, spraying, fertilizing, and harvesting, which

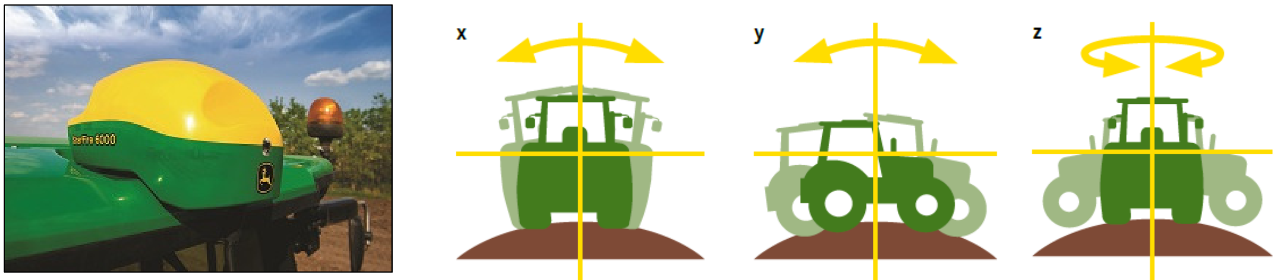


Figure 1. StarFire 6000 guidance system and terrain compensation (source: John Deere, www.deere.com.au).

reduces input costs and increases machine efficiency (Hameed et al., 2016; Antille et al., 2018b).

Automatic guidance systems differ in positioning accuracy based on the positioning technology being used. They also differ in the level of control, which ranges from lightbar guidance for the operator control to steering-wheel attachments for automatic control or even fully integrated automatic control (Han et al., 2004; Taylor et al., 2004). All major tractor manufacturers offer some form of automatic guidance, and systems are also available from companies that specialize in tractor guidance. Commercially available guidance systems still require some level of human intervention.

John Deere offers a guidance and steering control product called AutoTrac that uses NavCom's StarFire GNSS (Global Navigation Satellite System) guidance system. The StarFire system offers a range of positioning accuracies that can be selected based on application and is compatible with satellite-broadcast correction information or local RTK (real-time kinematic), which enables 2.5-cm positioning accuracy. The new StarFire 6000 system provides 3-cm accuracy using SF3 satellite broadcast corrections. John Deere guidance systems are also equipped with the Terrain Compensation Module (TCM) that uses sensors to compensate for the vehicle's roll, pitch, and yaw to provide accurate ground-level positioning (Figure 1). Broadcast RTK differential corrections can also be received with the Mobile RTK modem (Figure 2).

Case IH's AFS (Advanced Farming System) and New Holland's PLM (Precision Land Management) guidance solutions (AccuGuide, AutoPilot, and Intellisteer) work with various GNSS receivers and differential correction services including Omnistar and Trimble (Centerpoint RTX and Rangepoint RTX). Case IH has recently released a proprietary RTK correction service (AFS RTK+) in the U.S. and Canada, which uses an RTK-base station network installed by dealers, and corrections are broadcast through the cellular network (Figure 3). The guidance systems also provide terrain compensation to correct ground position measurement based on the vehicle's roll, pitch, and yaw. The AutoPilot system provides for direct integration with the electro-hydraulic system for steering control.

The CLAAS GPS PILOT S3 auto-steering system uses integrated steering control while the CLAAS GPS PILOT FLEX uses an electronic steering wheel attachment. Both systems include a navigation controller that uses sensors to compensate for roll, pitch, yaw, and lateral movement (terrain compensation). Several GPS correction signal options are available for CLAAS systems, including satellite broadcast signals (EGNOS, OMNISTAR HP/XP/G2); BASELINE HD, which uses a mobile reference station (short range radio); and RTK systems, including RTK NET that can provide corrections through the cellular network (Figure 4).

AGCO is partnered with TopCon Positioning Systems to provide automated tractor guidance. AGCO's Auto-Guide 3000 guidance system is part of its Fuse Technologies

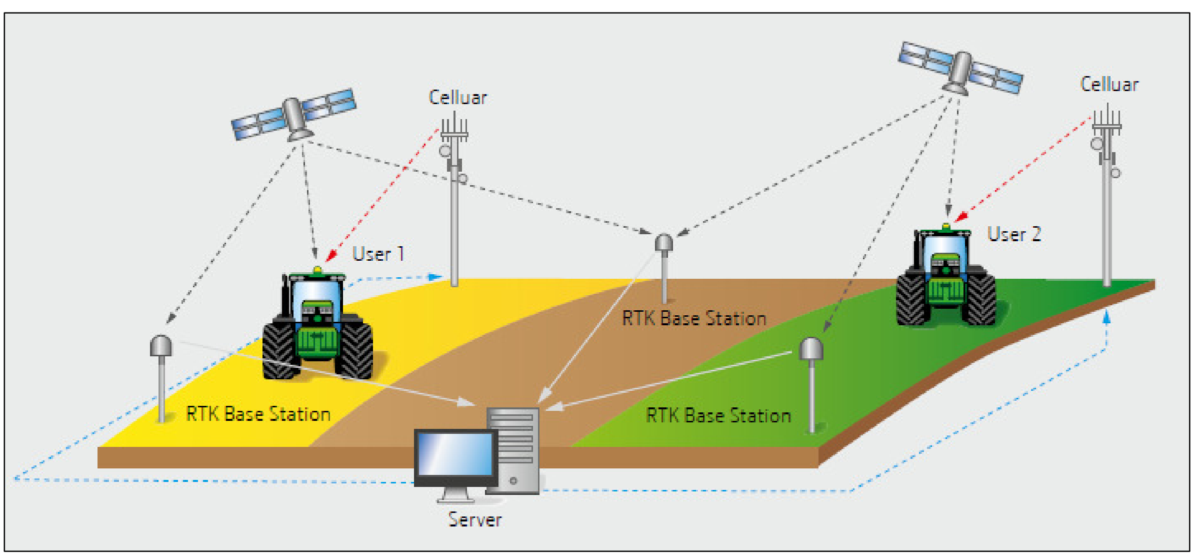


Figure 2. Mobile RTK corrections using 3G/4G communications (source: John Deere, www.deere.com.au).

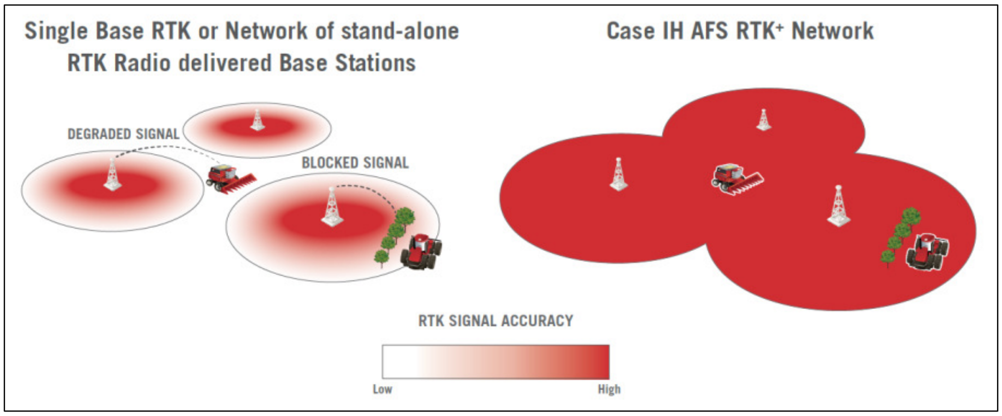


Figure 3. Case IH dealer network RTK correction service (source: Case IH, www.caseih.com/anz/en-au/home).

