Trends in the Automation of Agricultural Field Machinery

by: Scott A. Shearer[1], Santosh K. Pitla[2], Joe D. Luck[3]
Biosystems and Agricultural Engineering, University of Kentucky, Lexington, USA

1.   Introduction

Trends in the evolution and development of agricultural field machinery are often shaped by the technological development in other sectors of the world's economy such as defense and transportation. For example, without defense-related concerns over locating troop movements or guiding ordinates, it is doubtful that the civilian sector alone would have provided enough justification for space-based radio navigation or Global Navigation Satellite Systems (GNSS). Similarly, the truck, bus and automotive industries have contributed significantly to the deployment of micro-controllers in the off-road equipment sectors. Perhaps the single greatest factor in the adoption and deployment of microcontrollers is controller area networks (CAN), enabling the integrated control of multiple machine functions.

The purpose of this manuscript is to examine a number of controlling factors relating to the removal of man as a control element in agricultural field production systems. Many forces external to the industry will shape how automation develops and is adopted by producers. The objective of this manuscript are multifold; a brief review of historical trends in field machinery, a look at the physical limitations the industry faces, brief treatment of machine life and obsolescence, an extensive treatment of evolving automation technologies, and speculation on what trends we may see in the future. To a large extent the first three are an abbreviated summary of how the industry progressed to where it is today while the accuracy of the latter section will be borne out by similar reviews in the future.

2.   Historical Trends in Field Machinery

Beginning with the development of U.S. agriculture over 200 years ago man learned to harness animal power. Man as a power source only produces a mere 0.1 Hp (0.075 kW) over a sustained period of time. However, by harnessing the power of oxen and later draft horses, man found he could be more productive, effectively multiplying his effort six to seven fold or more. Along with the development of the external combustion engine can the ability to achieve a ten or more fold increase in productivity. With the ability to harness animal and heat engine power sources, man was transitioning from a power sources to a control element, the overseer of how power was acquired and utilized to accomplish field activities. Today with modern agricultural tractors man is in control of 600 Hp (450 kW) or more.

However, man as a control element is fallible. Further, the increased use of hired labor has separated and confused the control process. While the farm owners of the past were in the field check on the quality and productivity of every aspect of cultural practices, today, the decision making process is being moved from the field to the farm office, further complicating the

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[1]   *Professor and Chair*
[2]   *Engineer Associate*
[3]   *Engineer Associate*

feedback control processes. Because of other business related responsibilities, farm managers are continually forced to rely on hired labor to make decision regarding the overall profitability of increasingly larger operations. Further, as profit margins shrink, farm operators are forced to do more with less as they continue to substitute capital for labor. The end result, the overall power and size of agricultural field machinery continues to increase, and as this happens we note and increase in the magnitude of errors affecting the bottom line. The simple mistakes of yesterday are now replicated over 100 to 1000-fold of the area covered just 50 years ago.

3.　　Physical Limitations of Field Machinery

The Power Dilemma - When looking at modern farm equipment, specifically equipment utilized to produce grain crops, the trend has been to higher power machines. For example, today it is common to see 450 kW tractors on farms. To effectively utilize the power produced from the engine, the tractor must be adequately ballasted. In general there is a recommendations the tractor be ballasted at 60 to 70 kg per kW of engine power, or from 27,000 to 31,500 kg (60,000 to 70,000 lb$_f$) total mass (Goering, et al., 2003). Of course when ballasting a tractor it is not permissible to exceed tire manufacturer's recommendations for load and inflation pressures. In fact, because of the soil-tire interface, common practice dictates that tire inflation pressures be reduced to the absolute minimum to achieve the best possible performance and fuel efficiency. As tractor size increase above the current upper limits, one or more of the following limitations must be overcome: 1) allowable tire loads must increase for limited section sizes; 2) tires must be added to axles (i.e, duals and triples); 3) tire diameters must increase; or 4) drive trains must reconfigured to include more than two axle. The dilemma in European is that tractor manufacturers must work within the 3.0 and 3.5 m transport widths thereby limiting tire spacing and/or section widths. By today's standards it is impractical to achieve axle loads in excess of 15,000 kg (33,000 lb$_f$). The two viable options that remain are larger diameter tires, or more axles.

When matching tillage tools and seeding equipment with available power, it is common to see fully loaded no-till planter develop draft forces approaching 2,000 N/drill row (450 lb$_f$/drill row) from ASABE (2009). Assuming a seeding speed of 10.0 km/h (6.0 mi/h), this implement requires tractor engine power approaching 9.0 kW/row (12.0 hp/row). Putting this in perspective, a 36 row no-till planter will require 325 kW (430 hp) tractor assuming a tractive efficiency of 77% and a transmission efficiency of 90% for a four wheel drive (4WD) tractor. It is the combination of implement width, ground speed, draft and tractive efficiency that mandate the minimum tractor size. The tractor must be ballasted to take full advantage of the engine power. Typically, ballasted tractor mass be range from 64 to 67 kg per engine kW (105 to 110 lb$_f$/Hp) for a total tractor mass of around 21,000 kg (46,000 lb$_f$). With a 60/40 static weight split between the front and rear axles, as is typical of properly ballasted 4WD tractors, and assuming row-crop dual tires, each tire must support a load of up to 3,150 kg/tire (6,950 lb$_f$/tire). From manufacturer specifications the minimal acceptable tire is 480/80R42 at an inflated pressure of 48 kPa. When going to single tires the minimal acceptable tire size is a 900/50R42, again inflated to 48 kPa. For row crop tires the minimal tractor width is 3.53 m (11.57 ft) while for single tires the minimum width is 2.84 m (9.32 ft). The latter case is what most European producers are required to accept.

