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A Review of Center Pivot Irrigation Control and Automation Technologies

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Abstract: Electronic sensors, equipment controls, and communication protocols have been developed to meet the growing interest in site-specific irrigation using center pivot and lateral move irrigation systems. Onboard and field-distributed sensors can collect data necessary for real-time irrigation management decisions and transmit the information directly or through wireless networks to the main control panel or base computer. Equipment controls necessary to alter water application depth to meet the management criteria for relatively small management zones are now commercially available from irrigation system manufacturers and after-market suppliers. Selection of the communications system for remote access depends on local and regional- topography and cost relative to other methods. Communication systems such as cell phones, satellite radios, and internet based systems allow the operator to query the main control panel or base computer from any location at any time. Recent developments in the center pivot industry have led to contractual relationships between after-market suppliers and irrigation system manufacturers that should support further development of site-specific application of water, nutrients and pesticides in the future.

Keywords: site-specific irrigation, distributed sensor networks, wireless communication, variable rate irrigation,

Introduction

Agricultural fields are variable in terms of production for many reasons. This variability may include topographic relief, changes in soil texture, tillage and compaction, fertility differences, localized pest distributions and various irrigation system characteristics. The effects of different sources of variability on management can be additive and interrelated. Fortunately, recent advances in communications and microprocessors have enabled the general implementation of site-specific water applications by self-propelled center pivot and linear move sprinkler irrigation systems.

The design of a suitable site-specific irrigation system can be complex because of the need to address the numerous causes of the variation that may exist in each field, the system capabilities that may be needed to achieve the desired management level, constraints inherent in the currently existing equipment and the general management philosophy of the owner/operator (decision support). These considerations are not mutually exclusive, but they do not lend themselves well to categorization. These issues are discussed in more detail by Buchleiter et al., 2000; Evans et al., 2000; McCarthy et al., 2010; Sadler et al., 2000; and Perry et al., 2004. McCarthy et al (2010) developed a predictive-adaptive control model for site-specific irrigation water application of cotton using a center pivot. Various simulation models were used to evaluate alternative irrigation control options across a range of crop management and environmental conditions. The authors concluded that while the VARIwise framework accommodated a range of system control strategies, further work is necessary to explore procedures for using data with a range of spatial and time scales.

Decision support systems should be holistic approaches to irrigated crop management within a single field. Within the decision support program structure, the irrigator predefines the criteria and guidelines to be used by the software structure and simulation models in making basic decisions to be implemented by a microprocessor-based control system. Results of geo-referenced grid sampling of soils, yield maps and other precision agriculture tools can also be major components in defining rules for these management systems. These “rules” are used as the basis for analysis and interpreting the data from real time data networks, remote sensing, irrigation monitoring systems, agronomic and other information used to provide direction and implement the basic commands. Decision support systems can also include instructions for chemigation (e.g., nitrogen fertilizer) and provide alerts (e.g., insects, diseases) to the grower based on output from established models using real-time environmental data. In short, decision support provides more management flexibility by implementing short term, routine commands to direct irrigation schedules and other basic operations, which frees the irrigator to concentrate on managing other areas to minimize risk and reduce costs.

These integrated approaches will require the integration of a mix of various sensor systems (on the machine and in the field), hardware, GPS, controllers and computing power. The maximum benefits will be derived from a decision support system when the plant condition in selected areas of a field is monitored by some means to improve overall system management. Monitoring systems can be field-based measurements or remotely sensed or an integrated mix of several sensor systems.

Sprinkler Control Options

Existing center pivot systems span the evolution of technology from water to electric and hydraulically driven machines. Due to their design, center pivots are operating on varying topography, and often have a range in soil textures present under a single machine. Low infiltration rate soils challenge managers of standard machines with the need to provide little or no irrigation water to some areas while fully irrigating others. Each of these factors represents a reason for using some sort of monitor/controller to manage water applications based upon need. Precision application, variable rate irrigation and site specific irrigation are terms developed to describe water application devices with the goal of maximizing the economic and/or environmental value of the water applied via a moving irrigation system.

The most basic method to alter the water depth applied with a center pivot is to adjust the center pivot speed of travel based upon field soils or more frequently based upon field topographic features or different crops. Early developments provided a very limited set of controls to turn end guns on and off based upon field position. Other features included edge of field stops and stop-in-slot controls to cease irrigation due to obstructions or the completion of a complete rotation. Programmable control panels allow adjusting the speed of travel multiple times during an irrigation event. This is accomplished by entering the field position in a 360^o circle where the speed will be changed to apply more, less or no irrigation water. This approach could be used where portions of the field were planted to a different crop, but it lacked the flexibility necessary to supply water at rates required to meet management objectives of relatively small field areas with irregular shaped boundaries.