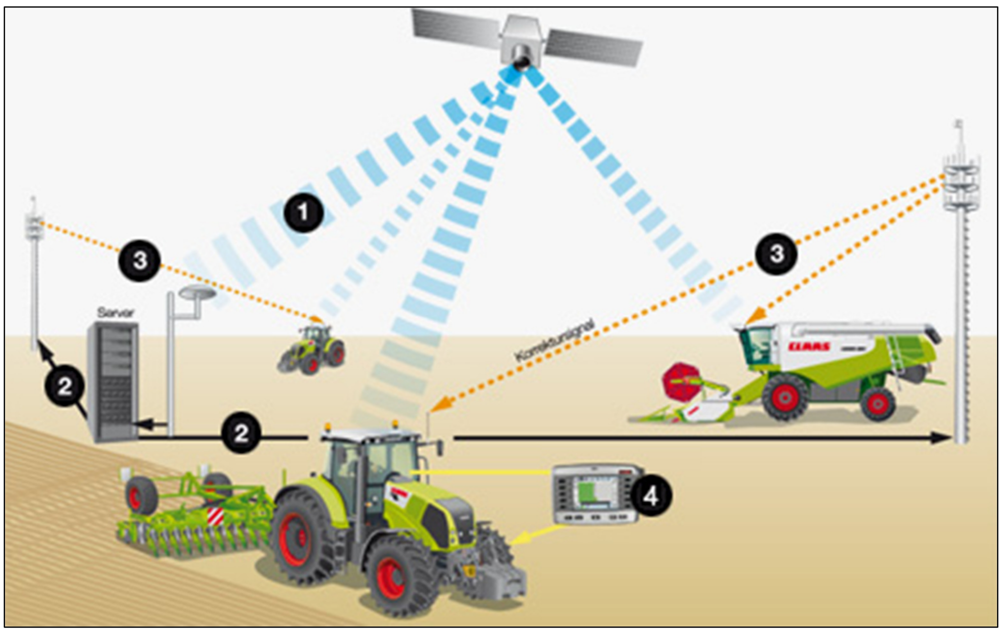


Figure 4. CLAAS differential GNSS corrections using RTK NET (CLAAS, www.claas.com.au/).

precision-agriculture (PA) platform. Prior to Auto-Guide, Fendt's VarioGuide was developed for automatic steering, and it uses TopCon or Trimble GNSS receivers and Fendt software and firmware.

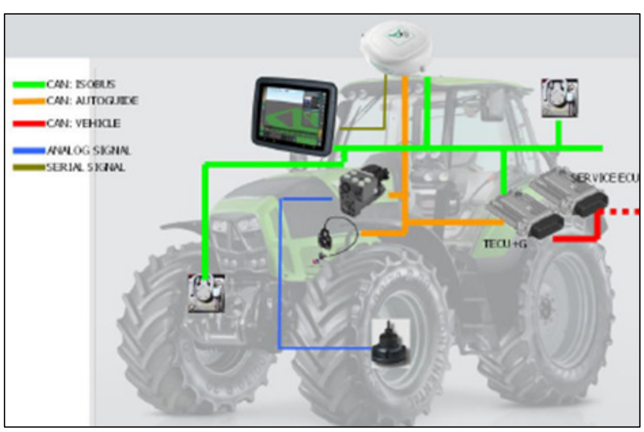


Figure 5. Data communications for auto-steer on Deutz-Fahr tractor (source: www.europeanlandowners.org).

SDF has also partnered with TopCon and provides the Agrosky automated guidance system. GNSS options include RTK, HP (High Performance), and DGPS (Differential Global Positioning System). Figure 5 shows the data communication system for auto-steer on a Deutz-Fahr tractor. With Agrosky Performance Steering, the tractor can be configured to be "Agrosky ready," enabling electronic control of hydraulic steering systems. New Deutz-Fahr Series 7 and 9 tractors have Performance Steering and the iMonitor2 control unit as standard.

Kubota's M7-1 tractor, released in 2016, is reported to have GNSS-compatible automatic guidance. However, no further information was found about the functionality of the system.

Two main sensing approaches have been proposed for automatic guidance (Hagras et al., 2002; Bak and Jakobsen, 2004). In one, a sensing and control system on the vehicle uses a highly precise positioning system like RTK GNSS to guide the vehicle through pre-established paths. Most currently available systems use this approach. A drawback is that such systems cannot automatically react to unexpected changes in field layout. In the other approach, a sensing and control system on the vehicle identifies crop rows as a reference for guidance. One available commercial system is provided by Headsight Harvesting Solutions and uses a mechanical sensing wand to identify a row of corn plants. Another similar system is the 360 Guide manufactured mainly for self-propelled sprayers by 360 Yield Center. Other systems that use machine vision have been developed (e.g., Morimoto et al., 2005; Boonporm and Tantawiroon, 2013), and they have reportedly been commercially available for several years (Slaughter et al., 2008).

Considering that the future will likely involve multiple fully autonomous vehicles operating in a single agricultural field, different navigation problems must be taken into account (Blackmore et al., 2009). Deere & Company's U.S. Patent 8396597 presents a structured-light based approach for generating a path plan for multiple mobile robots operating in a contained area. A guidance projection is generated with a three-dimensional map and then projected onto the contained area. One or more robots detect the guidance projection, identify a path within it, and then follow the path.One key challenge in path planning is optimal routing, which requires avoiding collisions with static and moving objects, minimizing distance travelled, and minimizing environmental impact (Bochtis et al., 2010a,b; Conesa-Muñoz et al., 2016; Spekken et al., 2016). Particular technologies have been developed and serve as building blocks for fully automated crop-row guidance (Canning et al., 2004; Nagasaka et al., 2004; Bechar, 2010; Bechar and Vigneault, 2017). For example, fiber-optic gyro sensors, GNSS, and accelerometers have been used to determine position and orientation. Rotary encoders have been used to establish steering angle, and proximity sensors have been used to monitor the vehicle's clutch and break position. Geometrical data structures have been used to compute a path between origin and destination. Digital controllers that regulate actuators have been used to control the vehicle's orientation and velocity. Fuzzy logic has been used to control the path of a robot. Other analytical techniques for path planning reported in the literature include probabilistic roadmaps, neural networks, and reinforcement learning (Almeida Bessa et al., 2015; Bechar and Vigneault, 2017).

Another key challenge in path planning is obstacle avoidance. Systems designed for this purpose can be used to assist human vehicle operators or on fully autonomous vehicles (De Simone et al., 2018; Liu et al., 2018). One type of obstacle-avoidance system uses local data about the vehicle's environment to control steering to avoid obstacles. However, this type of system reacts slowly when its algorithms approach data-space boundaries, discontinuities, or local maxima or minima, and a vehicle with a faltering detection algorithm is more likely to collide with an obstacle in its path. Thus, Deere & Company's U.S. Patent 8060306 aims at improving the search speed for a suitable obstacle avoidance path to avoid a collision. Requirements include a sensor that determines relative position between an obstacle and a vehicle and program modules that detect the vehicle's translational and rotational velocities, map vehicle surroundings, and calculate and filter possible paths. These path-selection modules identify admissible curved paths in which the vehicle can stop before reaching the obstacle.

Figure 6. John Deere iGuide (source: John Deere, www.deere.com.au).

Automatic Implement Guidance

Another important technology for autonomous vehicle operations is implement guidance, which works to correctly position the implement under variable loads and on slopes (Grečenko, 1984; Yisa et al.,1998). Implement guidance systems control tractor steering and position and sometimes implement steering to achieve accurate positioning of the implement rather than the tractor itself (Yisa and Terao, 1995a,b; Oksanen and Backman, 2016). Active implement guidance, in which the implement is steered independently of the tractor, may be particularly useful within an autonomous system, allowing implement guidance to operate somewhat independently of the vehicle guidance system.

John Deere's iGuide system provides passive implement guidance to ensure an implement is correctly positioned. A GNSS receiver mounted on the implement communicates to the tractor's AutoTrac system, which adjusts tractor guidance to maintain correct implement position. The iSteer system provides active implement guidance in which hydraulics installed on an implement are used to fine-tune its position (Figure 6).

Case IH's PLM and New Holland's AFS TrueGuide and TrueTracker implement guidance systems, developed by Trimble, provide implement guidance through integration with the tractor guidance system. TrueGuide adjusts the tractor's position to correctly position the implement. While TrueGuide is considered passive implement guidance, TrueTracker is considered active implement guidance in that it uses hydraulics mounted on the implement and terrain compensation to provide independent implement guidance.

Several companies specialize in implement guidance hitches that can be adapted to multiple vehicle brands. For example, MBW Products makes the ProTrakker implement guidance system, LaForge Systems makes the Dynatrac system, and Sunco Farm Equipment makes the Acura Trak system.