While this discussion is focused on tractors similar situations have arisen for other field machinery. Table 1 summarizes some of the equipment parameter becoming commonplace in the U.S. Of major concern is the continual increase in gross vehicle weight (GVW). Take for instance the Balzer 2000 grain carts where is quite possible to see the GVW approaching 69 T for the loaded cart alone.

Increasing Width Quandary - Many agricultural producers utilize large equipment to reduce labor costs and improve timeliness of their operations. In terms of spray application, producers have turned to faster sprayers with boom widths in excess of 30 m. Pesticide application errors, especially those associated with larger equipment, result in costly over application and reduced yield from crop injury or poor pest control. Over-application tends to increase with boom section width as operators attempt to control boom sections manually. A recent study found that manual operation of a 24.8 m boom (5 control sections) resulted in an average over-application of 12.4% across a wide range of field shapes and sizes (Luck et al., 2010a).

Table 1: **Summary Statistics for Modern Field Machinery Power and Mass.**			
Equipment Make and Model	**Unballasted Mass (kg)**	**Ballasted/Loaded Mass (kg)**	**Engine Power (kW)**
AGCO MT975B 4WD Tractor	22,900	27,200	464
Case IH Axialflow 9120 Combine w/ 16 Row Corn Head	21,500	31,600	390
Balzer 2000 Grain Cart (54.5 T Capacity)	14,800	69,300	-
AGCO Rogator 1396 SP Sprayer (4,160 L Tank)	13,700	17,860	323

Off-rate application errors also result from the velocity differential across the spray boom that occur when spraying while turning, pressure variation across the spray boom, and undulating terrain which affects boom-canopy distance causing irregularities in nozzle pattern overlap. Previous research has indicated that off-rate errors resulting from turning movements on a sprayer with a 24.8 m boom could affect between 3% and 23% of fields (variety of shapes and sizes) receiving an application rate beyond ±10% of the target rate (Luck et al., 2010b). Problems associated with off-rate application errors are exacerbated with larger equipment as increased boom widths result in greater velocity, pressure, and height variations across the spray boom.

4.   Machine Life and Obsolescence

ASABE (2009) lists the anticipated life of agricultural tractors at 10,000 h. However, some diesel engine manufactures boast the development of million mile engines. Assuming an average speed of 60 mph (95 kph), the expected life of an engine for line-haul trucks is nearly

17,000 h. In reality most farmers recognize and expect tractors to last for more than 10,000 h. Farm magazines, chat rooms, blogs and web sites are replete with examples of tractors lasting well past the 20,000 h mark. Looking at typical annual use, most Midwestern grain producers log approximately 500 h of actual field time each year. If, in fact, we can expect a modern tractor life of 20,000 h, producers can expect to operate new equipment for 40 cropping seasons. This reflects an entire career for most producers.

"Obsolescence" has been described by some as "an object, service or practice that is no longer wanted even though it may still be in good working order." Perhaps a more descriptive term may be "technological obsolescence." Technological obsolescence occurs with "the evolution of technology: as newer technologies appear, older ones cease to be used." Berreca (2000) discusses technological obsolescence and concludes the following "when technological obsolescence is present, mortality rates increase with the passage of time. Reliance on past mortality experience as the basis for future mortality patterns understates the true mortality of utility property, understates the depreciation requirement, and overstates the remaining life and value of the assets." Although the author applied his analysis techniques to the utility industry, one may argue they are applicable to agricultural production sectors as well, especially given the current field production practices.

Given the rate at which new technologies are being developed, is it reasonable to expect new tractors to become obsolete prior to the end of their physical life? In other words, can we ever expect to fully utilize the capacity of what is being produced by manufacturers today?

5.   Evolving Automation Technologies

Looking towards the future to a point in time when humans are removed from field machinery, there are several emerging technologies that will be essential for autonomous operation. In some cases infrastructure development such as densification of Real-Time Kinematic (RTK) GPS networks to generate Virtual Reference Stations (VRS) correction data along with the development of Internet connectivity via Wi-Fi and WLAN to support data transfer. What follows is a brief overview of the status of many of the allied technologies that will be essential for totally autonomous field machinery of the future.

Space-Based Positioning Systems - Advancements in sensing, communication and control technologies coupled with Global Navigation Satellite Systems (GNSS) and Geographical Information Systems (GIS) are aiding the progression of agricultural machines from the simple, mechanical machines of yesterday to the intelligent, autonomous vehicles of the future.

The U.S. Global Positioning System (GPS) is maintained by the U.S. government and has been in operation since the late 1970s. The benefits of GPS, specifically in the agricultural industry, have been well documented as they have progressed from point location mapping (soil sampling or yield monitoring) to real-time equipment control (auto-steer or map-based automatic section control) (USCGNC, 2010a). To increase the accuracy of the existing GPS network, additional technologies have been developed by both public and private institutions. The Nationwide Differential GPS System (NDGPS) was developed for use in the U.S. and included beacons maintained by the U.S. Coast Guard and the Department of Transportation. The Wide Area

Augmentation System (WAAS) is operated by the Federal Aviation Administration. The WAAS network has become available for a variety of other users desiring sub-meter accuracy who have compatible receivers. A more recently developed system for improving GPS accuracy is the Continuously Operating Reference Stations (CORS) that was initially created by the National Oceanic and Atmospheric Administration. Since its inception, additional organizations have joined the network and provide correction data from their land-based GPS stations (US-CGNC. 2010b).

