Evolution of Electronics for Mobile Agricultural Equipment

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Abstract. *Electronic components have become ubiquitous in modern agricultural machines. The evolution of electronics applied in mobile agricultural equipment is tracked from the era of the development of transistors to the present. Milestone events in the introduction of agricultural electronics are identified. The time between the introduction of new electronic technologies and their incorporation into mobile agricultural equipment is quantified. Future development of electronics for mobile agricultural equipment is examined, as well as potential progress tied to developments in electronics and software development methodologies.*

Keywords. *Electronics, Future, History.*

Electronic components have become ubiquitous in modern agricultural machines and are applied broadly in applications from seed-rate control to navigation. The extent to which electronics have become a necessary component can be seen in engine emission control systems. Nearly all self-powered agricultural equipment produced after 2008 will have embedded electronic engine controllers. These control systems are needed to meet the stringent "Tier 3 / Stage III" emission requirements for powered agricultural equipment now being phased in by the U. S. EPA and the European Community (U.S. EPA, 1998; U.K. Department for Transport, 2006). The existence of an electronic engine controller on a machine makes it desirable to utilize network-based instrumentation, and the likely result is that most powered agricultural equipment targeted for application in North America and Europe after 2008 will have on-board local area networks.

A review of the past accomplishments in electronics and their application in agricultural equipment is warranted as a basis for speculation regarding the potential future for the technology.

History of the Application of Electronics in Agricultural Equipment

Progress in the development of electronics has been rapid since the invention of integrated circuits by Jack Kilby at Texas Instruments in July 1958. The first practical application of Kilby's invention was seen in 1961 in a military computer, and the same year heralded the introduction of Texas Instruments 51 Series logic devices (Texas Instruments, 2007). By 1964, Texas Instruments had introduced the 54/74 series logic devices, a family of devices now sourced by numerous manufacturers that continue to be an element of electronics systems today. At nearly the same time (1959) as Kilby's work, Robert Noyce (1961) at Fairchild Semiconductor developed an integrated circuit concept that formed the basis for the early monolithic analog amplifier, the μA709 developed in 1963 by Widlar (1965).

Application of electronic devices in mobile systems followed closely the introduction of integrated circuits. In 1967, the D-Jetronic electronic fuel injection system was introduced by Bosch for automotive application (Bauer, 1999). Introduction of electronic devices for application in agricultural equipment occurred slightly earlier with the DICKEY-john Seed Population Planter Monitor introduced in 1966 (Sokol, 2000). This development was soon followed by patent applications for electronic hitch control by Renault in France in 1972 (Maistrelli, 1975) and later by J. I. Case in 1975 (Haney, 1977). These early electronic hitch control patents utilized analog electronics, and the J. I. Case patent refers directly to application of integrated circuits.

The introduction of electronics for use in agricultural equipment was reported by Sokol (2000). These developments, assembled chronologically from the material presented by Sokol and extended by the authors, are given in table 1. The material is not comprehensive, but it illustrates the steady progress that has been made in agricultural electronics over the past forty years.

The development of the integrated circuit provided a basis for the development of the microprocessor. These devices are the basis of modern embedded computer-based controls and a fundamental element in modern agricultural electronics. Intel introduced the 4004 microprocessor in 1971 (Mazor, 1995) and recognized some of the potential for the device in their 1971 advertisement in *Electronic News* (Leibson, 2006). Their prophetic advertisement declared: "Announcing a new era of integrated electronics."

The potential to apply microprocessor-based technology in agricultural equipment was greatly improved by the first introduction of a microcontroller, the 8048, in 1976 (Intel,

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Table 1. Chronology of developments in agricultural electronics.[a]

