Available online at www.sciencedirect.com
SCIENCE DIRECT®
Computers and Electronics in Agriculture 50 (2006) 1–14
Computers and electronics in agriculture
www.elsevier.com/locate/compag

Review

Wireless sensors in agriculture and food industry—Recent development and future perspective

Ning Wang [a,*], Naiqian Zhang [b], Maohua Wang [c]

[a] MS1-027, Department of Bioresource Engineering, McGill University, Ste Anne de Bellevue, Que., Canada H9X 3V9
[b] Kansas State University, Manhattan, KS, USA
[c] China Agricultural University, Beijing, PR China

Received 18 March 2005; received in revised form 12 September 2005; accepted 21 September 2005

Abstract

This paper presents an overview on recent development of wireless sensor technologies and standards for wireless communications as applied to wireless sensors. Examples of wireless sensors and sensor networks applied in agriculture and food production for environmental monitoring, precision agriculture, M2M-based machine and process control, building and facility automation and RFID-based traceability systems are given. The paper also discusses advantages of wireless sensors and obstacles that prevent their fast adoption. Finally, based on an analysis of market growth, the paper discusses future trend of wireless sensor technology development in agriculture and food industry.

Keywords: M2M; ZigBee; Bluetooth; RFID

Contents

Abbreviations: CAN, controller area network; CDMA, code division multiple access; GSM, global system for mobile communications; GPRS, general packet radio service; HVAC, heating, ventilation and air conditioning; IEEE, Institute of Electrical and Electronics Engineers; IrDA, a suite of protocols for infrared data exchange, defined by Infrared Data Association; IT, information technology; LAN, local area network; M2M, machine-to-machine, machine-to-mobile or mobile-to-machine; MEMS, micro-electro-mechanical systems; NCAP, network capable application processor; NIST, National Institute of Standards and Technology; PDA, personal development assistant; RAS, remote application server; RFID, radio frequency identification technology; SPWAS, solar-powered data acquisition stations; STIM, smart transducer interface module; TEDS, transducer electronic data sheet; TII, transducer-independent interface; USDA, US Department of Agriculture; WiFi, wireless fidelity, usually refer to any type of IEEE 802.11 network; WINA, wireless industrial networking alliance; WLAN, wireless local area network; WPAN, wireless personal area network; WPS, wireless probe system; WPSRD, wireless personal safety radio device

* Corresponding author. Tel.: +1 514 3987781; fax: +1 514 3988387.
E-mail address: ning.wang@mcgill.ca (N. Wang).

0168-1699/$ – see front matter
doi:10.1016/j.compag.2005.09.003

1. Introduction

Wireless technologies have been under rapid development during recent years. Types of wireless technologies being developed range from simple IrDA that uses infrared light for short-range, point-to-point communications, to wireless personal area network (WPAN) for short range, point-to multi-point communications, such as Bluetooth and ZigBee, to mid-range, multi-hop wireless local area network (WLAN), to long-distance cellular phone systems, such as GSM/GPRS and CDMA.

Most people feel the strong impact of wireless technology mainly due to the astonishing growth of cell-phone market. However, not many people have realized that the demand of bandwidth for wireless, interpersonal communications, such as cellular phones, will soon become a minority share of the total available bandwidth, perhaps only 3% by the end of the decade (Sensors Magazine, 2004). A far greater potential exists for development and applications of other types of wireless technologies, especially wireless sensors and sensor networks, starting from military and environmental monitoring, moving towards machine-to-machine communications (M2M), and eventually reaching all aspects of our lives.

A wireless sensor network is a system comprised of radio frequency (RF) transceivers, sensors, microcontrollers and power sources. Wireless sensor networks with self-organizing, self-configuring, self-diagnosing and self-healing capabilities have been developed to solve problems or to enable applications that traditional technologies could not address. Once available, these technologies would allow us to find many new applications that could not have been considered possible before.

Wireless sensor technology is still at its early development stage. Applications of wireless sensors in agriculture and food industry are still rare. This paper intends to give an overview of available wireless sensor technologies that are applicable to agriculture and food industry. Examples of such applications are provided through an extensive search of literature and Internet.

2. Why wireless sensors?

An obvious advantage of wireless transmission is a significant reduction and simplification in wiring and harness. It has been estimated that typical wiring cost in industrial installations is US$ 130–650 per meter and adopting wireless technology would eliminate 20–80% of this cost (Sensors Magazine, 2004). Additional savings in overall cost can be obtained by more efficient control of the equipment through effective monitoring of the environment. For example, Honeywell installed a wireless system to monitor steam traps and saved the company US$ 100,000–300,000 per year (Crossbow Technology Inc., 2004).

Wireless sensors allow otherwise impossible sensor applications, such as monitoring dangerous, hazardous, unwired or remote areas and locations. This technology provides nearly unlimited installation flexibility for sensors and increased network robustness. Furthermore, wireless technology reduces maintenance complexity and costs.

Wireless sensor networks allow faster deployment and installation of various types of sensors because many of these networks provide self-organizing, self-configuring, self-diagnosing and self-healing capabilities to the sensor nodes. Some of them also allow flexible extension of the network.

Wireless sensor technology allows MEMS sensors to be integrated with signal-conditioning and radio units to form "motes" with extremely low cost, small size and low power requirement. MEMS inertial sensors, pressure sensors, temperature sensors, humidity sensors, strain-gage sensors and various piezo- and capacitive sensors for proximity, position, velocity, acceleration and vibration measurement have been integrated to wireless sensor nodes and have become available on the market (Crossbow Technology Inc., 2004).

Another advantage of wireless sensors is their mobility. These sensors can be placed in transporting vehicles to monitor the "on-the-go" environment. They also can be placed on rotating equipment, such as a shaft to measure critical parameters.

Most wireless sensors have signal conditioning and processing units installed at the location of the sensors and transmit signals in the digital form. As a result, noise pick-up becomes a less significant problem. Moreover, since wires are deleted from the transmission, reliability of signal transmission is enhanced.

3. Hardware and software requirements for wireless sensors and "motes"

Hardware requirements for wireless sensors include: (1) robust radio technology, (2) low cost, energy-efficient processor, (3) flexible I/O for various sensors, (4) long-lifetime energy source and (5) flexible, open source development platform. Various types of "motes", which are integrated processor-radio units, have been developed to satisfy these requirements. Software requirements for wireless sensors include: (1) small footprint to run on small processors, (2) efficient energy use, (3) capability of fine grained concurrency, (4) high modularity and (5) robust ad hoc mesh networking that requires low power. The "TinyOS" operating system under development serves as a good example for such software (Crossbow Technology Inc., 2004).