The Global Navigation Satellite System (GLONASS) is a Russian-operated satellite network that was developed in the late 1970s and was extended to non-military use in 2007. GLONASS is comparable to the U.S. GPS system and was created to provide real-time positioning data to compatible receivers. The GLONASS system is continually upgraded as existing satellites exceed their service life and new series replace them. The GLONASS-M series is currently in operation, with the GLONASS-K1 series expected to become operational in 2011 (FSA-IAC, 2010).

The Galileo global navigation satellite system is currently being developed by the European Union (EU) to provide a separate network of satellites from the Russian and U.S. systems that are now in use. The Galileo system has been developed by the European Space Agency primarily to provide real-time positioning data for civilian use and was designed to be compatible with the Russian and U.S. systems. Two experimental satellites have been successfully launched and four additional satellites are planned to be launched in 2011 to validate system operation (ESA, 2010).

The accuracy of differential global position systems (DGPS) degrade with increasing distance to the reference station. For DGPS systems, an inter-receiver distance of a few hundred kilometers will yield a sub-meter level accuracy, whereas for Real Time Kinetic (RTK) systems a centimeter level accuracy is obtained for distances of less than 10 km. To service larger areas without compromising on the accuracy, several reference stations have to be deployed. Instead of increasing the number of real reference stations, Virtual Reference Stations (VRS) are created from the observations of the closest reference stations. The locations of the VRS can be selected freely but should not exceed a few kilometers from the rover stations. Typically one VRS is computed for a local area and working day.

The observations from the real reference stations are used to generate models of the distance dependent biases. Individual corrections for the network of VRS are predicted from the model parameters and the user's position. This kind of network applied to DGPS and RTK systems is known as wide-area DGPS (WADGPS) and network RTK respectively. An example of a commercially available network RTK is Trimble's VRS that provides high-accuracy RTK positioning for wider areas. A typical VRS network set up consists of GNSS hardware, communications interfacing and, modeling and networking software. Most of the existing network RTK systems have been installed in the densely populated areas of central Europe.

Wireless Communications - For large scale high-tech agricultural operations, establishing vehicle to vehicle and vehicle to office communication is becoming imperative to manage the logistics of the tasks and to ensure the safety of the machines working in the field. The capability

to transfer data wirelessly can help monitor the working statuses of these machines and allow dynamic reallocation of tasks in the event of malfunctions. Point to point and point to multi point communication can specifically be used for leader-follower systems. Cell GSM, Wi-Fi, WLAN and Wireless stand-alone modems are typically used for vehicle to vehicle and vehicle to office communications. These technologies compete with each other with regards to bit rate, mobility of terminals, signal quality, coverage area, cost and the power requirements. WLANs are used for high bit rate transfers whereas cellular GSM networks are used for large coverage areas. From a cost and power requirement perspective, cellular networks are far more expensive to establish and maintain than WLAN access points. The power requirement for a cell phone to transmit can be as high as several hundred milliwatts, while WLAN requires a maximum of 100 milliwatts (Wireless Center, 2010). In terms of mobility and controlled signal quality cellular GSM are superior to WLANs. WLANs suffer from low mobility, isolated coverage and vulnerability to interference. Each technology is strong where the other is weak and hence WLAN and cell GSM networks are complementary.

WLANs operate in the 2.4GHz unlicensed frequency band. The signaling rate is 11Mbps, and the terminals employ CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) to share the available radio spectrum. The distance between the transmitter and the receiver has the greatest influence on the signal quality and the thus the quality worsens with increase in the distance. For a 2.4 GHz spectrum band, if the distance is within 28 meters the data transfer rate can be up to 11Mbps whereas, for distances greater than 55 meters the transmission cannot be more than 1 Mbps. A GSM signal occupies a band width of 200 KHz and can have channel rates of up to 271 Kbps. The strengths of both cell GSM and WLANs are provided by wireless internet (Wi-Fi). These networks provide a coverage range of up to 600 ft (183 m) and operate typically at a frequency of 2.4GHz.

On-Vehicle Communications - With the introduction of microcontrollers to agricultural filed machinery it was not long until equipment designers realized the need to share and manage information between controllers. Following the lead of the truck, bus and automotive industries, equipment designers began looking for bus configurations and data structures to support continuing machinery development. Quickly, most designers realized the need for standardization to facilitate interoperability and interchangeability the industry came to grips with for hitching (ISO 730, 2009) and hydraulic systems (ISO 5675, 2008). The following discussion highlights some of the more significant milestones in the evolution of the of on-vehicle communications and concludes with a brief treatment of what the industry can expect in the near future.

The Landwirtschaftliches BUS-System (LBS) is regarded as the precursor to ISOBus. Development of this protocol began in Germany in the late 1980s by a committee formed from the German Farm Machinery and Tractor Association (Stone et al., 1999). CAN version 1 was used as the base for developing this new agricultural communication bus protocol (Aurenhammer, 1983). The protocol was developed with the goal of running distributed process control systems such as fertilizer distribution, pesticide application, and irrigation (Munack and Speckmann, 2001). Therefore, development on the protocol began with the goal of standardizing network data exchange between electronic components on agricultural tractors and implements.

Based on the preliminary work by Auernhammer (1983) in Germany, ISO was requested to begin development of a standardized protocol for agricultural equipment in the early 1990s.

