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A review of the state of the art in agricultural automation. Part II: On-farm agricultural communications and connectivity

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ABSTRACT. *Farming has recently experienced increasing automation, and further development is likely to include systems of multiple robots. Such systems will require development in machine-to-machine communication, telematics and infield communication, and data infrastructure for more sophisticated autonomy and decision support. Machine-to-machine communication technologies involve direct radio links between vehicles and are used to improve logistics and efficiency of multiple vehicle operation. Additionally, this type of communication enables the sharing of coverage maps and guidance lines to coordinate operations such as seeding, nutrient application and spraying, and grain unloading during harvest. Within machine-to-machine communication there are two major groupings: leader-follower technologies, and multi-robot systems. Within the multi-robot systems grouping are three sub-groupings: multi-robot interaction, multi-robot guidance, and control architecture. A number of telematics and infield communication solutions have been developed by tractor manufacturers, but it is unclear how open these communication platforms are and how well multiple systems are able to interact. Recent emergence of cloud-based farm management platforms (e.g., OnFarm®), which aim to integrate data from multiple sensors, vehicles, weather, and other sources across multiple manufacturers, and also to include decision support systems, could provide a more versatile data infrastructure in the future. This paper reviews and discusses the current state of communication systems, including patents, and the required improvements for universal commercial viability.*

Keywords. *Cloud-based farm management platforms, In-field communication, Leader-follower technologies, Multi-robot systems, Sensor fusion, Telematics.*

Introduction

This paper, the second in a series of four, reviews and discusses the current state of communication systems, and the required improvements for universal commercial viability. The other three papers in this series (Antille et al., 2018; Baillie et al., 2018a-b) critically review commercially-available sensor-based nitrogen management technologies, sensing technologies for optimization of machine operations and farm inputs, and both early and recent developments in agricultural machinery navigation, including tractor guidance and steering control systems, machine operation and path planning systems.

Machine-to-Machine Communications

Tractor machine-to-machine communication technologies involve direct radio links between vehicles and are used to improve logistics and efficiency of multiple vehicle operation. Machine-to-machine communication enables the sharing of coverage maps and guidance lines to coordinate operations such as seeding, nutrient application and spraying. It can be used to coordinate functions such as grain unloading during harvest, and supports leader-follower technologies where a single operator can control the speed and position of following vehicles.

Within machine-to-machine communications there are two major groupings; namely: (1) leader-follower technologies, and (2) multi-robot systems. Some leader-follower technologies are in the process of being commercialized, while the multi-robot systems are largely conceptual. Within the multi-robot systems grouping there are three sub-groupings; namely: (1) multi-robot interaction, (2) multi-robot guidance, and (3) control architecture. These technology groups are discussed in the following sections.

Types of Machine-to-Machine Communications

Leader-Follower Technologies

As automated equipment becomes increasingly prevalent in agriculture, new robotic equipment is often different from the operator-controlled equipment it is replacing, and does not allow for an operator to be present or take over vehicle operation. Semi-automated equipment, which is similar to previous operator-controlled equipment, but incorporates one or more automated operations, is more commonly used as it allows a human operator to intervene in case of risk or failure. It is likely that machine-to-machine communications is mostly applicable in the short-term to leader-follower type autonomy as full vehicle autonomy may require broader communications infrastructure (Keshmiri and Payandeh, 2016).

Deere & Co.'s US Patents 8229618 and 8989972 provides for controlling movement of a vehicle by having an operator located at a side of the vehicle along with multiple sensors located in the vehicle. The vehicle moves in a way that maintains the operator at the side of the vehicle while the operator is moving.

Forage harvesters 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.

US Patent 9313951 by Carnegie Mellon University and Deere & Co. 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.

Multi-Robot Systens

As automation of agricultural vehicles increases, groups of vehicles will be applied to complete an operation. A system to mitigate operational errors in navigation of multiple vehicles is needed. Deere & Co.'s US Patents 9274524 and 9026315 provide a mission planner that maintains line-of-sight (LoS) contact between multiple coordinated machines and ensures that the machines maintain a specified distance between each other for (1) accurate positioning, (2) safety, or (3) maintaining communication when signals might be blocked by earth, buildings, vegetation, or other obstacles.. Providing LoS contact can be accomplished with multiple sensing and communications system (e.g., GPS, imaging, LIDAR), allowing for mitigation of errors that may be encountered. The LoS 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.