In a wireless sensor network setting, a node in the network can be formed by a sensor/data acquisition board and a mote (processor/radio board). These nodes can communicate with a gateway unit, which has the capability of communicating with other computers via other networks, such as a LAN, a WLAN, a WPAN and the Internet. Wireless sensor boards available on the market include accelerometers, barometric pressure sensors, light sensors, GPS modules, temperature sensors, humidity sensors, acoustic sensors, magnetic RPM sensors, magnetometers, pyroelectric IR occupancy detectors, solar radiation sensors, soil moisture sensors, soil temperature sensors, wind speed sensors, rainfall meters and seismic sensors.

4. Wireless standards and proprietary wireless sensor technologies

Various wireless standards have been established. Among them, the standards for wireless LAN, IEEE 802.11b ("WiFi") (IEEE, 1999b) and wireless PAN, IEEE 802.15.1 (Bluetooth) (IEEE, 2002) and IEEE 802.15.4 (ZigBee) (IEEE, 2003), are used more widely for measurement and automation applications. All these standards use the instrumentation, scientific and medical (ISM) radio bands, including the sub-GHz bands of 902–928 MHz (US), 868–870 MHz (Europe), 433.05–434.79 MHz (US and Europe) and 314–316 MHz (Japan) and the GHz bands of 2.400–2.4835 GHz (worldwide acceptable). In general, a lower frequency allows a longer transmission range and a stronger capability to penetrate through walls and glass. However, due to the fact that radio waves with lower frequencies are easier to be more easily absorbed by various materials, such as water and trees, and that radio waves with higher frequencies are easier to scatter, effective transmission distance for signals carried by a high-frequency radio wave may not necessarily be shorter than that by a lower frequency carrier at the same power rating. The 2.4 GHz band has a wider bandwidth that allows more channels and frequency hopping and permits compact antennas.

Wireless LAN (IEEE 802.11) is a flexible data communication protocol implemented to extend or substitute for a wired local area network, such as Ethernet. The bandwidth of 802.11b is 11 Mbits and it operates at 2.4 GHz frequency. Bluetooth (IEEE 802.15.1) is a wireless protocol that is used for short-range communication. It uses the 2.4 GHz, 915 and 868 MHz radio bands to communicate at 1 Mbit between up to eight devices. The Bluetooth is considered a cable replacement for mobile devices. It is mainly designed to maximize the ad hoc networking functionality.

The IEEE 802.15.4 standard is a physical radio specification providing for low data rate connectivity among relatively simple devices that consume minimal power and typically connect over short distances. It is ideal for monitoring, control, automation, sensing and tracking applications for the home, medical and industrial environments. Features of IEEE 802.15.4 devices include:

- 868 MHz band, 1 channel, 20 kbps;
- 915 MHz ISM band, 10 channels, 40 kbps;
- 2.4 GHz ISM band, 16 channels, 250 kbps;
- connecting up to 255 devices per network;
- full protocol for transfer reliability;
- power management to ensure low power consumption.

ZigBee is established by the ZigBee Alliance that is supported by more than 70 member companies. It adds network, security and application software to the IEEE 802.15.4 standard. Owing to its low power consumption and simple networking configuration, ZigBee is considered the most promising for wireless sensors. Currently, the ZigBee specification is still under development. Table 1 compares the three wireless standards that are most suitable for wireless sensor network.

The wireless standards also address the network issues for wireless sensors. Three types of networks: star network, hybrid network and mesh network, have been developed and standardized. The Bluetooth technology uses star networks, which are composed of piconets and scatternets. Each piconet connects one master node with up to seven slave nodes, whereas each scatternet connects multiple piconets, to form an ad hoc network. The ZigBee technology uses hybrid star networks, which uses multiple master nodes with routing capabilities to connect slave nodes, which have no routing capability (Sensicast, 2004).

The most efficient networking technology uses peer-to-peer, mesh networks, which allow all the nodes in the network to have the routing capability. Mesh networks allow autonomous nodes to self-assemble into the network. It also allows sensor information to propagate across the network with a high reliability and over an extended range. In addition, it allows time synchronization and low power consumption for the “listeners” in the network and, thus, extending the battery life (Crossbow Technology Inc., 2004).

When a large number of wireless sensors need to be networked, several levels of networking may be combined. For example, an 802.11 (WiFi) mesh network comprised of high-end nodes, such as gateway units, can be overlaid on a ZigBee sensor network to maintain a high level of network performance. A remote application server (RAS) can also be deployed in field close to a localized sensor network to manage the network, to collect localized data, to host

Table 1
Comparison between wireless LAN, Bluetooth and ZigBee

Feature	WiFi (IEEE 802.11b)	Bluetooth (IEEE 802.15.1)	ZigBee (IEEE 802.15.4)
Radio	DSSS[a]	FHSS[b]	DSSS
Data rate	11 Mbps	1 Mbps	250 kbps
Nodes per master	32	7	64,000
Slave enumeration latency	Up to 3 s	Up to 10 s	30 ms
Data type	Video, audio, graphics, pictures, files	Audio, graphics, pictures, files	Small data packet
Range (m)	100	10	70
Extendability	Roaming possible	No	Yes
Battery life	Hours	1 week	>1 year
Bill of material (US$)	9	6	3
Complexity	Complex	Very complex	Simple

[a] DSSS, direct sequence spread spectrum.
[b] FHSS, frequency hopping spread spectrum.

web-based applications, to remotely access the cellular network via a GSM/GPRS or a CDMA-based modem and, in turn, to access the Internet and remote users (Crossbow Technology Inc., 2004).

Proprietary wireless sensor technologies have been developed even before the development of various standards. As an example, Crossbow Technology produced a series wireless sensor products, including motes running at different frequencies, various sensor boards and gateway units. A new model of motes was recently designed to conform to the ZigBee specification. Another new model of motes currently being developed will allow signal transmissions over a distance of several miles (Crossbow Technology Inc., 2004). Freescale Semiconductor also provides both standard-conforming and proprietary hardware and software products for wireless sensor networks (Freescale, 2004).