Individual sprinkler control of water application depth can be accomplished by using a series of on-off time cycles or as it has become known as “pulsing” the sprinkler through on-off cycles (Karmeli and Peri, 1974). Reducing the on-time is effective at reducing both the application depth and the water application rate. Later efforts in Washington State involved equipping a center pivot with a custom built electronic controller to activate water operated solenoid valves in groups of 2-4 nozzles (Evans, et al., 1996; Evans and Harting, 1999). Normally open solenoids allowed system control with the assurance that irrigation water was applied even if the control system failed. Chávez et al., (2010 a,b,c) reported that a remote irrigation monitoring and control system installed on two different linear move irrigation systems performed well. The systems proved to be highly flexible and capable of precision irrigation using a series of in-field and onboard wireless monitoring spread spectrum radios/sensors networks. Individual nozzle/solenoid valves were pulsed according to prescription maps. Deviations related to positioning of nozzles when irrigating were on average 2.5 ± 1.5 m due mainly to inherent DGPS inaccuracy.

A variable flow sprinkler was developed for controlling irrigation water application by King and Kincaid (2004) at Kimberly, ID. The variable flow sprinkler uses a mechanically-activated pin to alter the nozzle orifice area which adjusted the sprinkler flow rate over the range of 35 to 100% of its rated flow rate based upon operating pressure. The pin was controlled using either electric or hydraulic actuators. The main issue is that the wetted pattern and water droplet size distribution of the sprinkler changed with flow rate which created water application uniformity issues due to a change in sprinkler pattern overlap.

Controlling irrigation water application depth can also be accomplished through the use of multiple manifolds with different sized sprinkler nozzles to vary water and nitrogen application (Camp et al., 1998; Lyle and Bordovsky, 1981; Roth and Gardner, 1989). These systems included 2-3 manifolds where simultaneous activation of one or manifolds served to adjust the water application rate and depth across a range of depths that is not possible with a single sprinkler package. Control of each manifold was accomplished using solenoid valves similar to those described for the pulsing sprinkler option above.

As with any new technology, there are positives and negatives associated with each of these methods of controlling sprinkler flow rates. Certainly long term maintenance by producers is an issue. However, the biggest factor limiting their use is their installation cost that ranges from around $2000 for a system monitor to over $20,000 for control of individual sprinklers.

Sensors and Communications

Center pivot position is the most basic use of sensors for center pivot control systems. Until recently, alignment systems typically had an accuracy of $\pm 0.5^o$ to 1.5^o of the location of the first tower. At a distance of 390 m from the pivot point, the position of the last sprinkler could be off by 3 to 10 m. Research conducted by Peters and Evett (2005) found that resolver determined position errors could be up to 5 degrees or over 30 m on a 390 m long center pivot. Consequently, commercially available center pivots now employ a Wide-Area Augmentation System (WAAS) enabled GPS antenna option to identify the position of the end tower to < 3 m accuracy. The stop-start cycle of the center pivot typically allows determination of system position to less than 1 m accuracy. The net effect of being able to accurately determine the pivot lateral location is that management zone size can be reduced without increasing the potential for a misapplication of water, nutrients, or pesticides.

Recent innovations in low-power sensors, battery and wireless radio frequency technologies combined with advances in Internet technologies offer tremendous opportunities for development and application of real-time management systems for agriculture (Beckwith et al., 2004; Camilli et al., 2007; Liang et al., 2007; Coate and Delwiche, 2008; Kim et al., 2007, 2008; Pierce and Elliot, 2008; Vellidis et al., 2008). Wireless sensor networks (WSN) are preferred because they can eliminate problems and costs associated with stretching and maintaining wires across a field; however, power requirements of the field wireless systems can be a concern.

Decision support frameworks will necessarily rely on WSNs for real-time, automated, low power soil water and micro-meteorological instrumentation, infrared thermometers monitoring of plant temperatures or other sensors that are strategically distributed to provide continuous feedback of field conditions. Various sensors systems can also be mounted on the machine and provide real-time feedback for decision support as the machines move across a field (Peters and Evett, 2008; O'Shaughnessy and Evett, 2010). These field-based data may also be integrated with various remotely sensed data to help differentiate between various biotic and abiotic stresses.