ISOBus is a distributed network protocol specification (developed under ISO 11783) for equipment which utilize CAN technology for electronic communication in the agricultural industry. Development of this ISO protocol began in the early 1990s when a working group was formed to develop an interim connector standard (ISO 11786). In 1992, ISO 17783 was formed to continue development of the communications protocol standard. Initially, much of the ISOBus standard was based on protocols developed by the automotive industry (SAE J1939); however, revisions have been made to support applications in the agricultural and forestry equipment industres. The main goal of ISO 11783 was to standardize electronic communications between tractor components, implement components and the tractor and implement (Stone et al., 1999).

FlexRay is a distributed network protocol that has been developed to improve on existing CAN technology. These protocols are typically developed by the automotive industry, but are soon integrated into agricultural vehicles as was seen with the CAN protocol under ISO standard 11783. One of the problems associated with existing CAN protocols is that in some cases, manufacturers are coming to a point where bus capacity will be exceeded. FlexRay offers the ability for data to be transferred at higher frequencies (10Mbps) compared to existing CAN protocols (250kbps) typically used today (National Instruments, 2010). Another important aspect of FlexRay is that it utilizes a time-triggered protocol that allows data to be transmitted and received at predetermined time frames which helps to eliminate errors that can occur when multiple messages are sent out on the bus. Additionally, the FlexRay protocol is capable of operating as a multi-drop bus, star network, or hybrid (using both multi-drop and star) network. This allows the protocol to be adapted easily into existing bus protocols while also providing increased reliability where desired with the star network. As automotive and agricultural vehicles develop in the future, FlexRay will certainly be the next network protocol used to ensure efficient and reliable data communication.

Data Structures – While on-vehicle communication has relatively well defined data structures (ISO 11783), standards for transfer of data between the farm office and field machinery continue to evolve. The latter is being driven for the most part by software developers who recognize the need to reconcile data transfer from the farm office to field machinery and back again. Today, the need to reconcile data is being driven by map-based application. "Prescription maps" direct where and how inputs will be applied to crop production systems. Data regarding input metering and placement is further complicated by the nature of field equipment apply inputs. Crop production managers and suppliers have multifaceted data transfer needs that range from moving prescription maps form the farm office to field equipment and then returning plans field operations verification files along sensor data for summarizing crop health and performance to the field office.

One attempt at coordinating data transfer has been proposed and adopted by Macy (2003) and is termed the Field Operations Data Model (FODM). FODM was created as a framework to document field operations, and more recently has been expanded to support business functions. FODM is based on three components: description of field operation, framework and a general machine model. Field operations are described using one of four models; whole-field, product-centric, operations-centric of precision ag. The FODM framework is object-based which includes resources (people, machines, products, and domains) and operation regions (space and time). Data logged to summarize field operations can either be infrequently changing data (ICD) of frequently changing data (FCD). The general machine model (GMM) provides a description of the physical features of field machines including components, sensors and product storage or containers. An example of a machine definition using the GMM is shown in Fig. 1.
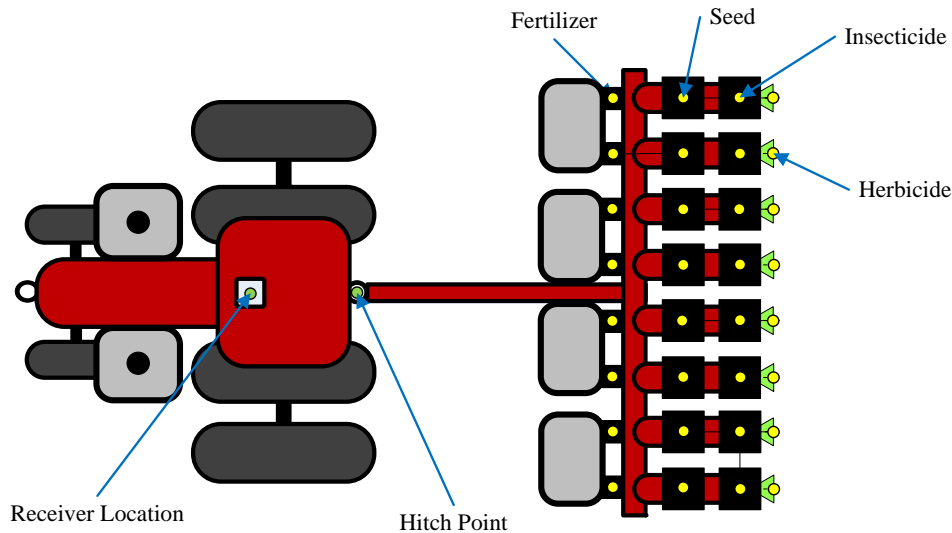
Figure 1: Illustration of a machine definition for a tractor/planter combination with multiple product metering and delivery systems using the GMM (adapted from Macy, 2002).

Automated Guidance - Systems designed to accomplish automated guidance on agricultural vehicles can be seen back as far as the 1920s when furrows were used to guide tractors across fields with reduced effort from the operator. Since that time, as technology has improved, automated guidance has evolved from mechanical sensing to electronic sensors, machine vision, and GPS to successfully navigate equipment across the field (Reid et al., 2000). In most cases, operators utilize automatic guidance to follow parallel paths through the field. At the beginning of field operations, an A-B line is input into the control console, and the GPS coordinates are stored. As the operator continues to cover the field, the automatic guidance system can be engaged and the equipment will attempt to follow parallel paths to cover the field based on steering sensor feedback and GPS data. Many systems also provide the ability to follow curved paths which are input in much the same way.