5. Wireless sensors and “smart transducers”

“Smart transducers” are sensors or actuators equipped with microcontrollers to provide local “intelligence” and network capability. Standardization efforts initiated by the National Institute of Standards and Technology (NIST) have led to development of the IEEE 1451 standards (IEEE, 1997, 1999a) for smart transducers. Architecture of a smart transducer comprises a smart transducer interface module (STIM), a network capable application processor (NCAP), a transducer-independent interface (TII) between the STIM and the NCAP, and a network. Each STIM and NCAP module contains an independent microcontroller. Transducers (sensors or actuators) and their signal conditioning circuitry are considered parts of the STIM. Analog and digital signals from sensors can be connected to the STIM’s microprocessor through an analog-to-digital converter (ADC) and digital input (DI) ports, respectively. Control signals can be sent to actuators through a digital-to-analog converter (DAC) or digital output (DO) ports of the microprocessor. Thus, an STIM module can accommodate a wide variety of sensors and actuators. The standards also specify a transducer electronic data sheet (TEDS) within the STIM to describe characteristics of the transducers. The NCAP functions as a gateway between a network structure and the STIM. It accesses the STIM transducer data on one side via the TII interface and accesses the network resources on the other side. The TII and the NCAP together provide a network-enable and network-independent capability for smart transducers.

A new standard (IEEE 1451.5) is currently being developed to bridge wireless sensors with the “smart transducer” concept to produce intelligent wireless sensors that combine sensing, computing and communication. Using this standard, intelligent sensors and actuators can be connected to a common network through both wired and wireless transmissions to perform sophisticated functions. The IEEE 1451.5 standard will address the integration of smart transducers with various wireless communication protocols, such as 802.11 (WiFi), 802.15.4 (Bluetooth) and 802.15.5 (ZigBee). A set of requirements for wireless sensor communications will be defined in the standard, including issues related to wireless sensor model, TEDS, user requirements, data integrity, security and bandwidth. The interface defined in this standard will replace the TII interface with wireless links.

6. Applications of wireless sensors and networks in agriculture and food production

Deployment of wireless sensors and sensor networks in agriculture and food industry is still at the beginning stage. Applications can be classified into five categories: (1) environmental monitoring, (2) precision agriculture, (3) machine and process control, (4) building and facility automation and (5) traceability systems.

6.1. Environmental monitoring

In spite of the rapid development of computer technology, field measurements of environment variables, such as weather data and geo-referenced water quality data still depend on stationary sensors and dataloggers, pencils and paper notebooks, which are labor-intensive and susceptible to recording errors during transcription (Vivoni and Camilli, 2003).

6.1.1. Weather monitoring

The Discovery Channel (2003) reported an application of a wireless sensor network in a vineyard in BC, Canada. Sixty-five motes were installed in a 1-acre land to remotely report temperature, moisture and sun light intensity to a central PC every 5 min. The owner could easily monitor each area of the vineyard in real-time to avoid frost, manage irrigation, determine fertilizer applications and arrange harvest schedule.

A solar-powered wireless sensor network was reported by Crossbow Technology Inc. (2004) to provide weather information in fields. A remote application server relayed data from the sensor network to local users via a WLAN and remote users via cellular network and the Internet.

6.1.2. Geo-referenced environmental monitoring

Vivoni and Camilli (2003) developed a wireless prototype system to acquire, store, display and transmit real-time, geo-referenced environmental data between multiple field teams and remote locations. In the system, field teams with handheld data collection units communicated to each other or with a field station server through a WLAN. The field station server combined information received from all the teams and periodically reported to a remote web/data server through a dual-frequency mobile phone (GSM/GPRS service at 900 MHz and 1.9 GHz). Field tests, conducted in MA, USA and NSW, Australia, demonstrated a great potential to improve efficiency and precision for field environment data collections.

Perkins et al. (2002) introduced a low cost, low power, self-organizing sensor network, neuRFon®, developed by Motorola Labs. The system can be used to sense agricultural, environmental and process parameters.

A passive remote identification and sensor system was developed by Rusko et al. (1999) using surface acoustic wave resonators in the European 433.92 MHz ISM-band. The system featured long durability and environmental compatibility for identification and environmental monitoring applications.

6.2. Precision agriculture

Wireless sensors have been used in precision agriculture to assist in (1) spatial data collection, (2) precision irrigation, (3) variable-rate technology and (4) supplying data to farmers.

6.2.1. Spatial data collection

A mobile field data acquisition system was developed by Gomide et al. (2001) to collect data for crop management and spatial-variability studies. The system consisted of a data collection vehicle, a manager vehicle and data acquisition and control systems on farm machines. The system was able to conduct local field survey and to collect data of soil water availability, soil compaction, soil fertility, biomass yield, leaf area index, leaf temperature, leaf chlorophyll content, plant water status, local climate data, insect-disease-weed infestation, grain yield, etc. The data collection vehicle retrieved data from farm machines via a WLAN and analyzed, stored and transmitted the data to the manager vehicle wirelessly. The manager and engineers in the manager vehicle monitored the performances of the farm machines and the data acquisition systems, and troubleshoot problems based on received data.

Lee et al. (2002) developed a silage yield mapping system, which included a GPS, load cells, a moisture sensor and a Bluetooth wireless communication module. The moisture sensor and the Bluetooth transmitter were installed on the chopper. Signal from the moisture sensor was sent to a Bluetooth receiver on a host PC at a data rate of 115 kbps and was used to correct the yield data.

Mahan and Wanjura (2004) cooperated with a private company to develop a wireless, infrared thermometer system for in-field data collection. The system consisted of infrared sensors, programmable logic controllers and low power radio transceivers to collect data in the field and transmit it to a remote receiver outside the field.

6.2.2. Precision irrigation

Damas et al. (2001) developed and tested a distributed, remotely controlled, automatic irrigation system to control a 1500 ha irrigated area in Spain. The area was divided into seven sub-regions with a total of 1850 hydrants installed. Each sub-region was monitored and controlled by a control sector. The seven control sectors communicated to each other and with a central control through a WLAN network. Field tests showed 30–60% saving in water usage.

Evans and Bergman (2003) are leading a USDA research group to study precision irrigation control of self-propelled, linear-move and center-pivot irrigation systems. Wireless sensors were used in the system to assist irrigation scheduling using combined on-site weather data, remotely sensed data and grower preferences.

6.2.3. Variable-rate technology

Cugati et al. (2003) developed an automated fertilizer applicator for tree crops. The system consisted of an input module for GPS and real-time sensor data acquisition, a decision module for calculating the optimal quantity and spread pattern for a fertilizer, and an output module to regulate the fertilizer application rate. Data communications among the modules were established using a Bluetooth network.

6.2.4. Supplying data to farmers

A web server developed by Jensen et al. (2000) provided information on pest and disease infestation and weather forecasts. Farmers can download the information directly via Internet and use them for operation scheduling.