As multiple vehicles are applied to complete an operation, it is advantageous for them to share sensor data among them. A system to use multi-vehicle data to mitigate operational errors in vehicle navigation is needed. Deere & Co.'s US Patents 8467928 and 8666587 provides a method for processing sensor data from multiple vehicles to control vehicle movement. It 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.

As sensors become relied upon to control agricultural equipment, it is important that sensor data from multiple vehicles in a group be available to all vehicles in such group. Deere & Co.'s US 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.

Multi-Robot Control Architecture

If one human could manage and monitor multiple robots, labor costs would be reduced and the farm productivity would be increased. However, eliminating the driver from each machine requires that sensors be added so that the robot can function in an unpredictable agricultural environment. It is also critical that a robust and fault tolerant control architecture guide robot operation to ensure functionality, safety, and efficiency. In multi-robot systems, control architecture becomes increasingly challenging as the number of robots increases. The control system must 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 between 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.

Blue Leaf and CNH's US Patent 9527211 describe an invention that involves a five-layer individual robot control architecture used to interpret and translate sensor information into useful robot actions. The architecture focuses on the aspects of homogeneity and heterogeneity, level of cooperation, type of inter-robot communication, and the role assignment 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.

Control Architecture – Multi-Robot Interaction

Farming has recently experienced increasing automation, and further development is likely to include systems of multiple robots. Most research in multi-robot control systems has involved: (1) intelligent agents and self-organizing systems, (2) artificial intelligence (AI) and distributed AI (DAI) in coordinated systems, (3) negotiation and problem solving, and (4) cooperating agents and aggregation. The development of complexity theory is a fairly recent addition to this body of work. The question the research has sought to answer is, how can an intelligent multi-robot system for optimal adaptation to dynamic environments can be designed?

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.

US Patents 8112176, 6904335, and 7343222 (by Neal Solomon and Solomon Research LLC) describe systems for multi-robot behavior by applying AI algorithms along with advanced robotic electronics and mechanics. Layers of the multi-robot system include: (1) the computation and electrical and mechanical hardware of each robot, (2) a hardware network layer that links the robots together with wireless communications, (3) a meta-computing layer that performs memory, database, and analysis functions in a node-to-node distributed computing model, (4) an omni-nodal artificial neural network (ANN) layer for DAI, (5) an evolutionary ANN layer for adaptive group learning, (6) an operating system layer, and (7) a layer for specific functional applications.

Control Architecture – Scheduling Tasks

Once small agricultural robots are devised to be capable of in-season management tasks, a system is needed in which several small autonomous devices can work cooperatively and efficiently together to complete tasks in multiple agricultural fields in a reasonable time. Rowbot Systems LLC's US 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 multiple ground contacting wheels and has a length, width, and height that allow it to navigate the space between plant rows. Each vehicle platform can autonomously navigate and avoid other vehicle platforms while performing in-season management tasks.

Machine-to-Machine Communications: Commercial Products

John Deere Machine Sync has been developed 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 vehicle 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 (John Deere, https://www.deere.com.au/en/technology-products/precision-ag-technology/guidance/john-deere-machine-sync/).

Tractor Implement Automation (TIA) allows for automated (independent) control of the tractor operation by the implement. The implement and tractor communicate using ISOBUS Class 3 and additional proprietary messages that allow the implement to request changes in tractor operating parameters (von Hoyningen-Huene and Baldinger, 2010). John Deere has developed the protocols (built on the ISOBUS Standard) that allow safe control of tractor parameters from certified implements. The implement is able to control tractor functions such as speed, accelerating, stopping (with the IVT transmission), hydraulics and the PTO. The system is typically used in baling applications where variable tractor speed control and frequent starting and stopping are needed during the baling process. Sensors can also be mounted at the front of the tractor to measure the swath width to inform speed control (von Hoyningen-Huene and Baldinger, 2010).