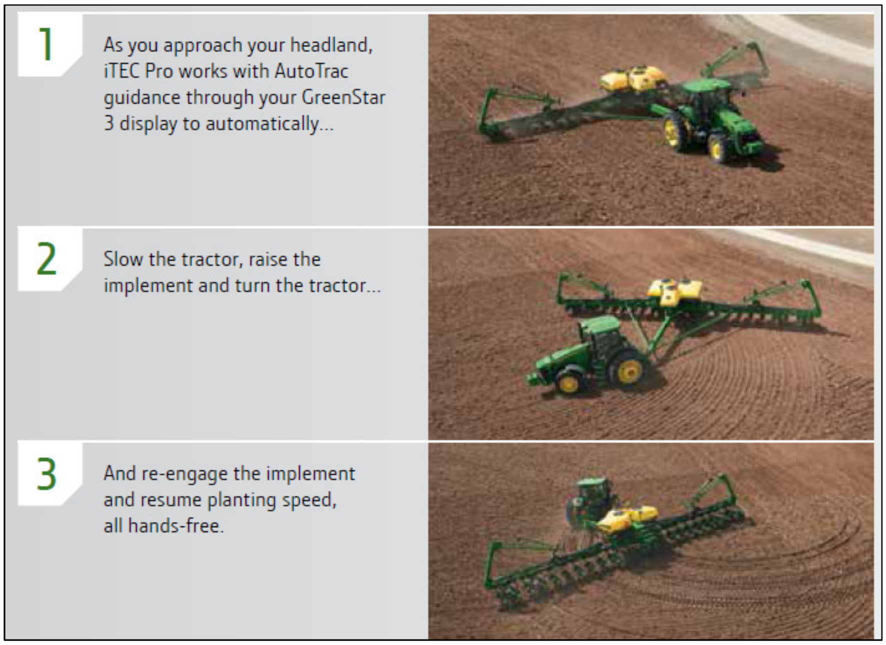


Figure 7. iTEC Pro vehicle and implement coordination at end turns for headland management (John Deere, www.deere.com).

Automatic Headland Sequence and Turn Management

Developments in automating machine operations involve executing sequences of implement and tractor tasks (Oksanen and Visala, 2009; Alshaer et al., 2013) for the purposes of increasing efficiency and reducing operator fatigue. For example, during planting, tractor turns at the end of a field (i.e., the “headland” or “turnrow”) may require a 180° turn with a sequence of several operations: slowing the vehicle, raising and lowering an implement, engaging and disengaging PTOs (power take-offs), engaging and disengaging a locking differential and 4WD (four wheel drive), and steering within the headland to correctly align for the next pass. This sequence of tasks may need to be performed many times in a day, contributing to driver fatigue (Kvíz and Kroulík, 2017). Headland management systems can be programmed to perform such a sequence of tasks in order to automate the most difficult and tedious aspects of vehicle operation. While these technologies have been developed to augment human operation of vehicles, they serve as key elements of eventual full autonomy. Most systems from the major equipment manufacturers require ISOBUS-compatible implements for headland management to be inclusive of implement tasks.

John Deere has developed iTEC (Intelligent Total Equipment Control) Pro, which can automate and coordinate vehicle and implement functions at end turns (Figure 7). The system reduces vehicle speed, automatically raises and lowers implements, and conducts the turn and alignment for the next pass.

The Case IH AFS and New Holland PLM products offer headland management systems that can record and replay sequences to assist operators in headland turns. These systems can control multiple operational elements including the transmission, engine speed, three-point hitch position, and electrohydraulic valves. Case IH’s AccuTurn automated headland-turning system provides automatic and accurate turns.

AGCO offers headland management in multiple AGCO brand tractors. An example is Fendt’s Variotronic headland management system that enables a sequence of actions to be pre-programmed and triggered by either the press of a button or by automatic GPS actuation at the headland line, if used in combination with Fendt’s Varioguide automatic guidance system. Programmed sequences can contain functions for engine and transmission control, front and rear PTO, front and rear linkage, and automated steering.

CLAAS offers the CSM (CLAAS Sequence Management) feature on some tractor models to execute task sequences. CLAAS also recently released the TURN IN feature and the more automated AUTO TURN feature that facilitate headland turn control with the GPS PILOT S3 guidance system. TURN IN considers machine alignment, steering lock, and speed, and identifies the next parallel track (Figure 8). The

Figure 8. CLAAS TURN IN guidance system extension (CLAAS, www.claas.com.au).

driver can influence track choice by changing parameters or intervening in steering. The AUTO TURN function automatically turns the machine at the headland in one sweep and guides it into the next pass.

SDF offers the Comfortip feature for headland management on some its Deutz-Fahr tractors. This feature works in conjunction with the Agrosky guidance system.

Kubota's M7-1 tractor has a system called Headland Management Control, which allows pre-recording of four programs, e.g., end-of-row sequences for slowing down; lifting an implement; disengaging the PTO, 4WD, and locking differential; and then reversing this sequence at the start of the next row. The driver presses a button to commence a program, and sequencing in the program is based on distance or time.

Sensing for Perception

Developments in sensing for perception by agricultural vehicles have been focused on automation, guidance, situational awareness, and process monitoring. Sensors for automated systems include GPS, infrared sensors, machine vision, light detection and ranging (LIDAR), and ultrasonic sensors (Hague et al., 2000; Tillett, 2006; Bechar and Vigneault, 2017). LIDAR and machine vision can also be used for guidance to enable positioning the vehicle relative to the crop (e.g., during harvesting). As previously mentioned, for some crops (e.g., corn) mechanical sensors are used to detect the position of the crop relative to the harvester head. Vision-based systems have been developed to improve situational awareness of equipment operators to improve safety (Gerrish et al., 1997). Available camera systems provide blind-spot visibility to vehicle operators (Ehlers and Field, 2017) as well as detect humans in front of the vehicle and prevent the tractor from starting forward, through control of the transmission.

Products associated with sensing for perception have been developed by the large equipment manufacturers to automate aspects of common machinery operations. For example, John Deere's AutoTrac Vision (Figure 9) uses machine vision to align a vehicle with crop rows, generally to minimize crop damage from the vehicle wheels during spraying (Fehr and Gerrish, 1995). John Deere's Active Fill Control uses stereo cameras for 3D monitoring and control of the filling of transport vehicles during forage harvesting (Figure 10). CNH has also developed optical sensing systems for harvesting. The Case IH AFS guidance system can be used with the Cruise Cut laser crop guidance system. The New Holland PLM guidance system can be used with SmartSteer for laser crop guidance. New Holland offers an infrared time-of-flight (TOF) camera system for 3D monitoring and control of bin filling on forage harvesters (Vázquez-Arellano et al., 2016, 2018). CAM PILOT is CLAAS's 3D stereo vision camera system, typically used for forage harvesting, and LASER PILOT is the associated laser-based sensor for crop-referenced guidance. AUTO-FILL is CLAAS's version of a 3D stereo camera system for automated truck filling in forage harvesting. The system can locate the truck, track the crop jet and hit point, and calculate the fill level (Vázquez-Arellano et al., 2016).

AGCO and SDF have developed imaging technology for operator awareness. Fendt's Variotronic monitor enables two cameras to be viewed by the driver, enabling vision in blind spots (see Figure 11). This concept has been developed into a 360° camera system for Massey Ferguson vehicles, providing views from around and above the vehicle. Deutz-Fahr's Driver Extended Eyes also extends the driver's view angle. This system runs automated image analysis and generates an alert via iMonitor if a person enters the blind spot (Figure 12). Additional cameras provide a 360° panoramic view, increasing driver visibility around corners.

A great deal of non-commercialized intellectual property falls into the sensing for perception classification of automation technologies. Major technology groupings include: (1) sensor-based metrics, (2) vision-enhanced navigation, (3) obstacle avoidance, (4) combining historic and real-time data for navigation, and (5) combining data from multiple sensors. Sensor-based metrics include technologies for determining crop attributes from proximally and remotely sensed imagery. At field scale, this includes determination of plant height, row spacing, canopy density, growth vigor, and predicting crop growth and expected yield. These parameters provide an indication of crop yield and quality for

Figure 9. AutoTrac Vision front mounted camera for crop-referenced guidance (source: John Deere, www.deere.com).