Integrated data sources and networks provide needed information to re-calibrate and check various simulation model parameters for on-the-go irrigation scheduling and adjustments (Andrade-Sanchez et al, 2007; Kim et al, 2007, 2008; Kim and Evans 2009; O'Shaughnessy and Evett, 2010). Integration of these technologies into the irrigation decision making process can determine when, where, and how much water to apply in real time; which enables implementation of advanced water conservation measures for economically viable production with limited water supplies, conserve energy, and enhance environmental benefits.

Local field-based sensor systems are generally a combination of an automated agricultural weather station providing meteorological data and WSNs that directly indicate localized field conditions from either one or multiple sensor types. Field sensors can include soil water levels, air temperatures and humidity, precipitation (and irrigation applications) and other information such as infrared (IR) surface radiometric measurements. The Smart Crop system (Mahan et al., 2010) is a recent example of an in-field wireless system commercialized for canopy temperature monitoring. These sensor stations can transmit data wirelessly to a datalogger for either direct use by the grower (common situation) or base computer for decision support programs (Pierce et al. 2006; Andrade-Sanchez et al. 2007; Kim et al. 2008; O'Shaughnessy and Evett, 2008; Peters and Evett, 2008; Kim et al 2009; Kim and Evans 2009). Wireless communications allow the base computer to be located with the control system on the irrigation machine or in a remote location.

Satellite and aerial imagery, GIS mapping services and GPS are becoming commonplace throughout the agricultural industry around the world. Remotely sensed information can be photometric (visible), thermal or multispectral acquired by aircraft and satellites in a variety of formats and resolutions. There are a number of ways that multispectral data can be used to enhance water and energy conservation by helping to determine the exact causes of the non-uniform appearance (and yield) of the crop (Gowda et al 2008, Hornbuckle et al 2009). Advanced pattern recognition software and other tools for multispectral or other remotely sensed data can be used to detect many problems in agriculture. However, two barriers to the widespread adoption and use of these integrated technologies in today's agriculture are the cost of these services and the difficulty for producers to understand and use the output in a timely manner. The timeliness of this type of information is critical to producers because it is much better for their bottom line if they can make adjustments as the problems develop, not after the fact. New analysis tools and interpretation aids as part of a comprehensive decision support system are needed for growers to take full advantage of these technologies.

Spectral and thermal ground-based remote sensors mounted on self-propelled irrigation systems are capable of providing information to farmers in a more timely manner than aircraft or satellite sources. Infrared thermocouple thermometers mounted on a moving pivot lateral provide radiometric temperature measurements of in-field crop canopy. Software to control drip and moving sprinkler systems has been integrated with this plant-feedback information and the Time-Temperature Threshold (TTT) algorithm (Evett et al., (2006), patented as the Biologically Identified Optimal Temperature Interactive Console (BIOTIC) for managing irrigation by the USDA under Patent No. 5,539637 (BIOTIC, Upchurch et al., 1996). Briefly, the TTT technique can be described as comparing the accumulated time that the crop canopy temperature is greater than a crop-specific temperature threshold with a specified critical time developed for a well-watered crop in the same region. The TTT technique has been used in automatic irrigation scheduling and control of plant water use efficiency for corn in drip irrigated plots, and soybean and cotton in LEPA irrigated plots (Evett et al., 1996; Lamm and Aiken, 2008; Peters and Evett, 2008; O'Shaughnessy and Evett, 2010). Peters and Evett (2004 and 2007) demonstrated that remote canopy temperatures could be predicted from a contemporaneous reference temperature and a pre-dawn temperature measurement. IRT measurements made from a moving sprinkler can then be used to provide spatial and temporal temperature maps that correspond to in-field water stress levels of crops.

General, broad-based and easily modified software for managing these decision support systems for a multitude of crops, climatic conditions, topography, and soil textures are not currently available from manufacturers, government or consultants. Development and updating of management maps for these irrigation systems is currently a painstaking and specialized process that is currently done only once a year or less.

Distributed Wireless Sensor Networks

Distributed in-field sensor-based irrigation systems offer the potential to support site-specific irrigation management that allows producers to maximize their productivity while saving water. However, the seamless integration of sensors, data interface, software design, and communications for site specific irrigation control using wireless sensor-based irrigation systems can be challenging (King et al., 2000). Power needs are often a major consideration and solar panels are often used.

Researchers have addressed the issues of interfacing sensors and irrigation control using several different approaches. Shock et al. (1999) used radio transmission for soil moisture data from data loggers to a central data logging site where decisions were made and manually changed. Miranda et al. (2003) used a closed-loop control system and determined irrigation amount based on distributed soil water measurements. Wall and King (2004) explored various designs for smart soil moisture sensors and sprinkler valve controllers for implementing “plug-and-play” technology, and proposed architectures for distributed sensor networks for site-specific irrigation automation. They concluded that the coordination of control and instrumentation data is most effectively managed using data networks and low-cost microcontrollers.

