CONTROLS FOR PRECISION IRRIGATION WITH SELF-PROPELLED SYSTEMS

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ABSTRACT

With appropriate controls, sensors, and decision making tools, self-propelled center pivot and linear move irrigation systems can be equipped and managed to account for spatial variations in water and some fertilizer requirements. A wide variety of communications protocols, control systems, and computer interfaces have been developed at various locations across the USA to interact with self-propelled irrigation systems, chemical injection systems, valving and sprinklers to implement site-specific management maps for water and agrichemical applications. Self-propelled irrigation systems also provide an outstanding platform on which to mount sensors for real time monitoring of plant and soil conditions and interact with the control system for optimal environmental benefits. Inexpensive real-time sensing of the soil and/or plant water status integrated with communications networks and control and decision support systems must be developed for site-specific irrigation to achieve its full potential and be practical on a large scale.
KEYWORDS: Precision agriculture, site-specific, irrigation, water management, controls, agricultural systems, self-propelled irrigation

VARIABLE RATE IRRIGATION TECHNOLOGIES

In the past, to improve in-season operational efficiencies on a whole-field basis, managers have resorted to practices such as manually changing sprinkler heads to match pre- and post-emergence conditions. Labor costs make this technique unreasonably expensive. For within-field variation in demand during the season, irrigators have had to vary end tower run speeds to adjust water applications. This modifies water applications to more closely meet water requirements of the field for a given angle of rotation. Until computerized center pivot panels became available, the field manager was required to either be at the controller when a speed change was needed or to use a switch at the pivot point and a second percent timer to vary the end tower speed. Now, with the use of a computerized center pivot control panel, the end tower speed can be changed based on a preprogrammed position in the field. This has greatly enhanced the ability of the field manager to apply water to meet spatially variable demand in wedge-shaped segments, but it still assumes an average demand across each wedge-shaped treatment area. Thus, areas of the field continue to be over- or under-irrigated, causing plant stress, reducing yield and quality, and increasing potential for leaching water and chemicals.

It is possible to control every sprinkler individually, but the increased cost reduces the likelihood that the system would be economically feasible. On the other hand, it is possible to group sprinklers and control them in groups of 3 or 4 heads. Increasing the number of sprinklers per control group would decrease cost, but the control system would lose some ability to match pre-selected treatment areas. In addition, individual control of heads may not be appropriate since growers can probably not practically manage areas for other cultural aspects of their operation less than 0.4 to 0.5 ha within a field. Since sprinklers are mounted every 1.5 to 3 m with wetted

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diameters ranging from 6 to 10 m or more, control groups of 3 to 5 heads tends to match these practical operational limits (Evans and Harting, 1999).

The control system should have the capacity for a wide range of application depths in both humid and arid areas. Analysis of field data in arid conditions (Evans et al., 1996a, 1996b) that assumed that the water infiltrated where it was applied have shown that application depths under precision irrigation with self-propelled machines in arid areas are normally reduced by either no more than 15-20% or by 100% (no application) as would be the case of rock outcroppings, areas where in-field runoff ponds, or waterways. However, when there are infield runoff and shallow subsurface flows that concentrate applied water in certain locations, it may be necessary to reduce applications between 30 to 40% or more. Humid areas require a wide range of application depths to match widely varying soil water holding capacities across a field. If low-volume chemigation with some pesticides is considered, it may be necessary to uniformly reduce application depths by 75-90% for that rotation.

Several innovative technologies have been developed to variably apply irrigation water to meet anticipated whole field management needs in precision irrigation, primarily with center pivot and lateral move irrigation systems. In general, the operation criteria for these systems include many of the following: be easy to retrofit to existing commercial center pivots, maintain good water application uniformity within and between treatment areas, have robust electronics, be compatible with existing center pivot equipment, have bi-directional communications, and be easily expandable for future development and functional requirements. In addition, the management of the precision water application systems must include interactions between individual sprinkler diameters and the start/stop movement of towers. Normally-open solenoid valves are typically used to turn sprinklers on and off. Most of these use standard, off-the-shelf equipment with much of the research effort directed towards developing the appropriate control strategies.