Two basic types of automated guidance systems are typically used today by producers. The first system consists of a steering actuator which is mounted to the tractor's steering wheel. The second system is integrated into the tractor's steering system and utilizes a control valve to actuate the hydraulic steering cylinder directly. The overall accuracy of these systems relies heavily on the type of GPS technology used (RTK GPS provides the highest accuracy) as well as proper installation and setup. Ultimately, these systems benefit producers by reducing operator effort and pass-to-pass overlap during field applications.

Automated Turns - After the successful development and employment of automated guidance on agricultural vehicles, the next logical step was to automate turning maneuvers. Creating a control system to automate turning at headland areas depends on several factors including headland width, equipment width, tractor dynamics, and the type of turn desired. One system that is currently available to producers which can automate turning movements is from Deere and Co. The iTEC Pro system (Deere & Company, 2010) uses tractor and equipment parameters and headland boundaries input by the operator to develop appropriate headland turns. Once

8

engaged, the system will automatically perform the headland turn once it has entered a headland area without any input from the operator. An additional function provided by iTEC Pro is implement control. Control sequences can be setup for the equipment as it enters and exits the headland area. For instance, as the equipment enters the headland, tractor speed may be reduced, the implement raised. As the implement exits the headland, the implement may be lowered and the tractor speed increased. Using these two functions included in the iTEC Pro system; headland turns can be completely automated such that the operator does not need to steer the tractor nor activate the implement being utilized.

Harvest Automation - Over the past two decades, yield monitors have been one of the most significant developments in harvesting technology. Manufacturers continue to improve these systems to provide yield and moisture measurements to the operator during harvesting operations as well as computer software for post-processing. Many producers utilize using automatic steering systems on harvesters to improve field efficiency. Most systems rely on GPS for guidance, however, systems have been developed which sense the stalks at the header to improve automated steering while harvesting corn (Deere, 2010). Improving grain quality and reducing grain loss is another method that producers can use to increase overall harvest efficiency. The development of hillside harvesters actually helped to improve cleaning capacity on steeper slopes, and harvesters are now offered by manufacturers including Deere and New Holland which have self-leveling cleaning shoes. Another recent development by New Holland is the Opti-Clean™ cleaning shoe which attempts to maximize the sieve stroke and throwing angles to further improve cleaning efficiency (New Holland, 2010a). The Grain Cam™ system from New Holland also seeks to improve harvester efficiency by providing an on-the-go analysis of grain quality which allows the operator to make adjustments to the harvester to reduce foreign material and broken grain (New Holland, 2010b). Another recent innovation is the Intellicruise™ system by New Holland which monitors header feeding load and adjusts harvester speed to maximize the throughput of crop material. This system essentially takes some of the guess work out of the load status of the machine, which has typically been observed by the operator (New Holland, 2010c). The common thread among the technologies discussed here is that they seek to improve overall harvesting efficiency while reducing the need for operator control.

6.   Future Trends in Automation

Liability – Perhaps one of the major impediments to development of fully autonomous field machinery is liability, and more important is who will assume or share the liability. For the foreseeable future, tractors will have drivers who in actuality are being relegated to baby sitters to a large extent because of equipment size and corresponding power levels. In short technology continues to remove much of the control responsibility from the operator. Perhaps the best examples include automated guidance and turns. Now on the horizon is automation of the combine threshing mechanism and cleaning shoe (New Holland, 2010a,b). Until manufacturers and producers reach a consensus as to how liability issues will be resolved, we can expect the operator to transition from commanding single machines to responsibility for multiple machines working in a coordinated behavior.

Use of multiple machines for increasing rate of work and productivity is common on most of the large scale farms worldwide. In a setup where multiple machines are used for agricultural production, one operator is required for each machine resulting in a one to one ratio of human

operators to number of machines. Row crop operations like grain harvesting require at least two machines with one operator for each machine. The capability to manage and monitor both the harvester and the wagon by one operator can increase the field efficiency and reduce labor costs drastically. Algorithms for operating a master-slave multi-robot system were developed by (Noguchi et al., 2004). In this system the master machine is controlled manually and the autonomous slave machine has the capability to either follow or go to a particular location as commanded by the master machine. Vougioukas (2009) proposed a method for coordinating teams of robots where one master machine specifies the motion characteristics of one or more machines (slaves). Although no experiments were done with the proposed method, the simulation experiments verified that the method can be used for coordinated motion of hierarchies of master-slave robots.

The transition to fully autonomous operation will include a progression that begins with smaller, low power machines operated in controlled settings. When possible, fences or natural barriers might be utilized to corral errant vehicles. Lowenberg-DeBoer (2002) recognized this possibility when he concluded "Autonomous farm equipment may be in our future, but there are important reasons for thinking that it may not be just replacing the human driver with a computer. It may mean a rethinking of how crop production is done. In particular, once the driver is not needed, bigger is no longer better. Crop production may be done better and cheaper with a swarm of small machines than with a few large ones."

First Generation Unmanned Machines - First generation unmanned machines are autonomous machines that require constant supervision despite the fact that they are autonomous. These machines lack the intelligence to cope with circumstances that are unexpected and dynamic. In the event of an emergency, the autonomous machine will either stop completely or alert a remote supervisor to aid it in mitigating the emergency. Few examples of autonomous machines that can be assumed as Gen-I machines are discussed in this section.