Figure 10. Machine vision (using a stereo camera system): Active Fill Control of transport trucks when forage harvesting (source: John Deere, https://www.deere.com.au/en/index.html).

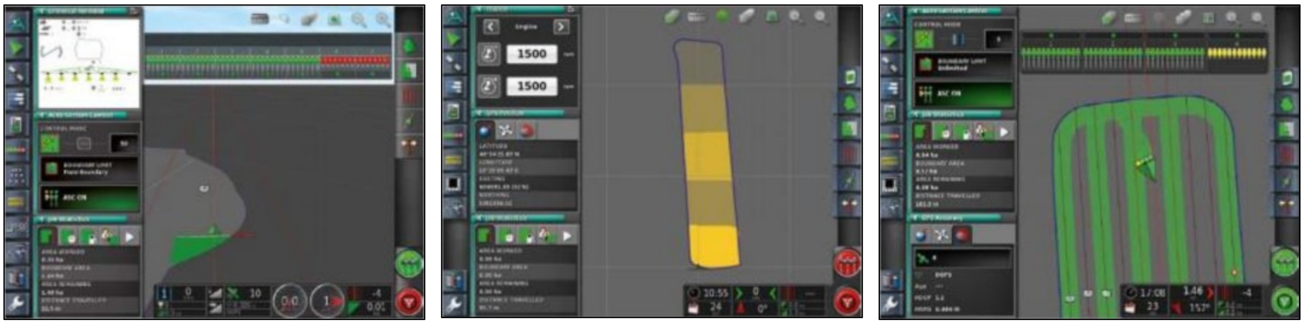


Figure 11. Section and variable rate control on iMonitor2 (source: Fendt Variotronic, https://www.fendt.com/uk/15599.html).

managing farming inputs. Vision-enhanced navigation technologies focus primarily on machinery navigation relative to the crop in conditions deleterious to GPS signals, or for enhancing GPS control and machine positioning based on an awareness of the crop and inaccuracies of the vehicle's or the crop's actual location.

Obstacle avoidance is a key component of agricultural-vehicle automation in the future. Technologies including laser range finders have been used to locate objects in a field of view, but their performance can be degraded by precipitation, fog, humidity, or dust. Technologies developed to overcome these limitations as well as alternative approaches involving stereo vision have been patented.

A key aspect of these inventions is processing the information in a timely manner for an autonomous machine to react in real time and in real-world situations. As automated agricultural equipment becomes increasingly prevalent, it is important to use all available information about a work environment to maximize safety and efficiency, so combining historic and real-time data is essential. Data-fusion technologies have been developed for real-time control of a moving vehicle based on a knowledge base of static information about the operating environment and dynamic information acquired as the vehicle spends time in a specific work area. Similarly, combining data from multiple sensors is essential. Sensor-fusion technologies have been developed for processing data from multiple sensors, sensor types, and sensor platforms for vehicle control in a changing operating environment.

Figure 12. Driver Extended Eyes and panoramic view from cameras on a Deutz-Fahr tractor (source: https://issuu.com/, Farming Precision Magazine).

Sensing for Variable-Rate (VR) Technologies

Automated technologies have been developed over the last two decades to improve crop management with PA techniques. Grain yield and protein sensors automatically make georeferenced measurements during harvesting for mapping yield and protein variability, which can facilitate PA management. While most equipment manufacturers provide yield monitors as standard options, John Deere also offers the Active Yield calibration system, which automatically calibrates yield sensors and thus minimizes the operator time required for maintaining accurate measurements. John Deere's HarvestLab is a near-infrared spectroscopic sensing system that can be mounted on forage harvesters to provide on-the-go analysis of moisture, dry matter, protein, starch, etc. This information can be used for automatic adjustment of forage cut length. The HarvestLab sensor can also be used to estimate manure properties (e.g., nutrients, dry matter, and volume) for site-specific application of manure/fertilizer.

CNH has also developed grain yield and moisture sensors and offers the CropScan 3000H grain protein sensor on Case IH and New Holland harvesters.

CLAAS offers the ISARIA crop sensor (Figure 13) to measure crop biomass and provide a nitrogen (N) index. This sensor is a red-infrared active-LED sensor for variable-rate (VR) application of N fertilizer. Calibration of the nitrogen index to nitrogen application rate can be specified by the user, but an available AUTO mode can simplify calibration based on a user-defined average application rate and adjustment range.

Figure 13. CLAAS ISARIA crop sensor (source: CLAAS, http://www.claas.com.au/products/easy/precision-farming/crop-sensor).

A component of Kubota's Smart Agri-System (KSAS) includes a sensor for estimating taste, yield, and moisture in rice.

VR technologies can enable precision application of many farm inputs including fertilizer, herbicide, and seed (e.g., using section control of implements to reduce seeding rate or herbicide overlap) (Goense et al., 1996; Witney, 2003). VR application and section control are implement functions, and a number of VR implements (e.g., fertilizer spreaders) are available from major equipment manufacturers and other more specialized companies.

Implement functions often depend on information provided by the vehicle and operator, e.g., implement position and speed, predefined prescription maps, and real-time sensor data. To facilitate common communications protocols between the implement and the vehicle and operator (through a terminal), the ISO 11783 (ISOBUS) Standard has been developed collaboratively by industry members. Communication among the vehicle, sensors, and implements in ISOBUS is handled by the task controller, which is also responsible for determining application rates based on prescription maps, sensor data, position, vehicle speed, etc. Task-controller products are available from equipment manufacturers and more specialized companies.

John Deere's Section Control system provides control of individual sections of planters, air seeders, and sprayers to reduce or minimize overlap. The system works with the StarFire GPS receiver for positioning and GreenStar display as an operator interface, and it can be used to control numerous ISOBUS-compatible implements.

The CNH AFS AccuControl and PLM IntelliRate systems also allow for VR control of fertilizer or section control in seeding and spraying operations. Both the AFS and PLM product lines include an ISOBUS Task Controller and Field-IQ, a control system developed by Trimble for managing crop inputs and supporting PA techniques. Field-IQ functions include VR control of seeding, chemical, and fertilizer applications based on prescription maps or data from the GreenSeeker optical sensor (Colaço and Bramley, 2018). CNH's system also includes boom height control for more uniform spray application based on sensors that measure the distance to the crop canopy or ground. Field-IQ also monitors seeding for on-the-go tuning of planters and early identification of seeding problems (e.g., blockage in air seeders) (Zagórda et al., 2017).

CLAAS has developed the CEBIS MOBILE ISOBUS-compatible terminal to support PA functions including VR applications and integration of the ISARIA crop sensor. The CLAAS S10 ISOBUS terminal was recently expanded with functions for section control and ISOBUS task management.

The AGCO Fuse Technologies PA platform includes AgControl, which provides control of application rate and up to 24 different sections. Data are logged on the terminal, enabling recording of application maps for future decision making.

The SDF iMonitor2 provides an interface for ISOBUS implements to enable section and VR control. Deutz-Fahr tractors provide for VR control and on/off control of up to 32 sections of an ISOBUS implement based on location. Yield maps from their combine harvesters can be used to generate application maps that can be displayed on iMonitor2.

Kubota's Smart Agri System (KSAS) includes GEOseed for precision seeding, GEOcontrol for section and VR control, and GEOspread for precision spreading.

Optimization of Machine Operation

The productivity of agricultural machines is expected to improve with automation due to increased efficiency, reliability, precision, and reduced need for human mediation (Burks et al., 2005; Schueller, 2014). Nevertheless, the progress of automation and robotics in agriculture has been slow compared to progress in industrial manufacture, in which well-defined, pre-determined, repetitive tasks are performed in relatively static environments (Hague and Tillett, 1996; Bechar and Vigneault, 2016, 2017). Agricultural operations are conducted in complex and dynamic environments (Kondo and Ting, 1998; Bechar, 2010), requiring more sophisticated robotic systems. This requirement is often suggested as a principal barrier to technology development and application in agriculture (Bechar and Vigneault, 2016; Oberti and Shapiro, 2016). A critical associated factor limiting the application of ARS in agriculture has been a lack of economic justification, but this shortcoming will likely be overcome as allied technologies become more affordable (Bergtold et al., 2009).