USDA (Flores, 2003) conducted a research in Mississippi to develop a high-speed wireless networking system to help farmers download aerial images via WLAN to their PCs, laptops or PDAs. The images were mainly used for precision farming applications.

6.3. Machine and process control—M2M

M2M is a technology that supports wired or wireless (WPAN, WLAN, cellular systems, ...) communications from machine to machine, from machine to mobile or from mobile to machine. M2M technology greatly enhances automation of a system (a machine system, a process or a business) and integrates discrete assets within the system with an IT system. To date, this concept has been developed mainly for industry and businesses. Application examples of M2M in agriculture given below can be categorized to (1) vehicle guidance, (2) machinery management, (3) robotic control and (4) process control, although none of these applications completely used M2M in its real sense.

6.3.1. Vehicle guidance

A WLAN-based, real-time, vehicle-to-vehicle data communication system was established by Guo and Zhang (2002) to exchange information between vehicles on vehicle states and operation control variables. Laboratory and field tests demonstrated the feasibility of real-time, wireless data communications between vehicles in autonomous, master-slave vehicle guidance.

Charles and Stenz (2003) implemented an autonomous tractor for spray operations in fields. During spraying, the tractor drove fully autonomously at least 90% of the time. This tractor could also be precisely controlled by a supervisor through a radio link.

Ribeiro et al. (2003) developed an autonomous guidance tractor for spray operations in citric and olive trees fields in Spain. A user-friendly visualization agent was developed for human operators to remotely control and supervise unmanned tractors in a field through WLAN.

Stentz et al. (2002) developed a wireless link between tractors and a human supervisor in a fleet of semi-autonomous tractors. Each tractor had the capability to detect people, animals and other vehicles in its predefined path and to stop before hitting such obstacles until it received control commands from a supervisor over a wireless link.

A wireless personal safety radio device (WPSRD) was developed to avoid collisions between human and vehicle (Chung et al., 2001). The WPSRD system included a host system, a number of stationary radio units installed on fixed properties, and a number of mobile radio units carried by personnel or autonomous vehicles, covering a known area. The host system communicated with all stationary and mobile units wirelessly, monitored the distance between any two units, and initiated various actions and warnings in response to possible collision.

6.3.2. Machinery management

McKinion et al. (2003, 2004a,b) established a WLAN-based data communication system to connect a farm station with machines, such as cotton pickers, spray equipment, variable-rate fertilized application equipment and hand-held personal digital assistant computers in the field and allowed a rapid, bi-directional communication of data and information.

Krallmann and Foelster (2002) reported a remote service system for agricultural machinery to achieve maximum availability and minimum break down time. A wireless LAN with a data transmission rate of 11 Mbits acted as the communication medium.

6.3.3. Robotic control

Hirakawa et al. (2002) designed a distributed wireless robot control system, in which the robot manipulator was controlled by local link controllers. A master controller sent/received control commends and data to/from each local controller through a radio frequency transmission. Meanwhile, a wireless power transmission system was designed using axial transformers. This wireless control eliminated wires and cables, increased the mobility of the robot arms, and improved the adaptability of the robot.

6.3.4. Process control

Heimerdinger (2000) designed a wireless probe system (WPS) to monitor moisture content of wood during the drying process in real-time. The WPSs installed at various locations of the wood had self-powered radio transmitter to send data to a receiver at a central station using unlicensed ISM bands of 900 MHz in North America or 433 MHz in Europe. The experiment proved that the WPS greatly improved the accuracy and efficiency of the drying processes and reduced the cost of the data acquisition system.

6.4. Facility automation

Agricultural facilities, such as greenhouses and animal-feeding facilities, includes HVAC, lighting control, energy management, access control, structural monitoring and fire/security. Standards for wired HVAC control systems (LonWorks, BacNet, etc.) have been established for a long time. Standards for wireless-based systems are currently under development (Crossbow Technology Inc., 2004).

6.4.1. Greenhouse control

Serôdio et al. (1998, 2001) developed and tested a similar distributed data acquisition and control system for managing a set of greenhouses. Several communication techniques were used for data communications. At a lower supervision level, inside each greenhouse, a WLAN network with a radio frequency of 433.92 MHz was used to link a sensor network to a local controller. A controller area network (CAN) was provided to link an actuator network to the local controller. Through another RF link (458 MHz), several local controllers were connected to a central PC. A high level data communication was provided through Ethernet to connect the central PC to a remote network.

Morais et al. (1996) implemented a wireless data acquisition network to collect outdoor and indoor climate data for greenhouses in Portugal. Several solar-powered data acquisition stations (SPWAS) were installed indoor and outdoor to measure and monitor the climate data. RF links were established among multiple (up to 32) SPWASs and a base station, which was used to control the SPWASs and to store the data.

Liu and Ying (2003) reported a greenhouse monitoring and control system using the Bluetooth technology. The system collected environment data from a sensor network in a greenhouse and transmitted the data to a central control system.

Mizunuma et al. (2003) deployed a WLAN in farm field and greenhouse to monitor plant growth and implemented remote control for the production system. They believed that this type of remote control strategy could greatly improve productivity and reduce labor requirement.

6.4.2. Animal-feeding facilities

Monitoring climate-related variables within an animal house can help maintain good animal health. Pessel and Denzer (2003) developed a portable, mobile instrument to measure temperature, relative humidity, noise, brightness and ammonia content in the air within the house and transferred the data wirelessly to a PC through an infrared data link.

The quality of indoor environment of a horse-riding arena is very important to the horses as well as the riders. To monitor temperature and humidity, several Hobo Pro dataloggers with wireless radio modems (Onset Computer Corporation, Pacasset, MA) were used by Wheeler et al. (2003) to measure temperature and humidity inside the arenas. Data were transmitted to a central controller via the 900 MHz license-free ISM band to realize on-line, indoor environment control.

6.5. Traceability systems (RFID)

With an increasing demand for security and safety, complete documentations for food products, from field to customer, have become increasingly demanding (Thysen, 2000). RFID has been accepted as a new technology for a well-structured traceability system on data collecting, and human, animal and product tracking (Sahin et al., 2002). It has been projected that the applications of RFID will grow rapidly in the next 10 years with a compound annual revenue growth rate (2003–2010) of 32.2% (Sangani, 2004). To support these great application potentials of RFID, much research has been conducted.