Case IH V2V synchronization uses wireless communications to synchronize driving and operation of a harvester and grain carting tractor. 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 (CNH Industrial, 2010). The Case IH V2V system was demonstrated in 2011, however it appears no commercial products are currently available. There appears to be no commercial products from CLAAS that demonstrate machine to machine communications.

The iMonitor2–SDF (http://www.sdfgroup.com/en/technologies/imonitor2) provides an interface for ISOBUS implements. Implements include section and variable rate control. Same Deutz Fahr is one of the core members of the Agricultural Industry Electronics Foundation (https://www.aef-online.org/home.html), which is a body that aims to resolve ISOBUS compatibility problems. In Same Deutz Fahr's Tractor Implement Management (TIM), the implement takes command. TIM can be implemented with products like the Krone baler (Figure 1).

Same Deutz Fahr has released an automatic hitch coupling system. A pair of markers installed on the implement is 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. This product was developed in partnership with Topcon (Figure 2).

The Kubota M7-1 Series (http://www.kubota.com.au/products/tractors/m7-series/) has an ISOBUS monitor, which allows for monitoring and adjustment of any ISOBUS connector-compatible implements (Figure 3). However, no information has been found about leader-follower technology or multiple machine awareness.

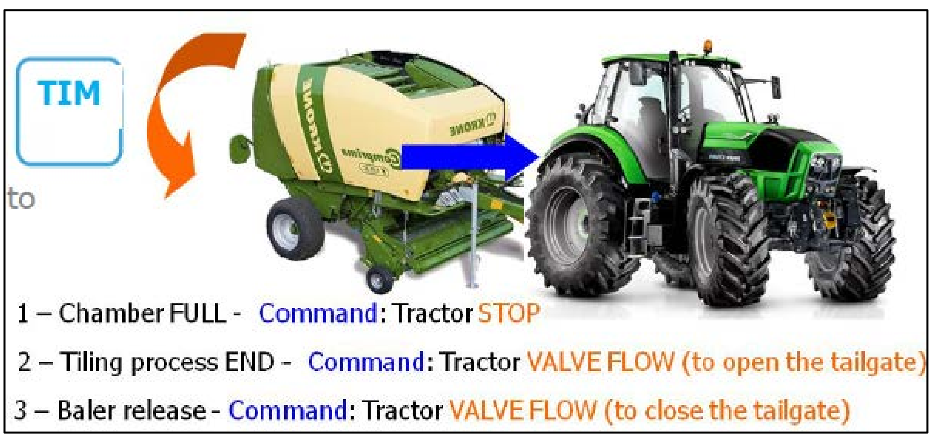

Figure 1. Commands from the implement to the tractor for a Krone baler (Source: www.europeanlandowners.org).

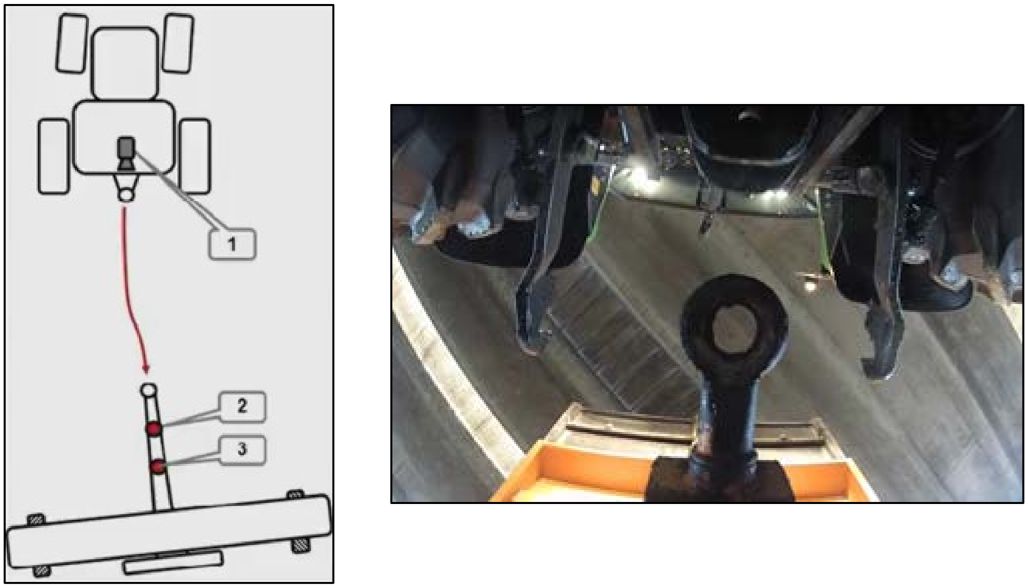

Figure 2. Automatic hitch coupling system (Source: Deutz Fahr, https://www.youtube.com/watch?v=hrjcJWPpV24).