Automated technologies have been developed over the last two decades to improve operational efficiency of vehicles, and recent developments have significantly improved various elements of equipment operation (Schueller, 2014). For example, continuously variable transmissions (CVTs) alleviate the process of selecting gear and engine-RPM combinations during vehicle operations (Coffman et al., 2010; Howard et al., 2013). The operator selects a vehicle speed, and the CVT is automatically adjusted to optimize engine

RPM according to power requirements for variable loads, typically improving fuel efficiency and reducing wear on the vehicle. Drive-by-wire steering-control systems can optimize steering to suit vehicle operations such as in headland turns, and they can use additional sensors like gyroscopes to optimize steering performance. On harvesting platforms, grain cleaning parameters such as fan speed and sieve openings can be automatically adjusted when climbing or descending slopes to improve grain quality and minimize losses. Machine vision measurements of grain quality can also be used to automatically adjust these parameters (e.g., Majumdar and Jayas, 2000a,b).

The John Deere infinitely variable transmission (IVT) automates a number of engine and transmission management functions typically required of the vehicle operator. It provides an infinitely variable speed range between zero and maximum. The electronic management system automatically coordinates engine and transmission to provide desired speed under variable loads and operations. Pressing the foot brakes causes the integrated AutoClutch to slow and ultimately stop the vehicle without use of a clutch or gear selection. The IVT includes the PowerZero function, which can hold the vehicle stationary even under load or on an incline. Automating engine and transmission operation within the vehicle lends itself to full vehicle autonomy, simplifying controller requirements and integration with other autonomous systems. Furthermore, John Deere's Active Terrain Adjustment product can automatically adjust fan speed and sieve openings within the grain cleaning functions of a harvester to minimize grain loss when ascending or descending hills.

Case IH and New Holland both offer a range of CVTs, which provide a continuous range of gear ratios. Case IH CVTs also include an Active Stop feature that allows the vehicle to stop and start on hills or accelerate smoothly under load without using a clutch or brake. Case IH CVTs also support new functions like the Feed-rate Control system, which allows a baler to automatically control tractor speed through ISOBUS III to optimize baler performance. The New Holland Ground Speed Management (GSM) system provides CVT-like functionality, automatically coordinating engine and transmission to maintain the operator-selected ground speed under changing loads (Figure 14). New Holland's TerraLock traction management system provides automatic control of 4WD and the front and rear differentials. The system can automatically engage or disengage 4WD based on forward speed and steering angle to improve turning circles and maneuverability.

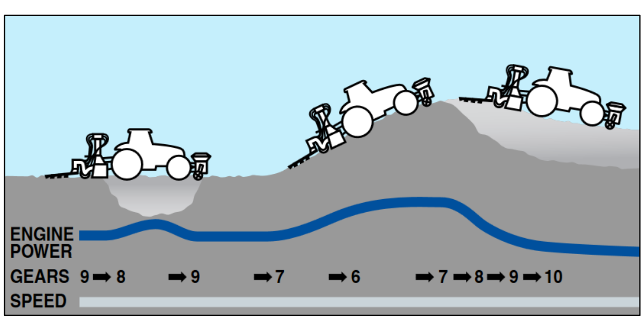


Figure 14. New Holland Ground Speed Management (GSM) system (source: New Holland, http://agriculture1.newholland.com/apac/en-au).

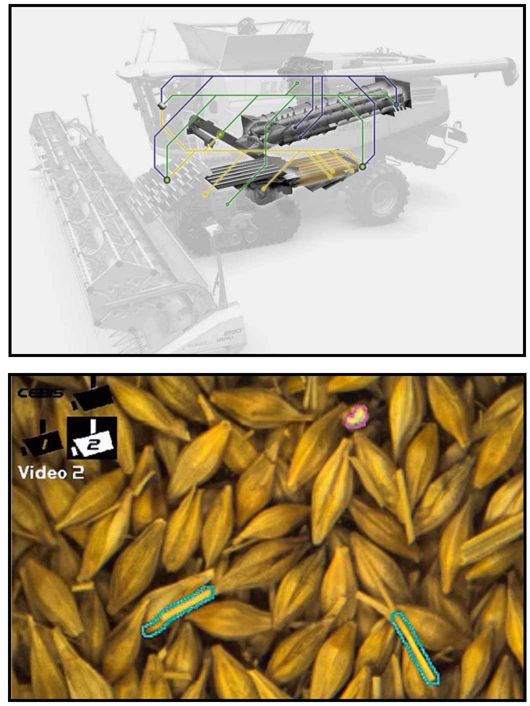


Figure 15. CLAAS CEMOS system and grain imaging sensor (source: CLAAS, http://www.claas.co.uk/products/easy/machine-optimisation/cemos).

CLAAS also offers CVTs on certain tractor models under the transmission technology name CMATIC. Furthermore, CLAAS's CEMOS system includes several additional technologies for optimizing machine performance (Figure 15). The CEMOS DIALOG version provides the operator prompts to guide configuration of the harvester systems for optimal performance. The CEMOS AUTOMATIC version uses machine-vision sensing of grain quality to automatically configure the harvester to optimize grain cleaning with the AUTO CLEANING and AUTO SEPARATION functions. The AUTO SLOPE function optimizes grain flow and separation on slopes by automatically reducing harvester fan speed when ascending hills and increasing it when descending. The CLAAS CRUISE PILOT system automatically controls speed to optimize harvesting operations. This system can monitor multiple harvester parameters including ground speed, engine load, crop volume in the feeder, and grain quality to adjust harvester speed to maintain efficiency under varying loads.

AGCO introduced CVTs on Fendt tractors in 1995. Deutz Fahr also has CVTs on mid-sized tractors, and Kubota offers its Kubota Variable Transmission on its M7 series tractors.

Machinery Coordination

In the transition from manually operated to automated agricultural equipment, semi-automated equipment is common. This type of equipment is similar to operator-controlled equipment but incorporates one or more automated operations while allowing a human operator to intervene in case of risk or failure. Leader-follower technologies are machinery-coordination technologies that tend to be semi-automated, with at least one human operator governing the overall operation. Companies making advances in this technology include AGCO, John Deere, Case IH, and Kinze Manufacturing. AGCO developed leader-follower technology for its Fendt GuideConnect system, which connects two machines by radio and communicates relative position so they can be controlled by one driver. John Deere developed Machine Sync to coordinate multiple machines and operations in the field, allowing coverage maps and guidance lines to be shared between vehicles to improve logistics and efficiency of multiple vehicle operations. For example, during harvest a grain cart can monitor the position and fill status of multiple harvesters to coordinate unloading. During unloading, Machine Sync can be used from the harvester to control the speed and position of the carting tractor to facilitate unloading. Case IH V2V synchronization uses wireless communications to synchronize driving and operation of a harvester and grain cart. When the grain cart enters the “active zone” alongside the harvester, the harvester is able to control the speed, alignment, and direction of the tractor to support on-the-go unloading of the harvester. The Case IH V2V system was demonstrated in 2011, but no commercial products appear to be currently available. Kinze has developed an autonomous grain cart system (designed as an add-on for various tractors) in which the cart follows a combine through the field at a safe distance, allowing the harvester to operate consistently without needing an additional operator for the tractor and cart.

Intellectual property on leader-follower technologies deals with specific capabilities that incrementally increase the level of automation. For example, Deere and Company’s U.S. Patents 8229618 and 8989972 provide for controlling movement of a vehicle by having an operator located alongside the vehicle and multiple sensors inside it. The vehicle moves in a way that maintains the operator at the side of the vehicle as the operator is moving.

Another leader-follower example approaching widespread application involves forage harvesters, which chop plants and unload them onto a transport vehicle that drives alongside. An operator commonly controls the position of an adjustable transfer device (spout) with a hydraulic handle to ensure the crop is unloaded onto the transport vehicle. Automatic spout control based on relative position between the harvester and transport vehicle container is challenging, because determining container position can be difficult, particularly when the transport vehicle must follow behind the harvester. U.S. Patent 9313951 by Carnegie Mellon University and Deere and Company involves an arrangement for controlling spout position including a camera and image processing system, electronic control unit, an actuator for adjusting spout position, and a sensor for determining spout position. The system displays an image of the container and overlays a symbol representing a predetermined location of the container, calculates spout position relative to the predetermined location, receives adjustment inputs and confirmation from the user interface, tracks the container within the image, and controls the actuator to fill the container with crop. It is notable that, as mentioned previously, John Deere, New Holland, and CLAAS have all developed systems to automate the monitoring and control of filling forage transport vehicles.