6.5.1. Animal identification and health monitoring

Nagl et al. (2003) designed a remote health-monitoring system for cattle that incorporated various sensors, including a GPS unit, a pulse oximeter, a core body temperature sensor, an electronic belt, a respiration transducer and an ambient temperature transducer. The system communicated wirelessly with a base station via Bluetooth telemetry. Taylor and Mayer (2004) reported a study on a "smart", comprehensive animal management system. Each animal is fed with a wireless sensor and a mote, which can provide accurate measurements of the location and health-related information of the animal wirelessly. Haapala (2003) tested the performance of electronic identification tags and various readers on cattle under extremely cold temperature in Finland. Brown-Brandl et al. (2001) tested a short-range telemetry system for measuring core body temperature in poultry, beef and dairy cattles. Temperature transmitters were implanted into the body of animals. A CorTemp^{TM} miniaturized ambulatory logger received the temperature data wirelessly. Test results showed good accuracy, resolution, and response time for temperature measurement. Kononoff et al. (2002) used a wireless automatic system to record the chewing and ruminating behaviors to study the dietary factors affecting normal rumen function of dairy cows.

Butler et al. (2004) developed a "moving virtual fence" algorithm for herding cows. Each animal in the herd is given a smart collar consisting of a GPS, a PDA, a radio unit (WLAN) and a sound amplifier. The animal's location was determined using the GPS and was verified through a measurement of proximity of the cow relative to the fence boundary. When approaching the perimeter, the animal was presented with a sound stimulus, which drove the animal away from the fence.

6.5.2. Food packaging

Wentworth (2003) conducted a study aimed at inexpensive, disposable RFID biosensor tags used on food products for history checking and contamination and inventory control. The biosensor was based on an acoustic wave platform and used antigen-antibody reaction to detect bacteria. Chandler (2003) discussed the potential of RFID tags for "smart packaging", automatic checkout, "smart appliances", "smart recycling" and marketing/promotional opportunities. He believed that this type of technology could improve security, productivity, inventory control, traceability and result in capital and operational savings.

6.5.3. Transportation

Gebresenbet et al. (2003) and Geers et al. (1998) proposed an on-the-road monitoring system for animals during transportation. The system included sensors installed in the animal compartment to identify the animals and to monitor the air-quality, vibration and animal behaviors. A GPS provided the location of the vehicle. A data transfer unit regularly sent data to a service center via the GSM network. It was reported that the system greatly improved animal welfare during handling and transportation.

6.5.4. Food inspection

Najjar et al. (1997) developed a handheld PC for quality inspectors of a food-processing plant. The system allowed inspectors to select a form, complete the form, and send the data to the plant manager's computer through a 16-bit, full duplex audio, and 2 Mb/s wireless data communication. The system also allowed mobile workers to use their voices, rather than their hands, to enter data from anywhere in the plant.

In recent years, wireless sensors have been adopted in food processing to monitor and control the quality attributes of food products. For example, a temperature sensor can be inserted into a food can to record the evolution of temperature, and transmit the temperature data wirelessly to a central controller. Marra and Romano (2003) developed a mathematical model to study the effects of different methods of inserting wireless temperature sensors into conductive canned food for monitoring thermal sterilization.

A wireless, passive resonant sensor was developed by Ong et al. (2001) to monitor the bacterial concentration in food products. The sensor was built on a thin film with an LC resonant circuit and was placed on a biological medium. The resonant signals related to the bacterial concentration in the medium were detected remotely by a loop antenna. The sensor showed great potential for food quality monitoring.

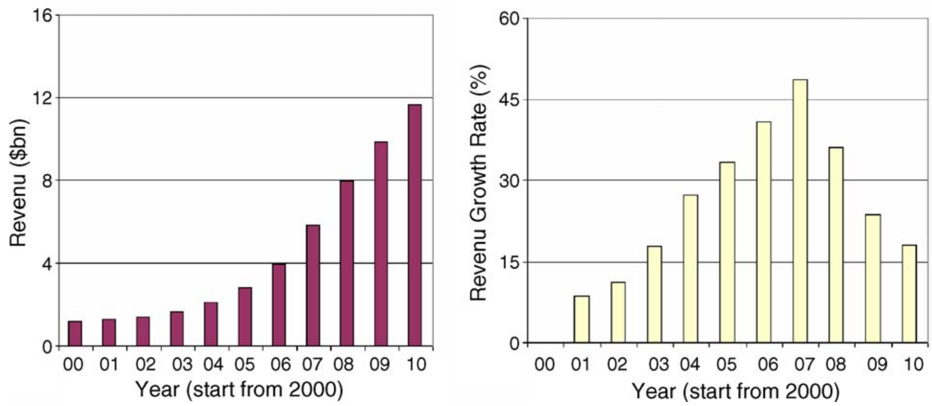

Fig. 1. Total RFID-base applications market: worldwide revenue forecasts, 2000–2010 (Frost and Sullivan, 2004).

7. Market growth

As sensors rapidly proliferate in a wide variety of applications and industries, the cost of sensors has been continuously declining. The recent trend of developing new standards with the help of industry alliances has greatly helped the industry move toward lower cost, higher functioning wireless systems. Development and adoption of wireless technologies remain fragmented with no single supplier or pervasive application dominating. Wireless sensing and the overall 'machine-to-machine' paradigm have continued to be proven financially beneficial while addressing near-term enterprise priorities.

The market for wireless sensors has had a steady increase over the past decade. In 2004, 200,000–500,000 wireless sensor networks have been sold. It is predicted that this number will increase to 6–10 million in 2006. In terms of dollars, shipments of wireless products will increase three times from 2003 to 2006. On World Inc. (2004), a wireless market research firm, also predicted that "Once the market reaches critical mass by 2008, . . . this segment will grow by at least 200% per year until the market is saturated".

As an important component of wireless sensor technology, revenue for RFID products is also predicted to grow steadily over the next 6 years (Fig. 1). Wireless M2M is expected to reach US$ 4 billion per year by 2008 (Alexander Resources, 2004).

It was also predicted that the cost for wireless sensor products would decline sharply over the next four years (Fig. 2). The price will fall by over 50% every 18 months at any given volume (Crossbow Technology Inc., 2004).

The wireless industrial networking alliance (WINA) sponsored by the US Department of Energy's Office of Industrial Technology forecast that widespread use of wireless sensors could improve manufacturing production and energy efficiency by 10%. WINA stated: "Wireless technology and wireless networking systems hold great promise to help US industry use energy and materials more efficiently, lower systems and infrastructure costs, lower production costs and increase productivity" (WINA, 2004).