Year	Company	Milestone	Year	Company	Milestone
1966	DICKEY-john	Seed population planter monitor	1988	Vicon	Seeder monitor with can bus
1967	DICKEY-john	Seed flow planter monitor	1989	KHD	Ag tractor hybrid instrument panel
1968	Smith Roles	Combine grain loss monitor	1989	Mid-Tech	Model TASC 6600 sprayer controller
1968	DICKEY-john	Combine shaft speed monitor	1990	Caterpillar	Challenger 75 electronic engine controls
1970	ASCI	Application rate control system	1991	DMC	On-the-go combine grain moisture monitor
1971	Vermeer	Large 2000 lb round baler controller	1992	Ag Leader	Ag leader 2000 combine yield monitor
1972	DICKEY-john	Optical planter population monitor	1992	Raven	Multi-product variable-rate controller
1972	SED	Model 902 piezo-acoustic grain loss monitor	1992	Mid-Tech	Model TASC 6500 sprayer controller with datalink
1973	DICKEY-john	Grain moisture meter	1993	New Holland	Genesis tractor instrumentation with CAN bus
1974	DICKEY-john	Universal equipment monitor	1993	Vicon Systems	Sprayer computer with CAN bus
1974	SED	Model 901 piezo-acoustic grain seeder monitor	1994	Micro-Trak	Graintrak yield monitor
1975	New Holland	Rotary combine monitor	1994	New Holland	Tx combine instrumentation
1975	New Holland	Generation-1 forage metal detector	1994	New Holland	Combine header height control
1976	DICKEY-john	Combine grain loss monitor	1994	John Deere	8000 series ag tractor electrohydraulics
1976	DICKEY-john	True ground speed sensor	1994	Müller Elektronik	Job controller
1976	BEE	Combine/seeder shaft monitor	1995	AGCO	Fieldstar multipurpose terminal
1977	SED	Prasco and Frigstad air seeder fan tachometer	1995	John Deere	Greenstar multipurpose terminal
1977	DICKEY-john	Tractor performance monitor	1996	Rawson	Site-specific planter control
1977	International Harvester	Variable-rate planter seed controllers	1996	Willmar	Sector precision farming system
1977	John Deere	Variable-rate planter seed controllers	1997	Caterpillar	Lexion combine with VGA terminal
1977	International Harvester	Axial-flow combine digital tachometer	1997	Vansco	True ground speed sensor
1978	Raven	Sprayer control system	1997	DICKEY-john	Precision control system
1978	SED	Model 943 sprayer monitor	1997	Kinze	Planter monitors
1979	SED	Model 948 sprayer controller	1997	Ag Leader	PF3000 precision farming display and controller
1979	SED	Model 955 tractor performance monitor	1997	Flexicoil	Flex-control task controller
1979	New Holland	Hay stacker control	1997	Agrocom	ACT multipurpose terminal
1980	Mid-Tech	Model CCI chemical injection sprayer control	1998	Vansco	VCOM3 universal display and controller
1981	BEE	Variable-rate air seeder controller	1998	JCB	Fastrac ag tractor instrument panel
1981	SED/ John Deere	Model 903 air seeder monitor with serial datalink	1999	Ag-Chem	Falcon II variable-rate control
1982	Micro-Trak	Calc-an-Acre, acre counter	1999	John Deere	50 series combine electronics
1983	New Holland	Combine instrumentation	1999	Vansco	VCOM5 industrial-grade Pentium computer
1983	Ford	Tractor performance monitor	2000	CNH	AFS touch-screen terminal
1984	New Holland	Combine stone trap controller	2001	Caterpillar (AGCO)	ISO11783 tractor electronic control unit (ECU)
1984	Steiger	4wd powershift transmission controller	2001	Mid-Tech	Legacy 6000 full-color user interface
1983	Vicon	Square baler controller with serial communication	2002	Kverneland	ISO11783 virtual terminal, seeder and sprayer ECUs
1985	Micro-Trak	Ground speed sensor	2003	John Deere	ISO11783 tractor electronic control unit, Model 6020
1985	Ag-Chem	Soilection application rate control	2003	Claas	ISO 11783 virtual terminal
1985	New Holland	Baler command round baler controller	2003	CNH	ISO 11783 virtual terminal
1985	Vicon	ED820 "electronic dosing" fertilizer application controller	2003	John Deere	ISO 11783 virtual terminal
1986	New Holland	Forage harvester knife adjuster	2003	Müller Elektronik	ISO 11783 virtual terminal
1986	New Holland	Bale wrap controller	2003	WTK	ISO 11783 virtual terminal
1987	Müller Elektronik	UNI control board computer with chipcard reader/ writer	2004	Vicon (Kverneland)	Wireless sensor on bale wrapper
1987	Bosch	Ag tractor electronic draft control	2006	Kverneland	ISO11783 task controller
1988	John Deere	Tractor instrumentation with C2D bus	2006	AGCO	ISO11783 task controller

[a] Compiled from Sokol (2000) with additions from the authors.