As automation of agricultural vehicles increases, groups of vehicles will be applied to complete an operation. Rowbot Systems LLC’s U.S. Patents 9265187 and 9288938 describe a robot system comprised of one or more autonomous vehicle platforms that are configured to perform various in-season management tasks. Each vehicle platform includes a base connected to wheels with length, width, and height that allow it to navigate the space between plant rows. Each vehicle can autonomously navigate and avoid other vehicles while performing in-season management tasks. Development of multi-robot systems has mainly focused on three concepts: interaction, guidance, and control architecture. Regarding multi-robot interaction, Deere & Company’s U.S. Patents 9274524 and 9026315 provide a mission planner that maintains line-of-sight contact between multiple coordinated machines and ensures that the machines maintain a specified distance between each other for accurate positioning, safety, and maintaining communication when signals might be blocked by obstacles such as earth, buildings, or vegetation. Providing line-of-sight contact can be accomplished with multiple sensing and communications systems (e.g., GPS, imaging, LIDAR), allowing for mitigation of errors that may be encountered. The line-of-sight mission plan for a work site includes a path plan for each machine, and accounts for topography and loading the path plan for each machine into all machines.

For multi-robot guidance, Deere & Company’s U.S. Patents 8467928 and 8666587 provide a method for processing sensor data from multiple vehicles to control vehicle movement. The concept involves a vehicle with multiple sensors that is unable to obtain needed sensor data, so that sensor data is requested from other vehicles to form alternate sensor data for controlling the vehicle. Deere & Company’s U.S. Patent 8818567 provides a method for processing sensor data, potentially from multiple vehicles, and controlling vehicle movement. Sensors on the vehicle provide information about the operating environment around the vehicle, and when a dynamic condition is observed, the vehicle is controlled accordingly. Sensor data is also received from multiple vehicles in a cooperative group, each having multiple sensors. If one vehicle among the multiple vehicles is unable to obtain needed sensor data from its own sensors, sensor data from other vehicles can be obtained to form alternate sensor data used to control the vehicle.

A multi-robot control architecture must enable work in a dynamic environment, accounting for changes in the configuration and capabilities of multiple robots, analytically assigning roles, and coordinating and synchronizing robot actions. This type of control system involves exchanging information among robots, so inter-robot communication is critical to success. The control system arbitrates and prioritizes information available from different sensors and converts sensor data into desirable actions. Most research in multi-

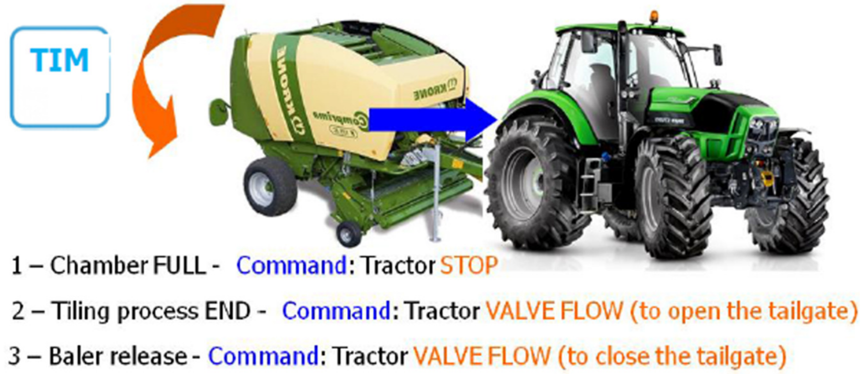


Figure 16. Commands from the implement to the tractor for a Krone baler (source: www.europeanlandowners.org).

robot control systems has involved intelligent agents and self-organizing systems, artificial intelligence (AI) and distributed AI in coordinated systems, negotiation and problem solving, and cooperating agents and aggregation. The development of complexity theory is a fairly recent addition to this body of work. By decentralizing numerous functions in a distributed architecture model, groups of robots can learn together, make group decisions together (cooperatively and competitively), negotiate and solve problems together, congregate together in various subsets, and reconfigure in non-overlapping subgroups. Using these unique approaches, agricultural robots can form and reform into various configurations of groups in a self-organized way, interacting with each other and with the environment in order to achieve production goals.

CNH's U.S. Patent 9527211 involves a five-layer individual robot control architecture that accounts for the level of homogeneity of the robot group, level of cooperation among the robots, complexity of inter-robot communication, and the assigned role of each robot during cooperative task execution. A key component of the architecture is the global information module, which receives as inputs information local to each robot as well as global information from other robots and outputs role assignments and messages required for inter-robot coordination. U.S. Patents 8112176, 6904335, and 7343222 (by Neal Solomon and Solomon Research LLC) involve a seven-layer control architecture that accounts for computation and electrical and mechanical hardware of each robot; linking the robots together with wireless communications; a distributed computing model for memory, database, and analysis functions; an artificial neural network (ANN) for distributed artificial intelligence; an evolutionary ANN for adaptive group learning; an operating system; and specific functional applications.

Another consideration in machinery coordination is the interaction between tractors and implements. John Deere's Tractor Implement Automation (TIA) feature allows for automated control of tractor operation by an implement. John Deere has developed protocols that allow safe control of tractor parameters from certified implements. Typically the implement can control tractor speed, accelerating, stopping (with the IVT transmission), hydraulics, and the PTO. On certain tractor models CNH also offers capabilities for an attached implement to control tractor speed, hitch position, and PTO speed through an ISOBUS III connection. CLAAS's ICT (Implement Controls Tractor) software also enables an implement to control the pulling tractor. In SDF's Tractor Implement Management (TIM) system, again the implement controls the tractor. As is typical for all these manufacturers, the SDF TIM is implemented with products like the Krone baler (Figure 16), where variable tractor-speed control and frequent starting and stopping are needed during the baling process. In these situations the implement and tractor communicate through ISOBUS III and proprietary messages that allow the implement to request changes in tractor operating parameters (von Hoyningen-Huene and Baldinger, 2010). Sensors can also be mounted at the front of the tractor to measure the swath width to provide for improved speed control (von Hoyningen-Huene and Baldinger, 2010). The Kubota M7-1 Series (http://www.kubota.com.au/products/tractors/m7-series/) has an ISOBUS monitor that allows for monitoring and adjustment of ISOBUS connector-compatible implements (Figure 17).

SDF has also released an automatic hitch coupling system developed in partnership with Topcon (Figure 18). A pair of markers on the implement are detected by a camera at the rear of the tractor, which then calculates the distance and orientation of the implement from the tractor and takes control of maneuvering the tractor to the implement.

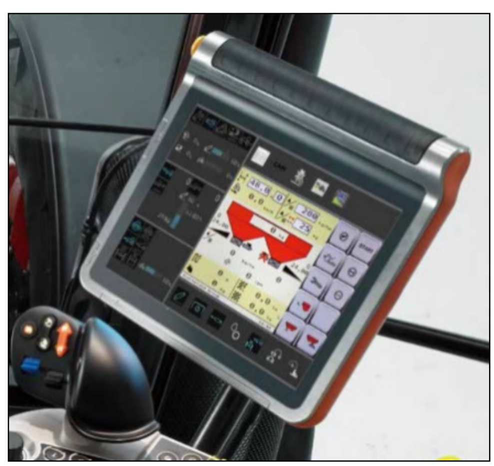


Figure 17. Kubota ISOBUS monitor (source: Kubota Precision drill PP1000 Series, http://www.kubota.com.au/product/pp1000-series/).