Lyle and Bordovsky (1981, 1983) used three individually-controlled manifolds, each delivering discrete but different flow rates, in various combinations of different sized sprinkler heads to achieve a series of discrete incremental application rates. This system was installed on a Low Energy Precision Application (LEPA) irrigation system to provide a range of application rates that were uniform for all segments along the truss. Roth and Gardner (1989) used three lines on a linear irrigation system to apply five different water depths to a series of plots, but the depth distribution among plots was fixed, and independent control of application depth either along the system length or travel direction was not possible. McCann and Stark (1993) patented a computer control system to provide site-specific application of water and chemicals for both linear and center pivot irrigation systems.

Idaho Control System

Researchers at the University of Idaho began developing and testing techniques to spatially vary water and chemical application with self-propelled irrigation systems in 1990. Various forms of control systems were tested on commercial center pivot systems starting with off-the-self components and more recently with in-house electronic designs for implementing variable rate application. This work led to the development of a Supervisory Control and Data Acquisition (SCADA) network system to provide variable rate water and chemical application as well as serve as a data acquisition system for decision support software. The SCADA network utilizes the 480 V 3-phase power line of the irrigation pivot system as the bi-directional communication medium for control and data acquisition. The SCADA network consists of nodes placed along the system lateral where control and/or data acquisition is required and the 480 V 3-phase power line is easily accessible (King and Wall, 1997). Each network node provides for 14 lines of digital I/O, one 0-20 ma analog output, one 0-4.096 VDC input (12 bit), and one RS-232 serial communication port.

King et al. (1999) and King and Wall (1998) provide a more detailed description of the Idaho SCADA network.

Field implementation of the SCADA network requires a network node at the master control point (pump or pivot point location) and one at every other system tower starting with the first tower. If the master control point is not at the pivot point, an additional network node is needed there to monitor the location of the system lateral using a digital angular position encoder. Variable rate water application is accomplished using a double sprinkler arrangement at each active outlet along the system lateral. One sprinkler is sized for 1/3 the design flow rate and the second one for 2/3 the design flow rate for the outlet. Step-wise variable flow rate is achieved by controlling operation of each sprinkler using solenoid-activated diaphragm valves on each sprinkler. Each system span is divided into three individual control zones by wiring the valves in corresponding groups. Variable-rate chemical application is achieved through variable rate water application and maintenance of a constant chemical concentration in the water supply using a variable-speed injection pump. Multiple application maps are stored in the master controller and the user can select which one to use. Maps and system operational data are transferred to and from the master controller over a RS-232 port using a laptop computer (McCann et al., 1997; King et al., 1999; King and Wall, 2000).

South Carolina Control System

A group with the USDA-ARS in Florence, SC, has worked for several years developing a computer controlled, programmable variable-rate water and nutrient application management system. The computer was mounted on the programmable logic controller (PLC) backplane (GE Fanuc model 90-30, Charlottesville, VA) and connected via the system buss. The PLC was mounted on the mobile portion of the system about five meters from the pivot center, from which it controlled all manifold solenoid valves. The computer also controlled irrigation system travel speed and chemical injection pump flow rate, both based on a spatially-referenced mapping system. Angular location (analog resolver) of the first span was obtained from the C:A:M:S™ (Valmont Industries, Inc., Valley, NE) management system. Initially, communication between the mobile PC and the stationary management system was accomplished via short-range, radio-frequency modems (900 MHZ, spread-spectrum modems; Comrad Corp., Indianapolis, IN). Later, a direct cable connection was used to increase communication reliability. Using custom, in-house-developed software, stored data, and continually-collected positional data, the PC controlled the PLC to operate the appropriate solenoid valves to provide the desired application depth within each field element. The control software included checks for out-of-range values and fail-safe operation. Additional details regarding the control system and overall center pivot operation were reported by Camp et al. (1996).