1976). These devices featured integrated permanent memory (ROM), read/write memory (RAM), and I/O ports in a single integrated circuit package. The Intel 8048 has 64 bytes RAM, 1024 bytes of ROM, an 11 MHz clock, two timers, and three 8-bit wide ports, not dissimilar from current low-cost microcontrollers.

The potential for application of microprocessor-based electronics was reported in ASAE (ASABE) literature as early as 1976 (Kranzler and Camp, 1976). Early applications of microprocessor-based designs in mobile agricultural equipment were disclosed by Steffen at DICKEY-john in 1978 in a patent application for a planter monitor (Steffen, 1980).

SED's model 943 sprayer monitor was introduced in 1978 and used the Intel 8048 microcontroller. Development of embedded electronics for application in instrumentation for mobile equipment was reported at ASAE (ASABE) meetings as early as 1977 (Formwalt, 1977). A review of the *Agricultural Engineering Index* from 1961-1970 shows no mention of electronics and only a few references that address embedding of electronics into agricultural equipment (Hall and Hall, 1972). In contrast, the same index from 1971 to 1980 shows reports from numerous researchers of applications of electronics in agricultural equipment, with most of those addressing application of microprocessors (Hall and Basselman, 1982).

Significant early work in the development of electronic monitoring and control systems for combine harvesters was done in the 1970s and can be tracked in the patent literature. Elfes (1971) and Botterill et al. (1971) with Massey Ferguson patented an automatic combine speed control in 1971. Elfes' device used vacuum tubes to amplify grain loss signals for modulation of combine forward speed. Fardal and Rickerd (1978) later described similar analog integrated circuit based speed control. Early electronic loss monitoring systems were patented by Girodot (1971) of Massey Ferguson and De Coene and Dewaele (1971) of Clayson, and a digital system was patented later by Northup et al. (1976) of Allis-Chalmers.

Many electronics based devices were marketed for agricultural equipment during the 1980s and forward, and it is likely that most were microcontroller based. These included planter monitors, tractor monitors, spray controllers, etc. (table 1). It is informative that the first integration of microcontrollers into agricultural equipment followed the introduction of microcontrollers by only about two years.

During the early development of microcontroller-based electronics for agricultural equipment, the need for distributing components about the machine or between tractor and implement became obvious. Sokol (2000) reported that one of the first introductions of agricultural electronics with a serial datalink or network was the New Holland bale wrap controller in 1986. An earlier use was found in the SED/John Deere model 903 air seeder monitor, in which a serial datalink was used to communicate seed flow information from a piezo-acoustic sensor in the seed delivery tube. Communication between electronic components on a tractor and elements on an implement allowed a simpler wiring system across the hitch and allowed better functionality in the product. The potential that exists for beneficial application of networks and the critical need for standardizing communications interfaces for agricultural equipment was recognized early by Auernhammer (1983) in Germany and initiated a standardization committee formed under the LAV (German Farm Machinery and Tractor Association), which selected CAN as a basis for a new standardized agricultural bus, LBS (DIN 9684). DIN 9684-1 was completed in 1989, and work began on the CAN-based system (DIN9684-2 to DIN9684-4), which was published in 1997. The critical need for standard communications interfaces was recognized at ASAE meetings in the mid-1980s (Bernard, 1986; Searcy and Schueller, 1986; Artman, 1986; Stone, 1987). The interest that developed worldwide has eventually culminated in the creation of ISO 11783, which provides a comprehensive international standard for electronics communications for agricultural equipment. Begun in 1989, work on ISO 11783 continues today and has provided a framework for network development since the mid-1990s. A more detailed review of ISO 11783 can be found in Stone et al. (1999).

Environmental standards for electronics have also served as an important milestone in advancing the use of electronic components in mobile agricultural equipment. ASABE Standard EP455 was approved in July 1991 and provides target environmental conditions to which electronic components may be tested (*ASABE Standards*, 2003). The existence of environmental standards allows manufacturers to better provide reliable electronic components. The need for worldwide environmental standards for mobile agricultural electronics has resulted in the recent adoption of ISO 15003 (ISO, 2006), which utilized information from EP455 and other sources to provide an acceptable worldwide standard.