Researchers at Carnegie Mellon University developed an autonomous harvesting machine known as Demeter system (Pilarski et al., 2002). The robotic machine harvested more than 40 hectares of crop without human intervention. The base machine was a retrofitted New Holland 2550 self-propelled windrower. Researchers at the Technical University of Denmark (Madsen and Jakobsen, 2001) developed an autonomous robot prototype specifically for weed mapping.This robot was developed to mitigate the adverse effects of weed species like waterhemp that are developing glyphosate resistance (Grift et al., 2006). French and Spanish institutions in collaboration with equipment manufacturers developed a citrus harvesting robot (IVIA, 2004). This robot is different from weeding or scouting robots as it has an on-board manipulator to identify and harvest citrus fruit. Similar research efforts to develop citrus harvesting robots were conducted at the University of Florida by Hannan et al. (2004).

Robotic harvesters for specialty crops like cherry tomatoes (Kondo et al., 1996), cucumbers (van Henten et al., 2002) mushrooms (Reed et al., 2001), cherries (Tanigaki et al., 2008) and others fruits (Kondo et al., 1995) have also been developed.Although, autonomous robotic manipulators are commercially available for milking and horticultural applications, mobile field robots are still not commercially available. The most sophisticated tractors available today feature automation

of numerous machine functions but, require an operator to closely monitor the tasks being performed.

John Deere Company is currently working on a project to enable a single, remote user to supervise a fleet of semi-autonomous tractors mowing and spraying in an orchard (Zeitzew 2006, Moorehead et al., 2009). In a similar effort, three autonomous peat harvesting machines performed 100 field test missions during tests conducted with end users (Johnson et al., 2009). The successful implementation of a multi-robot system by these researchers is a testimony to the fact that Ag-robots can work in real-world applications and the field of agriculture is evolving in to a high-tech work environment. Although autonomous, these first generation systems require close supervision by human operators and require further improvements to transform them into intelligent autonomous machines.

Individual Robot Control Architectures – Most of the initial work done on control architectures of mobile robots was carried out in the aerospace and artificial intelligence research laboratories to accomplish military missions and space explorations. Unlike industrial robots, where the environment is controlled and structured, the work environment of Ag-Robots is relatively unstructured, unpredictable and dynamic. An intelligent, robust and fault tolerant control architecture is essential to ensure safe and desired operation of the Ag-Robot. A behavior based (BB) control approach provides an autonomous mobile robot, the intelligence to handle complex world problems using simple behaviors. Complex behaviors of a robot emerge from simple behaviors (Brooks, 1986), behavior being defined as response to a stimulus (Arkin, 1990). BB control structure can be either reactive or deliberative in nature. Reactive behaviors are part of reactive control architectures where the behavior responds to stimuli and develops control actions. Deliberative behaviors on the other hand are pre-defined control steps which are executed to accomplish a given task. Associating these behaviors to actual actions of an agricultural robot is crucial to understand the capabilities of a robot. The importance of decomposition of agricultural tasks into robotic behaviors was illustrated by Blackmore et al. (2004). For the robot to tackle unknown environments and attain assigned goals both reactive and deliberative behaviors are important (Konolige and Myers, 1998) and thus a robust fault tolerant intelligence is achievable with a combination of reactive and deliberative behaviors.

An Autonomous Robot Architecture (AuRA) for reactive control was developed by Arkin (1990). Arkin (1998) mentioned three important aspects of a successful multi-purpose robot; motor behaviors that are used to describe the set of interactions the robot can have with the world, perceptual strategies that provide the required sensory information to the motor behaviors, and world knowledge both a *priori* and acquired that are used to select the motor behaviors and perceptual strategies that are needed to accomplish the robot's goals. AuRA consists of five basic subsystems; perception, cartographic, planning, motor and homeostatic control. Yavuz and Bradshaw (2002) did an extensive literature review of the available robot architectures and proposed a new conceptual approach to the design of hybrid control architecture for autonomous mobile robots. In addition to reactive, deliberative, distributed and centralized control approaches, fuzzy logic and modular hierarchical structure principles were utilized. Thus, three types of control architectures were acknowledged in the literature; hierarchical or deliberative, reactive and hybrid. The computability and organizing principles for each architecture differs and have their own peculiar set of building blocks. Essentially all BB architectures are software

frameworks for controlling robots. BB robotic systems are significant, in the case where the real world cannot be accurately modeled or characterized. Uncertain, unpredictable and noisy situations are inherent characteristics of an agricultural environment and hence utilizing BB robotic architecture principles may be ideal.

A specification of behavioral requirements for autonomous tractor was provided by Blackmore et al. (2001). The authors discussed the importance of a control system that behaves sensibly in a semi-natural environment, and identified graceful degradation as a key element for a robust autonomous vehicle. Using the BB robotic principles, Blackmore et al (2002) developed a system architecture for the behavioral control of an autonomous tractor. Blackmore followed the assumption that robotic architecture designs refer to a software architecture, rather than hardware side of the system (Arkin, 1998). In a more practical approach, a system architecture that connects high level and low level controllers of a robotic vehicle was proposed by Mott et al (2009). In addition to the aforementioned levels, a middle level was introduced to improve the safety of the autonomous vehicle. The middle level enforced timely communication and provided consistent vehicular control. When the high level was not transmitting appropriately, the middle level recognizes this condition and transitions to a safe mode where the vehicle shuts down and stops. Ultimately, the middle level acts as a communication bridge integrating the high and low level controllers providing robustness to the robotic vehicles. This concept was successfully deployed on a fully-autonomous stadium mower and a large-scale peat moss harvesting operation (Zeitzew, 2006).