Figure 3. Kubota ISOBUS monitor (Source: Kubota Precision drill PP1000 Series, http://www.kubota.com.au/product/pp1000-series/).

Machine-to-Machine Communications: Communications Standards

Standardized connectors, data formats and communication protocols are required for equipment from different agricultural machinery manufacturers to be compatible with each other. ISOBUS and the Agricultural Electronics Foundation are two efforts for standardization of agricultural machinery which will be increasingly important for automation of farming operations with different pieces of mahcinery and equipment.

ISOBUS Standard

The principal effort aimed at standardizing farm equipment that creates and handles farm data is the *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).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. The primary goal of ISOBUS is thus to standardize the communication that takes place between tractors and implements while ensuring full compatibility of data transfer between the mobile systems and the office software used on the farm. Agricultural equipment manufacturers worldwide have agreed on ISOBUS as the universal protocol for electronic communication between implements, tractors, and computers.

Agricultural Electronics Foundation

A secondary, but critical, effort to standardize farm equipment that creates and handles farm data is the work of the Agricultural Electronics Foundation (AEF, https://www.aef-online.org/home.html), 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, thus, as follows:

- To define guidelines for implementation of electronic standards in a structured and aligned way, in particular with first priority for ISOBUS,
- To coordinate technical improvements in ISOBUS, including management and enhancement of certification tests,
- To coordinate international cooperation in agricultural electronics technology,
- To establish and continue the international development and expansion of electronic technology as well as implementation of electronic standards,
- To build synergistic partnerships between agricultural equipment manufacturers for the benefit of end-customers, and
- To organize certification support, training, workshops, marketing activities and consulting relating to any agricultural electronics international standards.

A modern ISOBUS system consists of various components, including the tractor, the connection terminal, and the implement .It is critical to the overall system compatibility that the Universal Terminal and the implement are capable of performing separately and together. To increase user understanding of compatibility, the AEF have defined ISOBUS functionalities, which are now the basis for the 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 USA.

The Conformance Test involves testing by these labs 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 (www.aef-isobus-database.org).The aim is a clearer description of the effectiveness of a manufacturer-independent ISOBUS system and increased operational reliability for the farmer.

Telematics and Infield Communications

More sophisticated autonomy and decision support is dependent on the development of robust in field communication and data infrastructure (Yan et al., 2013). Tractor manufacturers appear to be developing their own telematics solutions, but it is not immediately clear how open these communication platforms are and how well multiple systems can 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, weather, and other sources across multiple manufacturers and also to include decision support systems, could provide a more versatile data infrastructure in the future.

Telematics and Infield Communications: Commercial Products

John Deere has developed a telematics solution (JDLink™, https://www.deere.com.au/en/technology-products/precision-ag-technology/data-management/jdlink/) using mobile communication (3G/4G) or satellite option. The system provides real time information on vehicle locations, diagnostics and performance information to assist management and logistics of farm operations. The JDLink™ Modular Telematics Gateway (MTG) can also now be used for communication in the John Deere Machine Sync and Mobile RTK applications. John Deere also has the Field Connect™ (Figure 4) system (https://www.deere.com/en/technology-products/precision-ag-technology/field-and-water-management/field-connect/) that provides a soil moisture and environmental monitoring solution. John Deere is also an OnFarm Ready™ partner, which is a new cloud-based farm data management collection and management system that automatically collects data from many sensors and devices (from many manufacturers), provides data management and visualization, and built-in crop and disease models for decision support.

Case IH's Advanced Farming Systems (AFS) and New Holland's Precision Land Management (PLM) systems include the Connect™ telematics component, which provides telematics for 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.