The availability of the U.S. Department of Defense's NAVSTAR satellite-based global positioning system (GPS) has had a significant effect on electronics for mobile agricultural equipment. The GPS system became fully operational in March 1994 (Pace et al., 1995). The 100-meter accuracy of the GPS system at the time was not adequate for agricultural applications, and the availability of the Radio Technical Commission for Maritime Services RTCM SC-104 protocol for differential correction paved the way for differential correction signals to be used with GPS (DGPS), with accuracies in the one-meter range (RTCM, 1990). Development of DGPS made possible low-cost, dynamic, meter-level resolution positioning. The technology has enabled precision farming applications.

The introduction of GPS-based agricultural electronics preceded the full operational availability of the NAVSTAR GPS system by about two years. The Ag Leader 2000 was introduced in 1992 (Sokol, 2000) and offered yield monitoring as well as yield mapping. Schueller et al. (1985) reported the need for effective grain yield measuring systems, and Schueller and Bae (1987) later reported development of a yield mapping system using microwave positioning. Commercial introduction of the SoilTeq, Inc., position-based precision farming system was reported by Lullen (1985) and described by Ortlip (1986). Early work in yield measurement included the volumetric based opto-electronic grain flowmeter reported by Pfeiffer et al. (1993), and the mass flow based continuous weighing system developed by Schrock et al. (1995). Commercial yield monitoring systems acquire area-specific grain yield in a combine harvester and record that information along with GPS-based latitude and longitude, allowing a map of yield to be later displayed and analyzed. Yield monitoring systems also typically include on-line moisture content measurement needed to correct the measured yield information.

Since the NAVSTAR GPS system became operational in 1992, many components of precision farming systems have been developed to measure and map various performance parameters associated with crops and to allow that information to be used in managing farming systems. Performance of these systems has been examined (Burks et al., 2003; Rudolph and Searcy, 1994), and test standards are evolving for assessing performance of these technologies (*ASABE Standards*, 2007).

The need for higher precision in agricultural systems has been addressed by the introduction of wide-area differential GPS (WADGPS). These systems can deliver sub-decimeter level positioning precision and allow automated steering to be implemented. The StarFire WADGPS introduced by Deere and Co. has been commercially operational since 1999 (Dixon, 2006). An important milestone in the integration of GPS into agricultural electronics is the use of 32-bit CPUs. Most GPS systems incorporate a 32-bit CPU

The network communications standards, DIN 9684 and later ISO 11783, provided a framework for the introduction of multifunction precision farming systems (Stone et al., 1999). These systems have a multifunctional display or virtual terminal (VT) and integrate GPS and implement electronics into a system to support precision farming. Early examples of these systems are the Job Controller by Müller Electronik in 1994 (Sokol, 2000), Fieldstar by AGCO (Dronningborg) in 1995 (Sokol, 2000; AGCO, 2007), and Greenstar by John Deere in 1995. These systems are now transitioning to second-generation systems with greatly expanded functionality. Most VT designs are based on high-performance 32-bit microcontrollers and may have touch-screen displays with graphic resolution of 0.25 megapixels or greater.

During the early 2000s, automatic guidance systems for agricultural machines have rapidly emerged (Buick, 2006). These systems use differential GPS (DGPS) or real-time kinematic GPS (RTK) technology coupled with closed-loop steering control systems and an operator interface to provide automatic steering. A review of these guidance systems and associated technology can be found in Reid et al. (2000).

A natural extension of the development of automatic guidance is development of fully autonomous or robotic agricultural machines. Though there are currently few commercially available robotic agricultural machines, research and development with this focus is active. Promising work has been done to develop machine vision technology to allow fruit picking robots (Sites and Delwiche, 1985; Harrell, 1987). Burks et al. (2005) reviewed the research in this field and estimated that a 7 to 10 year program with funding at a high level is yet needed to bring this technology to fruition. Early work in development of robotic field equipment was done by Hoffman et al. (1996), who reported a fully automated swather that used GPS guidance with machine vision applied to manage obstacle avoidance and guidance enhancement. Gerrish et al. (1997) reported a vision-based automatically guided tractor. More recent studies include incorporation of high-resolution GPS, inertial guidance, and laser distance finding (Zhang and Qiu, 2004; Subramanian et al., 2006; Nagasaka et al., 2004). In a study examining control and safety needs for autonomous agricultural robots, Reid (2002) noted that they are yet a "long way from reality" with regards to safety, control, and cost.