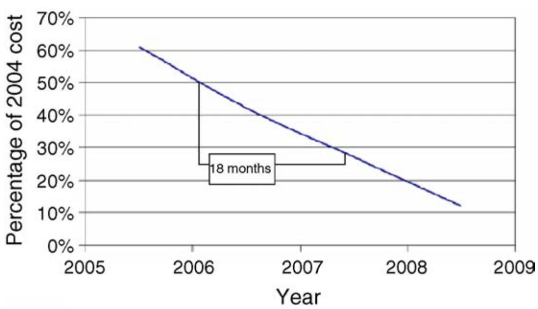

Fig. 2. Projected price reduction for wireless sensor products (Crossbow Technology Inc., 2004).

8. Obstacles

Development of wireless sensor technology has traveled a “zigzag” path. Despite the fact that the great potentials of this technology have been recognized by many and that development of this technology has been supported by enthusiastic industry alliances, adoption of wireless sensor technology has not been as fast as one would imagine. Main obstacles may include:

1. Standardization is not yet completed. A big sign, “Path ahead is still under construction”, is in most people’s minds.
2. Early adopters are still “smoothing out the bumps” and many potential adopters are waiting on the sidelines for proofs of successful and safe adoptions.
3. The massive data generated by wireless sensors have the potential to overwhelm while providing limited values unless the structure and process are in place to take advantage of all their potential.
4. Existing IT infrastructure, predominately wired communication structures, were simply not designed for pervasive inputs and require significant overhaul.
5. Compatibility with legacy systems is not addressed so that many existing systems prevent adoption of wireless products. Complete adoption may require abolishment of existing, wired infrastructure and changes to status quo. Once implemented, the flexibility of infrastructure may be restricted.
6. Security issues need to be resolved; the WLAN security crisis may serve as an example.
7. Complexity and high cost for coverage in large plants prevent fast adoption.
8. Power supply is always a great concern for wireless systems.
9. The reliability of wireless system remains unproven and it is considered too risky for process control.
10. Lack of experienced staff for troubleshooting.

9. Future trends

In the past, excessive wiring was considered a sign of technological advancement for mobile vehicles. In 1955, the total length of electrical wires on a state-of-the-art automobile was about 45 m. This number grew to 4 km on a high-end vehicle in 2002. Although networks on mobile vehicles, such as the controller area network, have greatly reduced the amount of wires and harness, the most advanced control technologies on modern vehicles still are closely tied to “wire”, “steer-by-wire”, “break-by-wire”, “suspension-by-wire” and “throttle-by-wire”. Replacing “X-by-wire” with “X-by-wireless” still is considered unreliable and unsafe. While auto industry has started considering replacing wired controls with wireless controls, an important aspect of the M2M revolution, agricultural machinery industry has not. It has been projected that the auto industry will eventually start adopting wireless technologies before the end of this decade (Fig. 3) and it is safe to project that a similar trend will become apparent to farm machinery industry, only with a phase delay.

Large-power and heavy weight farm machines have become the de-facto tools for agricultural operations, a status quo. These machines cause permanent damage to fields by compaction. They consume an enormous amount of fuel, and their large size prevents “farming by foot” and “farming by plant”, the real sense of precision agriculture. It has been suggested that small robots that can be programmed to execute various functions in crop fields, in greenhouses, as well as in orchards, forestry and plantations may eventually replace the large machines. Wireless sensors and computer-controlled robots are a perfect combination to fit in this trend. Local wireless sensor networks can be overlaid with a wireless LAN to accomplish various farming operations in a systematic, precise and well-managed fashion.

As the demand for food quality, health benefits, and safety increases, more stringent scrutiny on the inspection of agri-food products have become mandatory. Also being increasingly demanded is “traceability”, which requires not only rigorous inspections, but also systematic detection, labeling and recording of quality and safety parameters while archiving the entire agri-food production chain, from farms to consumers’ tables. RFID has been considered the most important identification tool to establish an effective “traceabilty system” (Sahin et al., 2002). Compared with the traditional barcode method, RFID allows an “intelligent tag” assigned to each individual product to be read at any position without physical contact with the readers. Furthermore, the intelligent tag can be updated along the entire supply chain to provide complete archives of information on the growth, processing, packaging, transportation, distribution, storage, shelving and recycling. When combined with wireless sensors, the RFID system also can record

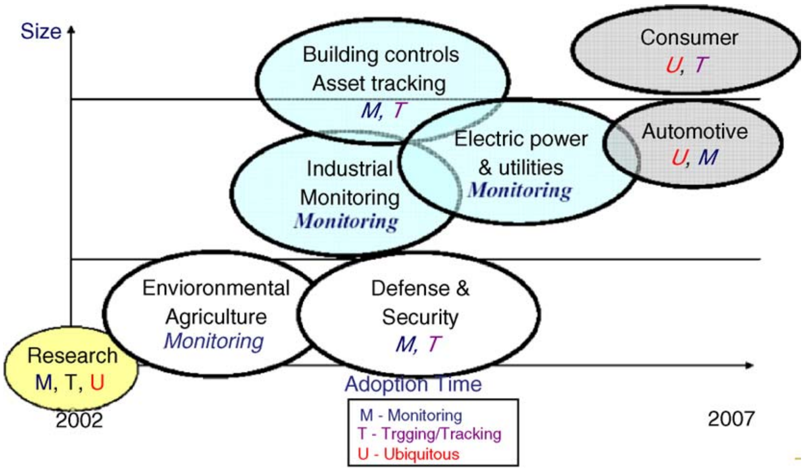

Fig. 3. Summary and projection of wireless market (Crossbow Technology Inc., 2004).

environmental parameters and specific quality/safety attributes of the product along the chain. It can be predicted that deployment of RFID and wireless sensors in traceability systems will experience a great boom in the near future.

Since computers entered our lives 60 years ago, computing has experienced three waves: the first (1940–1980) was mainframes, where one computer was shared by many people. The second wave, still peaking, puts a computer and a person across the desktop, staring at each other uneasily. The third wave, just beginning, has many computers serving each person everywhere in the world. People call it "ubiquitous computing", or the age of *calm technology*, where technology recedes into the background of our lives to free our minds from a large amount of "intelligent" work, so that we can concentrate on the main challenges (Weiser, 1996). Sensors Magazine (2004) interpreted the idea of ubiquitous computing as "virtually everything can be embedded with tiny wireless sensor-based systems (including microprocessors and communication capabilities), which can connect to an infinite network of other devices that affect changes on behalf of humans". Obviously, this concept can be applied to any field, including agriculture and food industry. Wireless sensors and sensor networks have just entered farms and food plants. They will have a bright future.