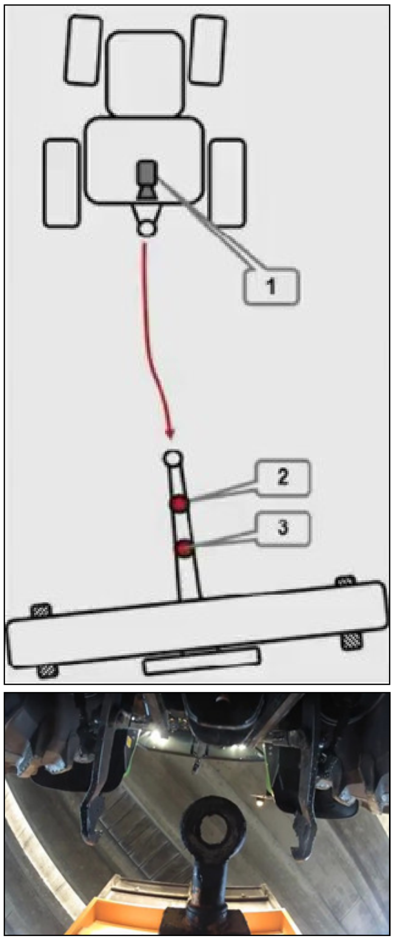


Figure 18. Automatic hitch coupling system (source: Deutz Fahr, https://www.youtube.com/watch?v=hrjcJWPpV24).

Machinery Communication

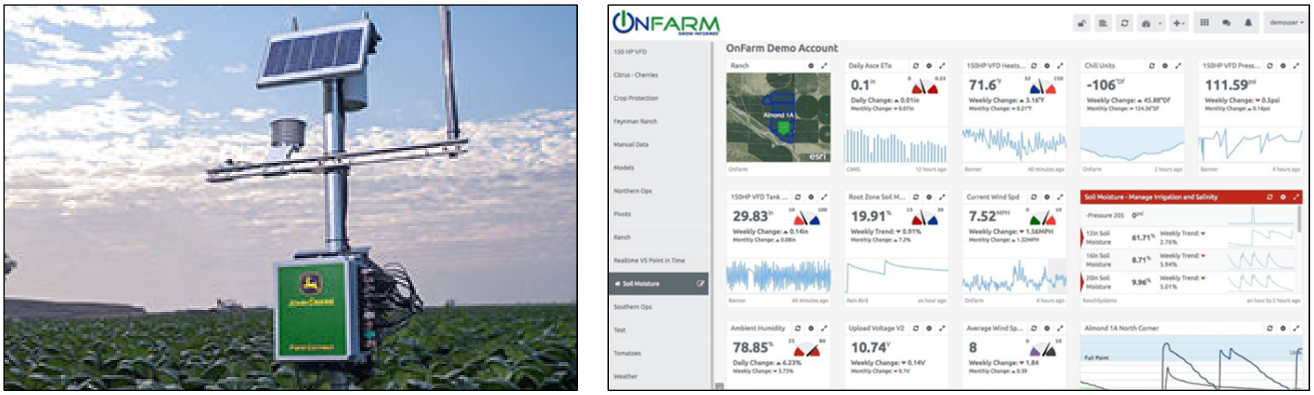
Farmers commonly use tractors of one brand with implements from another, and if they have incompatible electronic systems, each tractor and implement combination would require an individual connection terminal and data format translator. Thus, standardized connectors, data formats, and communication protocols are required for equipment from different agricultural machinery manufacturers to be compatible with each other. The principal effort aimed at standardizing farm equipment that creates and handles farm data is ISO Standard 11783, "Tractors and machinery for agriculture and forestry — Serial control and communications data network," also known as ISOBUS (Oksanen et al., 2005; Lee et al., 2017). The primary goal of ISOBUS is to standardize communication between tractors and implements and promote compatibility of data transfer between mobile systems and office software used on the farm. Agricultural equipment manufacturers worldwide have generally agreed on ISOBUS as the universal protocol for electronic communication between implements, tractors, and computers.

A secondary but critical effort to standardize farm equipment that creates and handles farm data is the work of AEF (Agricultural Electronics Foundation), which was founded in 2008 by seven agricultural equipment manufacturers and two associations, and currently has over 150 members worldwide. As manufacturers began to implement ISOBUS, it became clear that not all compatibility issues were solved (Katayama et al., 2005). The main objectives of AEF are, in summary, to define guidelines for implementing ISOBUS standards, to coordinate improvements in ISOBUS, to manage certification tests, to coordinate international cooperation in agricultural electronics, to build partnerships between manufacturers to benefit end customers, and to organize training and marketing activities for ISOBUS.

A modern ISOBUS system consists of various components, including the vehicle, the connection terminal, and the implement. Critical to overall system compatibility is that the Universal Terminal and implement are capable of performing separately and together. To increase user understanding of compatibility, AEF has defined ISOBUS functionalities that are now the basis for certification of ISOBUS products. Information about which functionalities are supported by an ISOBUS product or combination is provided in the new AEF ISOBUS Conformance Test, including an independent certification (https://www.aef-online.org/products/conformance-test.html). In order to manage the process of ISOBUS certification, the AEF developed an automated conformance test for its members and the four AEF-accredited test laboratories in Italy, Germany (two), and the U.S. The Conformance Test at these labs involves testing of ISOBUS products against AEF Functionalities. When a product has passed the Conformance Test, these laboratories may publish the AEF-certified component into the AEF Database. The aim is a clearer description of the effectiveness of a manufacturer-independent ISOBUS system and increased operational reliability for the farmer.

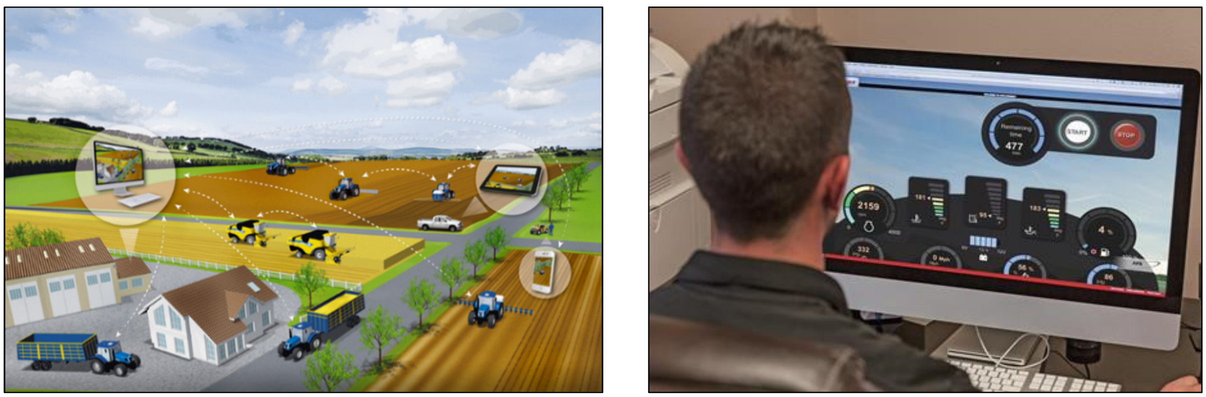
More sophisticated autonomy and decision support are dependent on development of robust in-field communication and data infrastructure (Yan et al., 2013). Tractor manufacturers appear to be developing their own telematics solutions, and it is not immediately clear how open these communication platforms are and how well different systems interact. The recent emergence of cloud-based farm management platforms such as OnFarm (http://www.onfarm.com/) that aim to integrate data from a number of sensors, vehicles, and weather and other data sources, across multiple manufacturers and also to include decision support systems, could provide a more versatile data infrastructure in the future.

John Deere has developed a telematics solution, JDLink, that uses mobile communication (3G/4G) or a satellite option. The system provides real-time information on vehicle locations, diagnostics, and performance to assist with the management and logistics of farm operations. The JDLink Modular Telematics Gateway (MTG) can also be used for communication in Machine Sync and Mobile RTK applications. In addition, John Deere has the Field Connect (Figure 19) system, which provides a soil moisture and environmental monitoring solution. John Deere is also a partner of OnFarm Ready, a new cloud-based farm data management system that automatically collects data from sensors and devices from several manufacturers and provides data visualization and built-in crop and disease models for decision support.



(a) **(b)**

Figure 19. (a): John Deere Field Connect (www.deere.com), and (b): OnFarm sensor dashboard (www.onfarm.com).



(a) **(b)**

Figure 20. CNH Connect telematics,(a): architecture, and (b): live dashboard display (source: www.caseih.com).