Future Potential for Electronics Applications in Agricultural Equipment

The embedding of electronics into mobile agricultural equipment has allowed the equipment to better meet our expectations of functionality, efficiency, and environmental compatibility. Critical functionality of modern agricultural equipment could not be achieved without electronic systems. Market forces have driven the integration of electronics in the past and include the need to improve agricultural sustainability, provide profitability, meet regulatory requirements, and at the same time provide machines that are easily and comfortably managed. These forces are likely to shift in emphasis, but will remain to drive future development.

The current state of embedded electronics for mobile agricultural equipment is characterized by systems formed of multiple electronic control units interconnected in serial communications networks. The more advanced systems are constructed with 32-bit microcontrollers and include high-resolution, color, touch-screen display technology for operator interfaces. It is difficult to envision how further increases in computational performance will be leveraged in future systems, but emerging electronics technologies have been rapidly adopted in agricultural electronics since electronics technology emerged, and the trend is likely to continue. Moore (1965) observed that the number of devices per chip was doubling every 18 to 24 months. This trend is continuing yet today and presages very powerful embedded devices for mobile agricultural equipment.

The framework developed in ISO 11783 envisions support not only for basic implement-to-tractor communications but for a comprehensive information system for the full range of agricultural equipment. The standard provides an expansible message system and provides identity for most of the parameters used in machines today and support for messaging in the future. The existence of parameter and machine identity within ISO 11783 allows data communication throughout a farm-scale and larger information system. The possibility exists, for example, for a financial management system to be updated automatically for expenses and products used in field operations. ISO 11783 provides for communication of data to or from agricultural machines to or from off-board systems. Future systems are likely to better integrate information available at the field level with enterprise-wide information systems.

The information systems framework and computational resource is being developed to support future electronic systems for mobile agricultural equipment. Difficult problems will need to be overcome to allow development of more complex and powerful electronics-based systems in the future. Software development for current embedded systems continues to be done primarily in the C/C^{++} programming language. The process to create a new electronic system starts with comprehensive system requirements, which are translated by skilled designers into electronics hardware designs and program code. The result is tested and revised until suitable. Work is underway to produce development tools that can translate graphical chart specifications into embedded code. IAR, National Instruments, and Mathworks now make code generators that can translate statecharts into embedded code (National Instruments, 2005; IAR, 2007; Mathworks, 2005). National Instruments and other manufacturers have systems that compile high-level code specification directly into custom digital integrated circuits (field-programmable gate arrays, or FPGAs). Mathworks offers a "model-based design" environment that allows graphical modeling and simulation of physical prototypes to be integrated into the same environment in which control models are generated. The likelihood is that systems will develop that can translate carefully formed product requirements directly into custom digital integrated circuits.

Communication systems will remain one of the difficult issues as electronics evolve on mobile agricultural equipment. Connector costs for electronic control modules now rival the cost of other components in the system. The development of multiplexing network communications systems as standardized in ISO 11783 addresses minimization of wiring and connector costs. A further reduction in the wiring complexity of on-board mobile equipment and simplification of off-board communications may be at hand with the development of low-cost wireless technology. Standardization efforts have begun at ISO that may provide a framework for wireless systems for agricultural application. Higher data rates for network systems may also be at hand. Plastic optical fiber technology with the potential to increase data rates by ten-fold is now being pioneered in the automotive industry (Wei et al., 2005; Navet et al., 2005).

More powerful electronics and new production techniques will also create new possibilities in sensor technology. More accurate and more robust implement control systems require more sensitive sensors combined with the capability to process more data. In particular, the application of image processing and the integration of signals from different sensors in control loops will benefit from the increase in processing power and memory capacity at the same or less cost.

Embedded electronics are likely to become even more critical to the performance of mobile agricultural machines in the future. Some of the changes in mobile agricultural that may occur in the future, including autonomous machines, full integration of on-board information with off-board information systems, integration of power sources that use bio-based fuels, and integration of biosensor technology to improve implement function, will require more advanced electronic systems. Based on the developments in the past, the future looks promising for mobile agricultural electronics.

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