It is often not feasible or desired to have in-field sensing stations that use wires to connect to a base station because of the cost, labor and maintenance, especially if the distances are greater than 10 m. Wires can also be damaged by farm equipment and small animals; and wires create more opportunity for lightning damage. Wireless data communication systems avoid many of these problems and provide dynamic mobility and easy relocation and replacement of stations. Radio frequency technology has been widely adopted in consumer's wireless communication products and provided opportunities to deploy wireless signal communication in agricultural systems.

Adopting a standard interface for sensors and actuators allows reuse of common hardware and communication protocols such as communication interface and control algorithm software. Instrumentation and control standards for RS232 serial (voltage based) and RS485 (current based) communication protocols have been widely applied and well documented for integrating sensors and actuators, particularly in industrial applications. Two wireless protocols that are commonly used for this purpose are Bluetooth (802.15.1) (IEEE Std. 802.15.1, 2005) and ZigBee (802.15.4) (IEEE Std. 802.15.4a, 2007).

Bluetooth and ZigBee (IEEE 802.11 standards) are designed for radio-frequency (RF) applications for mobile applications that require a relatively low data rate, long battery life, and good network security. These are “line-of-sight” (LOS) systems and crop canopies, small trees, and fences can interfere with transmissions. ZigBee is a low-cost, nonproprietary wireless mesh networking standard, which allows longer life with smaller batteries, and the direct-sequence spread spectrum (DS/SS) mesh networking provides high reliability. Bluetooth is a faster but more expensive standard than ZigBee, and uses spread spectrum modulation technology called frequency hopping (FH/SS) to avoid interference and ensure data integrity. ZigBee has lower power needs than Bluetooth, but it also transmits effectively over less distance (e.g., 30 m). Enhanced Bluetooth transmitters are available that can transmit up to 1 km.

Bluetooth wireless technology has been adapted in sensing and control of agricultural systems (Lee et al., 2002; Oksanen et al., 2004; Zhang, 2004; Kim et al 2008; Kim and Evans, 2009). Zhang (2004) evaluated Bluetooth radio in different agricultural environments, power consumption levels, and data transmission rates. He observed 1.4 m as an optimal radio height for maximum 44 m radio range and reported limitations of significant signal loss after 8-hours continuous battery operation and 2-3 seconds of transmission latency with the increase of communication range. Oksanen et al. (2004) used a PDA with Bluetooth to connect a GPS receiver for their open, generic and configurable automation platform for agricultural machinery. Lee et al. (2002) explored an application of Bluetooth wireless data transportation of moisture concentration of harvested silage and reported a limitation of 10-m short range. However, the limitations reported by reviewed publications about Bluetooth applications in agricultural systems can be solved or minimized by system design optimization. The power shortage can be solved by using solar power that recharges the battery. The radio range and transmission latency can also be extensively improved by using an upgraded power class and antenna. The same techniques can be applied to Zigbee-based systems.

Drawbacks in using wireless sensors and wireless sensor networks include provision for ample bandwidth, existing inefficiencies in routing protocols, electromagnetic interference, interference by vegetation, radio range, sensor battery life (Zhang, 2004), and synchronous data collection (Dowla, 2006). An immediate limiting factor in self-powered WSN operations is battery life, which can be addressed to some degree by decreasing the duty cycle of the sensor nodes. Researchers are also concentrating on RF communication protocols to increase the energy efficiency of a WSN by investigating algorithms for multi-path routing, data throughput and energy consumption (Li and Ephremides, 2007) and by reducing idle listening and collisions that occur during the medium access to realize power conservation (Demirkol and Ersoy, 2009). However, reducing quiescent current draw is typically a significant method for impacting battery longevity (Hebel, 2006). Other identified challenges specific to WSNs and agriculture include interference with radio propagation due to crop canopy height (Goense and Thelen, 2005). Andrade-Sanchez et al. (2007) determined that power consumption and power output varied significantly among transceivers, and the average measure of signal strength as a function of distance resembled the shape of the theoretical prediction of path loss in free space. In addition, the received signal strength indication (RSSI) was influenced by the spatial arrangement of the network in both the vertical and horizontal planes in tests with line-of- sight. Signal obstruction issues relating to crop height and in-field equipment are inherently reduced when the moving sprinkler is used as the sensor platform; but infield sensors require manual adjustment above crop canopy.