Multi-Robot Control Architectures – Coordinating multiple autonomous robots for achieving an assigned task presents an engineering challenge. When multiple robots are working together to accomplish a task the foremost question to be resolved is the type of inter-robot communication required. Inter-robot communication forms the backbone of a MRS. Identifying the specific advantages of deploying inter-robot communication is critical as the cost increases with the complexity of communication among the robots. Three types of inter-robot communication were explored by Balch et al. (1994).They found that communication can significantly improve performance in some cases but for others, inter-agent communication is unnecessary. In cases where communication helps, the lowest level of communication is almost as effective as the more complex type. Rude et al. (1997) developed a wireless inter robot communication network called IRoN. The two important concepts of the network were implicit and explicit communications. A modest cooperation between robots is realized using implicit communication and a dynamic cooperation is achieved by using explicit communication. The authors utilized two robots to implement IRoN and were able to identify the changes which reduced the motion delay time ranges from 1000 ms to 50 ms. Wilke and Braunl (2001) developed flexible wireless communication network for mobile robot agents. The communication network was an explicit communication method which was applied to team members of a RoboCup team playing soccer. The communication network allowed broadcasting, transmission of messages between individuals and communication with a remote computer workstation. Fung et al. (1994) utilized a wireless transmitter and receiver to communicate position data. In their approach the position of a robot is gathered from infra-red sensor data and then transmitted to other robots via a radio link. The communication network is dedicated to sending only infra-red sensor data which makes it an inflexible network. A sophisticated technique called Carrier Sense Multiple Access/Collision Detection (CSMA/CD) was developed by Wang and Premvuti (1994). The

CSMA/CD protocol allows wireless inter-robot communication among multiple autonomous vehicles with a centralized supervisor.

To date, most of the research work done on multi-agent robot systems has been conducted in areas other than agriculture. Research work done on the architectural specifications of a MRS specifically deployed for agricultural production is rarely found in the literature. Thus, there is a need to understand, explore and research the control methodologies of a MRS so that multiple Ag-Robots can be deployed for agricultural production. Furthermore, the rapidly evolving contemporary agriculture industry may be poised to adopt MRS for increasing production efficiency

Next Generation of Autonomous Field Machinery – The next generation machines can be envisioned to accomplish agricultural production tasks autonomously using the intelligence provided by robust control architectures. As an example, two autonomous vehicles are assumed to perform baling and bale moving operations. Establishing communication between the baler and bale spear vehicles, hay bale location identification, navigation to the bale, spearing of the bale and relocation to the edge of the field will be done with minimal human supervision. Momentary wireless communication is established between the baling and bale spear vehicles during the spearing operation (see fig. 2). The baling vehicle sends the location where it dropped the hay bale to aid the bale spear vehicle in path planning. The baling and spearing vehicles each have message frames to communicate the status and location of the bale. When bale is ejected, the vehicle transmits the location and timestamp through the Tx-message frame to the spear. The information about the bale is received by the Rx-message frame of the spearing vehicle which acknowledges the reception by transmitting a Tx-message frame. The baling and spearing vehicles, in addition to point to point communication, broadcast their messages with information containing their unique IDs, states, time stamp and the status of the assigned work to Central Monitoring Station (CMS).

In another instance, three Ag-robots are assumed to be a Combine, Grain Cart I and Grain Cart II. Grain Carts I and II (followers) receive instructions from the Combine (leader) to navigate t along specific paths to off-load the harvested grain. Continuous point to multi-point communication between the Combine and Grain Carts is established. Grain Cart I and II maintains their trajectories at (b, 0) and (b, L) relative to the trajectory of the leader for receiving the harvested grain (see fig. 3). In addition to point to multi-point communication the states of the all the vehicles are broadcasted to the CMS.
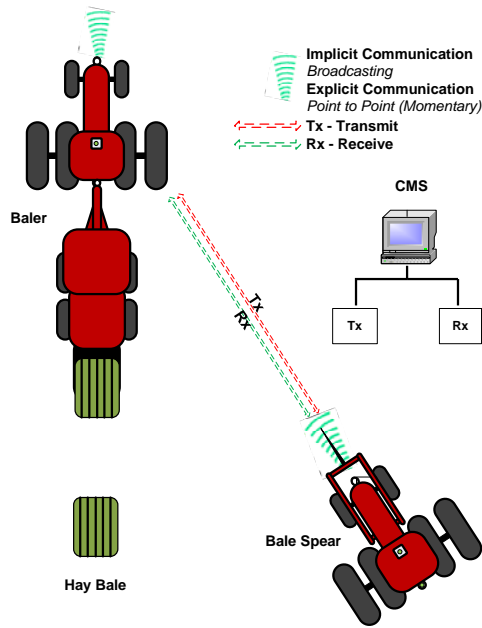
Figure 2: Coordinated vehicle navigation for performing point to point retrieval operations.
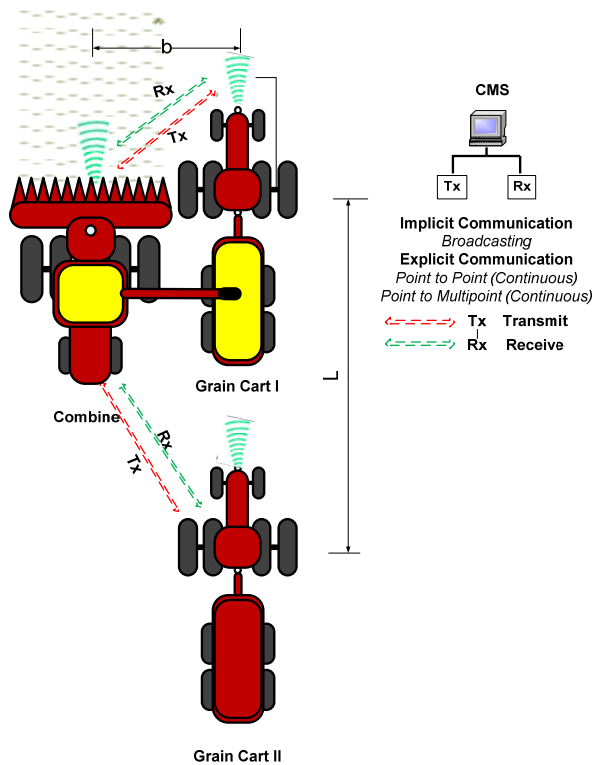
Figure 3: Coordinated vehicle operation for accomplishing biomass harvest, accumulation and transfer operations (leader–follower behavior).