Communications for Connect™ telematics is via the mobile phone network with the DCM-300 modem, which provides both Wi-Fi and 3G connectivity. The system has time limits on real time data streaming, and otherwise provides a one-minute data update rate, which is the fastest update rate in the industry (Figure 5).

CLAAS has developed telematics products (TELEMATICS) and was one of the first manufacturers to develop and release a telematics solution. The development of TELEMATICS on Implements (TONI) allowed implement data to be captured from compatible ISOBUS implements so as to assist in the evaluation and optimization of implement performance.

AgCommand™ in AGCO’s Fuse® Technologies is a remote monitoring option for Challenger, Massey Ferguson and Valtra tractors, and is not limited to AGCO vehicles. AgCommand™ collects machine performance data and GPS location every 10 seconds, which is transmitted to a PC or mobile device (source: MasseyFerguson.com.au). AgCommand™ can generate geo-fence alerts, efficiency reports, vehicle traces, and show parameters from the CANBUS (Figure 6).

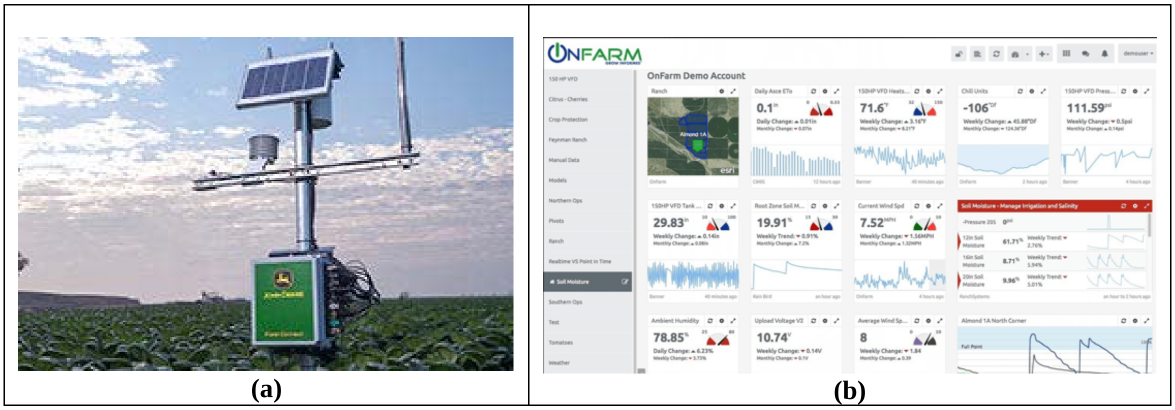

Figure 4. (a): John Deere Field Connect™ (www.deere.com), and (b): OnFarm® sensor dashboard (www.onfarm.com).

Figure 5. CNH Connect™ telematics,(a): architecture, and (b): live dashboard display (Source: www.caseih.com).

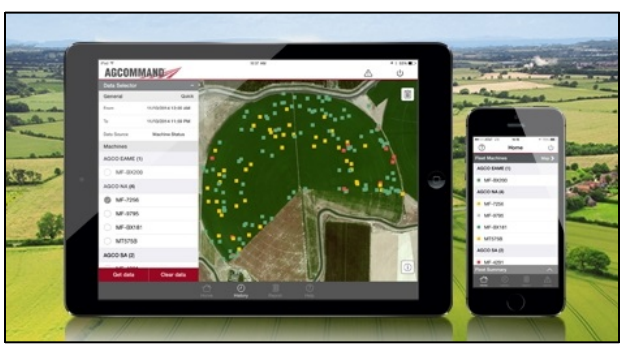

Figure 6. AgCommand™app (Source: www.agcotechnologies.com).

The Fuse® Technologies Go-Task™ app (www.agtechnologies.com) allows wireless transfer of farm job data between machinery and AGCO-supported Farm Management Information Software (FMIS). A range of FMIS options are available (e.g., BASF, Helm), presumably using ISOXML data format. AGCO machinery with C1000, C2100 or C3000 model terminals are compatible.

Prior to AgCommand™, Fendt VarioDoc provided farm job management by recording tractor and implement parameters and GPS to the VarioTerminal. Data synchronization between the terminal and a PC was achieved via Bluetooth or the mobile network, whenever the tractor was in range (Figure 7). 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).