Remote Communications with Self-Propelled Irrigation Systems

There are several methods for remotely communicating with self-propelled sprinkler irrigation systems. Many of these are being marketed by the manufacturers of this equipment and include cell phones, RF radios, and satellite radio communications for relatively basic monitoring and control of the systems. Hybrid systems relying on internet to connect computers at or near the site are combined with wireless RF systems for the link to the machine. Each manufacturer has developed unique hardware and software that allow the owner to access the main control panel to determine system status including travel direction, speed of travel, application depth, and field position (Table 1). More sophisticated software provided by an office base station uses visualization software to allow the owner to see year-to-date summaries of water and chemical application events. All information can be archived for record keeping purposes.

Selection of the communications system for remote access depends on topography and cost relative to other methods. Cell phone systems with modems at the control panels are the least costly and probably the most common. Satellite radio communications are often preferable when there are large topographic differences that limit cell phone service. Higher powered, licensed, radio systems (e.g., 5-10W) with data modems may also be an option but may also be affected by topographic relief. Repeater stations for LOS radio frequency systems can also be quite expensive, especially if there is a need to communicate long distances over diverse topography.

Recent developments in the center pivot industry have resulted in contractual arrangements with developers of after-market control and monitor systems such as FarmScan, AgSense, and PivoTrac. These additions to the existing onboard control capabilities of center pivot panels make site-specific irrigation a reality for irrigation zones less than the 100 m^2. The main considerations remaining include the development of decision support systems that maximize the value of the applied water or chemical based on field-based information and the cost recovery potential of the cropping system since system costs up to $20,000 are possible when there is a large number of management zones along the system length.

Table 1. Monitor, control, communication, and data reporting capability of center pivot control panels.

	Reinke	T-L	Valmont	Zimmatic
Monitors				
Position in field and travel direction	Y	Y	Y	Y
Speed of travel	Y	Y	Y	Y
Wet or dry operation	Y	Y	Y	Y
Pipeline pressure	Y	Y	Y	Y
Pump status	Y	Y	Y	Y
Auxiliary components[β]	Y (7)	Y (2)	Y (6)	Y (3)
Stop-in-slot and auto restart	Y	Y	Y	Y
Wind speed	Y	N	Y	Y
Controls				
Start and Stop	Y	Y	Y	Y
Speed of travel	Y	Y	Y	Y
Auto restart and auto reverse	Y	Y	Y	Y
End gun	Y	Y	Y	Y
High and Low pressure shutdown	Y	Y	Y	Y
High and Low voltage shutdown[£]	N/Y	N/Y	Y/Y	N/Y
System stall shutdown	Y	Y	Y	Y
Auxiliary components[β]	Y(7)	Y(2)	Y(6)	Y(3)
System guidance[§]	Y	Y	Y	Y
Maximum control points per circle[¶]	3600	180	72	180
Sprinkler application zones	2	3	30	NL
Remote Communications				
Cell phone	Y	Y	Y	Y
Radio	Y	Y	Y	Y
Computer	Y	Y	Y	Y
Subscription required	Y	Y	Y	Y
Data Collection and Reports				
Soil water content	Y	Y	Y	N
Precipitation per season	Y	Y	Y	Y
Application date and depth	Y	Y	Y	Y
Irrigation events per season	Y	Y	Y	N
Chemical application rate	N	N	N	Y
Chemical application per season	N	N	N	Y
System position by date	Y	Y	Y	Y

[£] N/Y indicates no automatic shutdown for high voltage is provided but the panel does provide automatic shutdown for low voltage.

[β] Y(7) indicates that up to 7 auxiliary components (injection pumps, end guns, etc.) can be controlled by the panel.

[§] System guidance provided by above ground cable, below ground cable, furrow or GPS.

[¶] Number of positions in a revolution where set points may be changed.

Conclusions

Electronic sensors, equipment controls, and communication protocols have been developed to meet the growing interest in site-specific irrigation using center pivot and lateral move irrigation systems. Onboard and field-distributed sensors can collect data necessary for real-time irrigation management decisions and transmit the information through wireless networks to the main control panel or base computer. Equipment controls necessary to alter water application depth to meet the management criteria for relatively small management zones are now commercially available from irrigation system manufacturers and after-market suppliers. But decision systems for automatic control are incomplete. Selection of the communications system for remote access depends on local and regional topography and cost relative to other methods. Communication systems such as cell phones, satellite radios, and internet based systems allow the operator to query the main control panel or base computer from any location at any time. Recent developments in the center pivot industry have led to contractual relationships between after-market suppliers and irrigation system manufacturers that should support further development of site-specific application of water, nutrients and pesticides in the future.

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