In a more complex multi-robots system behavior instance, four autonomous vehicles simultaneously seed the same field. The Vehicles divide the seeding task into multiple working zones and perform work in their own zones. The control architecture provides intelligence to the seeding vehicles that divide the task and delegate specific vehicles to work in their own zones (see fig. 4). The autonomous seeding vehicles broadcasts messages with information containing their unique IDs, states, time stamp and the status of the assigned work to the CMS. Each vehicle is assigned a unique ID. The status of work in this case would be the percentage of total area seeded by each vehicel. The CMS receives the data and stores all the data in its database for monitoring and post processing.
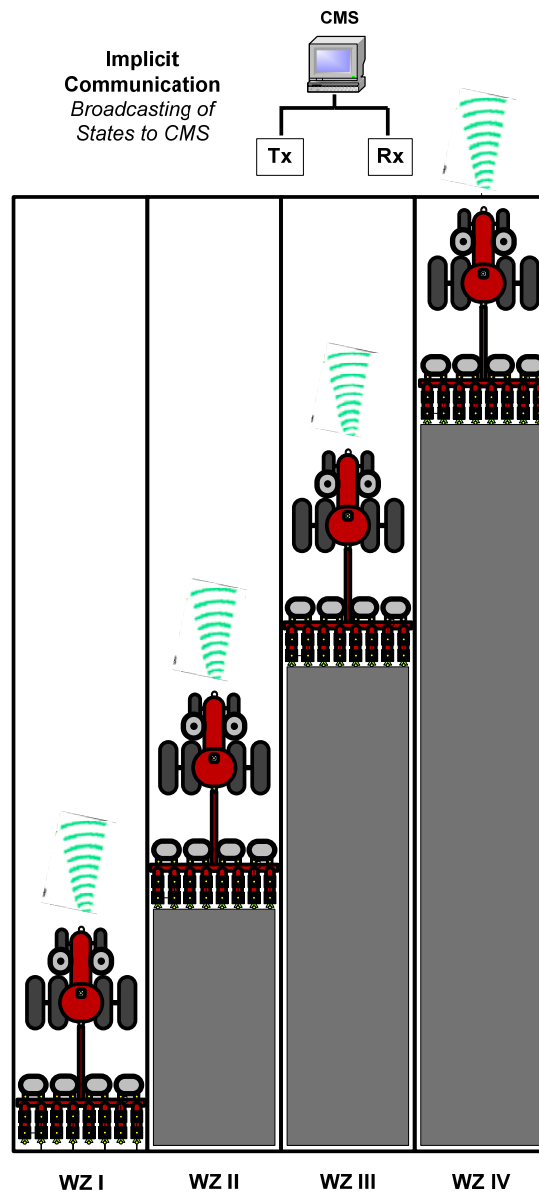
Figure 4: Coordinated navigation of multi-vehicle system for accomplishing a production task such as planting.

## 7.	Moving Forward

Currently, several autonomous vehicles development programs are underway targeting various agricultural production sectors. Unfortunately, liability concerns will stymie the commercialization of these machines, in part because of larger vehicle size. Until control systems can be perfected and development costs recouped, the growth in automated field production systems will come in fits and starts.

Parallel to autonomous vehicle development efforts we will continue to see the densification of highly precise and accurate radio-navigation facilities along with the necessary expansion of wireless communications technologies that will facilitate internet connectivity and data exchange between manned vehicles, businesses and the farm office. Similarly, we will continue see the development of crop and field condition sensors that will ease the burden for equipment operators while improving the efficiency and productivity of existing machines.

So what is the paradigm shift that will accelerate the transition from manned to fully autonomous vehicles? Perhaps the current emphasis on reducing labor costs through up-sizing equipment will begin to lose its appeal as we learn more about the damage being done to soil structure through high GVWs. Or, maybe producers will demand that vehicle life be brought in line with technical obsolescence. Drawing on the information presented in this manuscript the authors believe that we will see a paradigm shift in the size of field machinery. The first commercially successful autonomous agricultural vehicles will be low power (<30 kW) and lightweight (< 2 T). Principal field tasks will be low-draft operations such as no-till seeding and spraying. The shift to smaller sized equipment autonomous vehicles will be accompanied by a reduction in machine life (< 25% of current machines). The philosophy will be to design vehicles that mechanically fail at about the same point they reach obsolescence (< 5 cropping seasons). Further, symmetry will be utilized to minimize the overall number of parts require to build the power units thereby increasing volume and reducing productions costs. Perhaps the most crucial and tangible benefit to follow from the reduced equipment size will be the ability of manufacturers and producers to manage the liability of fully autonomous machines.

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