No information was found about telematics from Same Deutz Fahr machines back to the office. However, Same Deutz Fahr's 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 8).

Kubota has a partnership with Nippon Telegraph and Telephone (NTT) for farm sensing and site-specific management, which is currently at a research and development phase. NTT will provide GPS-technology and artificial intelligence systems to predict the weather and crop yields. A report in the Nikkei Asian Review describes that a new service will use sensors positioned around rice paddies to measure temperature and water levels. Sensor data and drone imagery of crops will be used to analyze plant growth. The system can then decide timing of fertilizer application and harvest for each paddy, and send job information and directions to farm equipment via the internet.

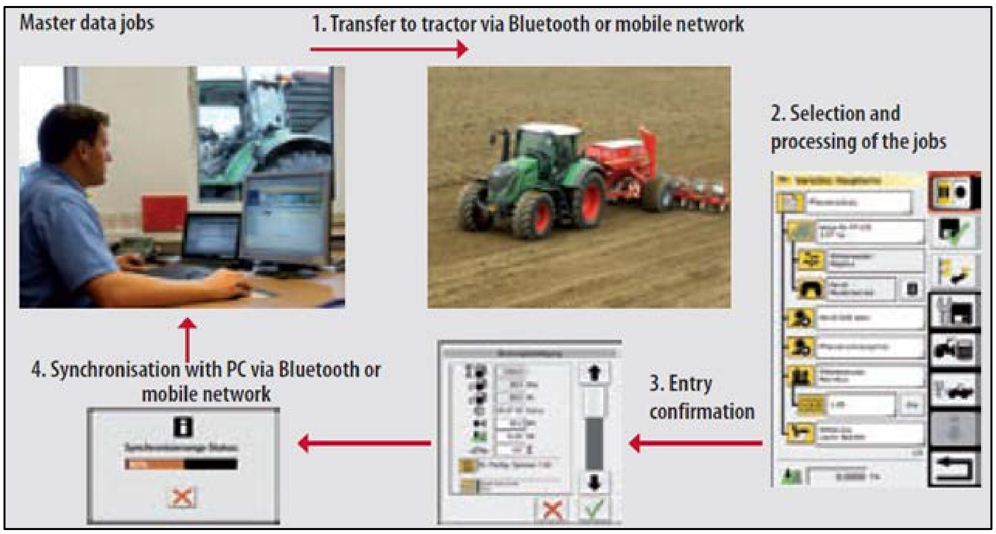

Figure 7. Data management with Variotronic(Source: https://www.fendt.com/uk/15599.html).

Figure 8. Job planning on iMonitor and on desktop in the office (Source: AGROSKY, http://www.deutz-fahr.com/en-gb/search-results/1220-agrosky).

Conclusions

Farming has recently experienced increasing automation, and further development will continue to include systems of multiple robots. Such systems will require development in machine-to-machine communication, telematics and infield communication, and data infrastructure for more sophisticated autonomy and decision support. Several telematics and infield communication solutions have been developed by tractor manufacturers, but it is not clear how open these communication platforms are and how well multiple systems can interact. Recent emergence of cloud-based farm management platforms, which aim to integrate data from multiple sources and across multiple manufacturers, including also decision support systems, could provide a more versatile data infrastructure in the future.

There has been only limited product development in machine-to-machine communications. The only commercial product appears to be the John Deere Machine Sync. However, there are a number of ongoing research and development efforts in this field by the major tractor manufacturers. It is likely that machine-to-machine communications is mostly applicable in the short-term to leader-follower type autonomy as full vehicle autonomy may require broader communications infrastructure.

Several telematics solutions have been developed by the manufacturers, but it is unlikely that these systems will be directly applicable to autonomous vehicles where the requirements for data bandwidth and reliability will likely exceed those necessary for fleet management and logistics support. The use of open data standards for communication between the vehicle (implement) and management software, however, will be beneficial (e.g., ISO-XML), and it appears that most, if not all manufacturers, will subscribe to these standards.

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Reference to commercial names or products in this work is solely for the purpose of providing accurate information and does not represent endorsement or otherwise by the authors or their organizations. The graphical information presented in this review is fully credited to the original sources.

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