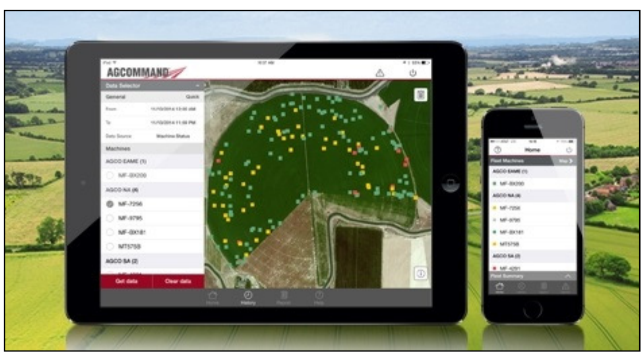


Figure 21. AgCommandapp (source: www.agcotechnologies.com).

Case IH's AFS and New Holland's PLM systems include the Connect telematics component, which facilitates functions such as fleet management and logistics, two-way data transfer (e.g., prescription and application maps), real-time vehicle and implement monitoring (e.g., dashboards), and RTK corrections. Connect communications are via the cellular network with the DCM-300 modem, which provides both Wi-Fi and 3G connectivity. The system has time limits on real-time data streaming but provides a fast one-minute data update rate (Figure 20).

CLAAS's TELEMATICS was one of the first of such solutions in the industry. The development of TELEMATICS on Implements (TONI) has enabled implement data to be captured from ISOBUS implements to assist with evaluation and optimization of implement performance.

AgCommand is a remote monitoring option within AGCO's Fuse Technologies for Challenger, Massey Ferguson, and Valtra tractors, and some non-AGCO vehicles. AgCommand collects machine performance data and GPS location every 10 seconds and transmits them to a PC or mobile device. AgCommand can generate geo-fence alerts, efficiency reports, vehicle traces, and show parameters from ISOBUS (Figure 21). The Fuse Technologies Go-Task app allows wireless transfer of farm job data between C1000, C2100, and C3000 model machinery and AGCO-supported Farm Management Information Software (FMIS) like BASF and Helm. Prior to AgCommand, Fendt VarioDoc provided farm job management by recording tractor and implement parameters and GPS data to the VarioTerminal. Data synchronization between the terminal and a PC was achieved via Bluetooth or cellular network when the tractor was in range (Figure 22). VarioDoc on the terminal presented field record data in ISOXML format, which enabled data exchange with various field record systems in Europe (e.g., BASF, Helm).

The SDF iMonitor has a USB port for transfer of completed work data. Desktop software for Agrosky enables importing of field boundaries to the tractor, viewing of job data (e.g., client, field size, fuel consumption), and creation of reports. Use of the ISOXML standard enables field jobs to be planned and evaluated with numerous field records (Figure 23).

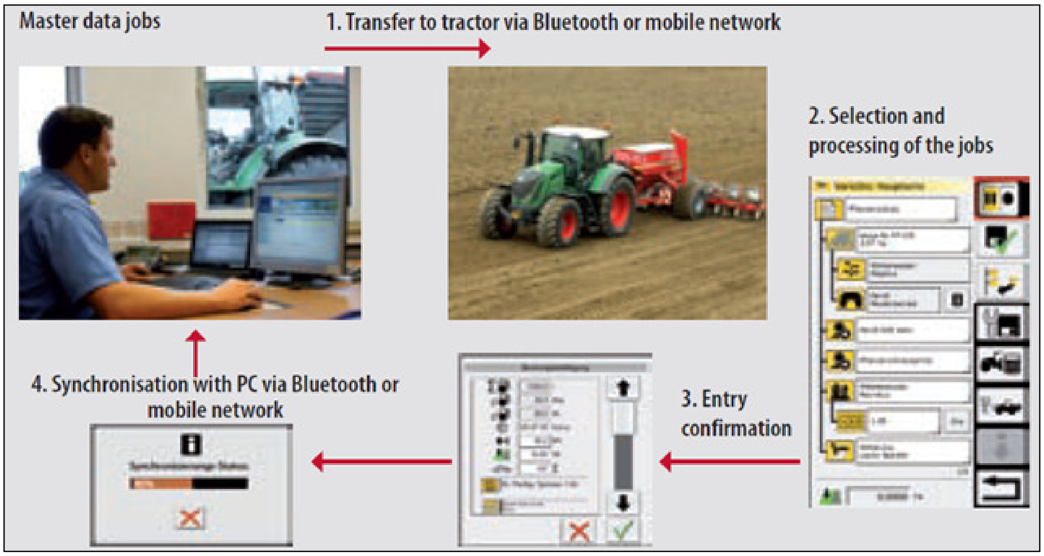


Figure 22. Data management with Variotronic (source: https://www.fendt.com/uk/15599.html).

Kubota has a partnership with Nippon Telegraph and Telephone (NTT) for farm sensing and site-specific management, which is currently in the research and development phase. The expectation is that NTT will provide satellite-positioning as well as AI to predict weather and crop yields. A new service that will use sensors positioned around rice paddies to measure temperature and water levels has been reported. Field job information and directions are to be sent to farm equipment via internet.

Conclusions

Automatic guidance and steering control enable agricultural vehicles to be positioned precisely in the field or relative to the crop with minimal driver interaction. These are fairly mature technologies that all major equipment manufacturers offer, and systems are also available from companies that specialize in tractor guidance. Most systems compensate for vehicle roll, pitch, and yaw to determine accurate ground positions, and most also offer automatic steering integrated with electro-hydraulic steering control.

Automatic implement guidance controls the steering of the tractor and/or implement to accurately position the implement rather than simply the tractor. Some major manufacturers (John Deere, CNH, and AGCO) and a few specialized companies appear to have the only available products in this area.

Headland management involves automatically performing a sequence of tasks to automate turning at the end of a field and aligning precisely for the next pass. Again, some major manufacturers (John Deere, CNH, and CLAAS) appear to have the only available products in this area.

Sensing for perception involves gathering information on surroundings. Commercial technologies to improve vehicle operators' situational awareness are fairly advanced, with products available from AGCO and SDF appearing to be the most advanced. John Deere, CNH, and CLAAS are apparently the most advanced in detecting proximity to the crop.

Sensing for VR technologies involves collecting, analyzing, and utilizing information on field variability so that PA management strategies can be applied. Grain yield and moisture monitoring is standard on many harvesters, and some unique products involve sensing of various crop quality characteristics. Most manufacturers offer section control and VR for crop inputs, but some have more established and comprehensive product lines.

Optimizing machine operation involves sensors and electromechanical systems to maximize machine efficiency. Most manufacturers have some type of CVT available on specific vehicle models, enabling efficient coordination of transmission and engine speed. A number of commercial sensing products are used to automate process monitoring to maximize product quality and efficiency during harvest.

Machinery coordination (e.g., for multiple robots in a field) will require development in machine-to-machine communication, telematics and infield communication, and data infrastructure for more sophisticated autonomy and decision support. Some leader-follower technologies are in the process of being commercialized, while multi-robot systems are largely conceptual. Maturing open-data standards (ISOBUS, etc.) will benefit further automation in terms of communication between vehicles and implements as well as with farm management software.

Several telematics solutions have been developed for machinery communication, but these systems are unlikely to be directly applicable to fully autonomous vehicles, because data bandwidth and reliability requirements will likely exceed those necessary for fleet management and logistics support. Limited development has occurred in machine-to-machine communications, although the major tractor manufacturers are engaged in ongoing efforts. Several telematics and infield communication solutions have been developed by equipment manufacturers to enable automated in-field management and monitoring of vehicle performance (Stafford, 2000), but it is not clear how open these communication platforms are nor how well multiple systems interact.

Figure 23. Job planning on iMonitor and on desktop in the office (source: AGROSKY, http://www.deutz-fahr.com/en-gb/search-results/1220-agrosky).

The last two decades have seen great progress in multiple technologies associated with equipment automation, and the major manufacturers and some specialized companies are bringing these technologies together in ways that provide major improvements to farm operations. This article is a brief snapshot of the current status of some major technologies, and it is clear that the future is very bright for autonomous vehicles in agriculture.

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