References

Alexander Resources, 2004. Wireless M2M and Telemetric: Gaining Value in Vertical Markets, http://www.alexanderResources.com.

Brown-Brandl, T.M., Yanagi, T., Xin, H., Gates, R.S., Bucklin, R., Ross, G., 2001. Telemetry system for measuring core body temperature in livestock and poultry. ASAE Paper No.: 01-4032. The American Society of Agriculture Engineers, St. Joseph, Michigan, USA.

Butler, Z., Corke, P., Peterson, R., Rus, D., 2004. Virtual fences for controlling cows. In: Proceedings of the 2004 IEEE International Conference on Robotics and Automation, New Orleans, LA, USA, April 26–May 1, pp. 4429–4436.

Chandler, S., 2003. Vision of the future for smart packaging for brand owners. In: Proceedings of the International Conference on Smart and Intelligent Packaging, Barcelona, Spain, October 28–29, pp. 253–269.

Charles, K., Stenz, A., 2003. Automatic Spraying for Nurseries. USDA Annual Report. Project Number: 3607-21620-006-03. September 22, 2000–August 31, 2003. USDA, USA.

Chung, Y.C., Olsen, S.L., Wojcik, L., Song, Z., He, C., Adamson, S., 2001. Wireless safety personnel radio device for collision avoidance system of autonomous vehicles. In: Digest of 2001 IEEE Antennas and Propagation Society International Symposium, Boston, MA. USA, July 8–13, pp. 121–124.

Crossbow Technology Inc., 2004. Smart Dust/Mote Training Seminar. Crossbow Technology, Inc., San Francisco, California, July 22–23.

Cugati, S., Miller, W., Schueller, J., 2003. Automation concepts for the variable rate fertilizer applicator for tree farming. In: The Proceedings of the 4th European Conference in Precision Agriculture, Berlin, Germany, June 14–19.

Damas, M., Prados, A.M., Gómez, F., Olivares, G., 2001. HidroBus® system: fieldbus for integrated management of extensive areas of irrigated land. Microprocessors Microsyst. 25, 177–184.

Discovery Channel, 2003. http://www.exn.ca/video/?video=exn20030925-wine.asx.

Evans, R., Bergman, J., 2003. Relationships Between Cropping Sequences and Irrigation Frequency under Self-Propelled Irrigation Systems in the Northern Great Plains (Ngp). USDA Annual Report. Project Number: 5436-13210-003-02. June 11, 2003–December 31, 2007.

Flores, A., 2003. Speeding up data delivery for precision agriculture. Agric. Res. Mag.: The United State Department of Agriculture (USDA) 51 (6), 17.

Freescale Semiconductor, 2004. http://www.freescale.com.

Frost and Sullivan, 2004. http://www.mindbranch.com/products/R49-216.html.

Gebresenbet, G., Ljungberg, D., Van de Water, G., Geers, R., 2003. Information monitoring system for surveillance of animal welfare during transport. In: Proceedings of the 4th European Conference in Precision Agriculture, Berlin, Germany, June 14–19.

Geers, R., Saatkamp, H.W., Goossens, K., Van Camp, B., Gorssen, J., Rombouts, G., Vanthemsche, P., 1998. TETRAD: an on-line telematic surveillance system for animal transports. In: Computers and Electronics in Agriculture, vol. 21. Elsevier, pp. 107–116.

Gomide, R.L., Inamasu, R.Y., Queiroz, D.M., Mantovani, E.C., Santos, W.F., 2001. An automatic data acquisition and control mobile laboratory network for crop production systems data management and spatial variability studies in the Brazilian center-west region. ASAE Paper No.: 01-1046. The American Society of Agriculture Engineers, St. Joseph, Michigan, USA.

Guo, L.S., Zhang, Q., 2002. A wireless LAN for collaborative off-road vehicle automation. In: Proceedings of Automation Technology for Off-Road Equipment Conference, Chicago, Illinois, USA, July 26–27, pp. 51–58.

Haapala, H.E.S., 2003. Operation of electronic identification of cattle in Finland. In: The Proceedings of the 4th European Conference in Precision Agriculture, Berlin, Germany, June 14–19.

Heimerdinger, U., 2000. Wireless probes revolutionize moisture measurement when drying wood. In: Proceedings of the 51st Western Dry Kiln Association Meeting, Reno, Nevada, USA, May 5–7, pp. 63–66.

Hirakawa, A.R., Saraiva, A.M., Cugnasca, C.E., 2002. Wireless robust robot for agricultural applications. In: Proceedings of the World Congress of Computers in Agriculture and Natural Resources, Iguacu Falls, Brazil, March 13–15, pp. 414–420.

IEEE, 1997. Smart Transducer Interface for Sensors and Actuators-Transducer to Microprocessor Communication Protocol and Transducer Electronic Data Sheet. IEEE Standard 1451.2. The Institute of Electrical and Electronics Engineers Inc., 345 East 47th Street, New York, NY.

IEEE, 1999a. Smart Transducer Interface for Sensors and Actuators-Network Capable Application Processor (NCAP) Information Model. IEEE Standard 1451.1. The Institute of Electrical and Electronics Engineers Inc., 345 East 47th Street, New York, USA.

IEEE, 1999b. Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Higher-Speed Physical Layer Extension in the 2.4 GHz Band. IEEE Standard 802.11b. The Institute of Electrical and Electronics Engineers Inc., 345 East 47th Street, New York, USA.

IEEE, 2002. Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Wireless Personal Area Networks (WPANs). IEEE Standard 802.15.1. The Institute of Electrical and Electronics Engineers Inc., 345 East 47th Street, New York USA.

IEEE, 2003. Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs). IEEE Standard 802.15.4. The Institute of Electrical and Electronics Engineers Inc., 345 East 47th Street, New York, USA.

Jensen, A.L., Boll, P.S., Thysen, I., Pathak, B.K., 2000. Pl@nteInfo: a web-based system for personalized decision support in crop management. Comput. Elect. Agric. 25, 271–293.

Kononoff, P.J., Lehman, H.A., Heinrichs, A.J., 2002. A comparison of methods used to measure eating and ruminating activity in confined dairy cattle. J. Dairy Sci. 85, 1801–1803.

Krallmann, J., Foelster, N., 2002. Remote service systems for agricultural machinery. In: Proceedings of the 2002 ASAE Automation Technology for Off-Road Equipment, Chicago, Illinois, USA, July 26–27, pp. 59–68.

Lee, W.S., Burks, T.F., Schueller, J.K., 2002. Silage yield monitoring system. ASAE Paper No.: 02-1165. The American Society of Agriculture Engineers, St. Joseph, Michigan, USA.

Liu, G., Ying, Y., 2003. Application of Bluetooth technology in greenhouse environment, monitor and control. J. Zhejiang Univ., Agric. Life Sci. 29, 329–334.

Mahan, J., Wanjura, D., 2004. Upchurch, Design and Construction of a Wireless Infrared Thermometry System. The USDA Annual Report. Project Number: 6208-21000-012-03. May 01, 2001–September 30, 2004.

Marra, F., Romano, V., 2003. A mathematical model to study the influence of wireless temperature sensor during assessment of canned food sterilization. J. Food Eng. 59, 245–252.

McKinion, J.M., Jenkins, J.N., Willers, J.L., Read, J.J., 2003. Developing a wireless LAN for high-speed transfer of precision agriculture information. In: Proceedings of the 4th European Conference on Precision Agriculture, Berlin, Germany, June 15–19, pp. 399–404.

McKinion, J.M., Turner, S.B., Willers, J.L., Read, J.J., Jenkins, J.N., McDade, J., 2004a. Wireless technology and satellite Internet access for high-speed whole farm connectivity in precision agriculture. Agric. Syst. 81, 201–212.

McKinion, J.M., Willers, J.L., Jenkins, J.N., 2004b. Wireless local area networking for farm management. ASAE Paper: 04-3012. The American Society of Agriculture Engineers, St. Joseph, Michigan, USA.

Mizunuma, M., Katoh, T., Hata, S., 2003. Applying IT to farm fields—A Wireless LAN. NTT Tech. Rev. 1, 56–60.

Morais, R., Cunha, J.B., Cordeiro, M., Serodio, C., Salgado, P., Couto, C., 1996. Solar data acquisition wireless network for agricultural applications. In: Proceedings of the 19th IEEE Convention of Electrical and Electronics Engineers in Israel, Jerusalem, Israeli, November 5–6, pp. 527–530.

Nagl, L., Schmitz, R., Warren, S., Hildreth, T.S., Erickson, H., Andresen, D., 2003. Wearable sensor system for wireless state-of-health determination in cattle. In: Proceedings of the 25th IEEE EMBS Conference, Cancun, Mexico, September 17–21.

Najjar, L.J., Thompson, J.C., Ockerman, J., 1997. Wearable computer for quality assurance inspectors in a food processing plant. In: Proceedings of the 1st IEEE International Symposium on Wearable Computers, Cambridge, Massachusetts, USA, October 13–14, pp. 163–164.

Ong, K.G., Puckett, L.G., Sharma, B.V., Loiselle, M., Grimes, C.A., Craig, A., Bachas, L.G., 2001. Wireless, passive, resonant-circuit sensors for monitoring food quality. In: Proceedings of SPIE—The International Society for Optical Engineering, vol. 4575, Boston, MA. USA, October 28–November 2, pp. 150–159.

On World Inc., 2004. http://onworld.com.

Perkins, M., Correal, N., O'Dea, B., 2002. Emergent wireless sensor network limitations: a plea for advancement in core technologies. In: Proceedings of the 1st IEEE International Conference on Sensors, Orlando, Florida, USA, June 12–14, pp. 1505–1509.

Pessel, G.J., Denzer, H., 2003. Portable and mobile instrument for continuous stable climate measurement. In: Proceedings of the 4th European Conference in Precision Agriculture and the 1st European Conference on Precision Livestock Farming, Berlin, German, June 14–19.

Ribeiro, A., Garcia–Perez, L., Garcia-Alegre, Guinea, M.C., 2003. A friendly man-machine visualization agent for remote control of an autonomous tractor GPS guided. In: The Proceedings of the 4th European Conference in Precision Agriculture, Berlin, Germany, June 14–19.

Rusko, M., Buff, W., Binhack, M., Goroll, M., Ehrenpfordt, J., Klett, S., 1999. Passive resonator identification TAG for narrow-band wireless telemetry. In: Proceedings of the IEEE Ultrasonics Symposium, vol. 1, Caesars Tahoe, NV, USA, October 17–20, pp. 377–380.

Sahin, E., Dallery, Y., Gershwin, S., 2002. Performance evaluation of a traceability system: an application to the radio frequency identification technology. In: Proceedings of the 2002 IEEE International Conference on Systems, Man and Cybernetics, vol. 3, Yasmine Hammamet, Tunisia, October 6–9, pp. 647–650.

Sangani, K., 2004. RFID sees all. IEE Rev. 50, 22–24.

Sensicast, 2004. http://www.sensicast.com/.

Sensors Magazine, 2004. Editorial: this changes everything—market observers quantify the rapid escalation of wireless sensing and explain its effects. Wireless for Industry, Supplement to Sensors Magazine, Summer, pp. S6–S8.

Serôdio, C., Monteiro, J.L., Couto, C.A., 1998. Integrated network for agricultural management applications. In: Proceedings of the 1998 IEEE International Symposium on Industrial Electronics, vol. 2, Pretoria, South Africa, July 7–10, pp. 679–683.

Serôdio, C., Cunha, J.B., Morais, R., Couto, C.A., Monteiro, J.L., 2001. A networked platform for agricultural management systems. In: Computers and Electronics in Agriculture, vol. 31. Elsevier, pp. 75–90.

Stentz, A., Dima, C., Wellington, C., Herman, H., Stager, D., 2002. A system for semi-autonomous tractor operations. Autonomous Robots 13, 87–104.

Taylor, K., Mayer, K., 2004. TinyDB by remote. In: Presentation in Australian Mote Users' Workshop, Sydney, Australia, February 27.

Thysen, I., 2000. Agriculture in the information society. J. Agric. Eng. Res. 76, 297–303.

Vivoni, E.R., Camilli, R., 2003. Real-time streaming of environmental field data. Comput. Geosci. 29, 457–468.

Weiser, M., 1996. Open House, http://www.ubiq.com/hypertext.weiser/wholehouse.doc.

Wentworth, S.M., 2003. Microbial sensor tags. In: The 2003 IFT (The Institute of Food Engineering) Annual Meeting Book of Abstracts, Chicago, Illinois, USA, July 12–16.

Wheeler, E.F., Zajaczkowski, J.L., Diehl, N.K., 2003. Temperature and humidity in indoor riding arenas during cold weather. ASAE Paper No.: 03-4090. The American Society of Agriculture Engineers, St. Joseph, Michigan, USA.

WINA, 2004. http://wina.org.