Software was written in Visual Basic for DOS (Microsoft Corp., Redmond, Wash.) to convert a set of control values to on-off settings in the directly-addressable solenoid control registers of the PLC (Omary et al., 1997; Sadler et al, 1996). The on-board PC repeatedly interrogated the stationary computer management system to determine the angular position of the first span and other parameters to provide assurance of proper operation. From the angular position and the fixed radius of each segment along the truss, the segment location, expressed in polar coordinates, was established for that time. The control program checked each segment to see whether a zone boundary had been crossed. If not, the interrogation cycles continued until a zone boundary was crossed by one or more segments, and a change was needed. When a zone boundary was crossed, the appropriate table lookup was performed, and the solenoid registers were set accordingly. The software also determined the correct system speed from the table and set the appropriate value in the stationary management system. The software also included a routine, based on position measurements, to correct consistent errors in truss angular position reported by the stationary management system. If one of several system variables (pressure, flow rate, position, voltage, etc.) was reported as out of the specified range, the PLC controller closed all solenoid valves and stopped the center pivot drive system. The problem was recorded to a log file for user information.

Colorado Control System

A group with the USDA-ARS in Fort Collins, CO has developed a variable-rate water application system on a 4 span, linear move machine using commercially available equipment. Since this system was used to irrigate many small research plots with various irrigation amounts, it was necessary to vary application depths in both directions while achieving high uniformity within each plot and minimizing the areas of transitional depths between plots. A C:A:M:S™ (Valmont Industries, Inc., Valley, NE) control panel was used to vary system speed and consequently application depth, in the direction of travel. This microprocessor-based controller can be programmed to change speed or control output relays by time, position, or a status change of an input port. Up to nine independent programs can be stored in the panel memory.

The nozzle package was designed for maximum uniformity so the orifice size and instantaneous application rate were the same for all nozzles. Different water depths along the mainline were obtained using the concept of pulse irrigation where the time-averaged discharge depends on the pulsing frequency of the control valves (Fraisse et al., 1992). Uniformity of closing times for each valve model is very important in obtaining uniform application in a field (Duke et al, 1992). One disadvantage was that the closing times for individual valves varied by up to 5 seconds. Therefore it was necessary to measure and adjust for the different closing time of each valve in PLC program.

Each half span was supplied by a 38-mm diameter PVC manifold pipe mounted below the mainline pipe. Two 24 VAC, normally closed solenoid valves mounted at each tower, controlled flow to the manifold lines in both directions. Flexible hose drops (19-mm diameter) spaced at 1.5-m, connected Quad LEPA nozzles with 40-kPa pressure regulators (Senninger Irrig. Inc., Orlando, FL) to the manifold line. Check valves were installed above each LEPA nozzle to prevent drainage from the manifold and drops when the solenoid valve was off in the pulse cycle.

A 9-conductor, 16-ga. electric cable running the length of the machine, connected the GE Fanuc Model 90-30 PLC to each of the solenoid valves. The PLC program used a 60- second cycle interval and the duty cycle (time on/cycle interval) could be programmed from 1 to 100%. Multiple programs stored in the PLC, produced various combinations of duty cycles for the 8 half spans. The program running in the C:A:M:S™ panel selected the PLC program for pulsing by setting the appropriate input ports connected to the PLC. However, because of the experiments under this linear move, only 3 programs were routinely used and were controlled by switches parallel to the input ports.

Unlike pivots, there was no commercially available position location device to accurately monitor the location of a linear move machine. Although several ideas were tested, the most reliable system used a detection unit developed for the electric utility industry, which was mounted on the linear move cart to locate markers buried along the cart's path. The system was designed so when a buried marker was detected, an input signal port in the C:A:M:S™ panel closed. The panel program detected the status change and changed speeds and closed relays that set the input ports to the PLC. The accuracy of this approach was about ± 1.5 m. However, the reliability of this design was never fully tested because of overriding operational requirements of another research project under this irrigation system. A GPS location sensor has subsequently been developed that is more robust with an accuracy of about 2-3 m. Future plans are to implement this pulse irrigation concept to center pivots.

Washington Custom Addressable Controller System

Researchers with Washington State University, USDA-ARS (Prosser) and industry partners developed and tested a prototype precision irrigation system on a commercial 45-ha center pivot system (Evans et al., 1996a; 1996b; Evans and Harting, 1999). The center pivot was divided into zones of two to four heads each. Every rotator spray head (Nelson Irrigation, Inc, Walla Walla, WA) included a pressure regulator and an electric presssure-assisted, normally open solenoid valve (could irrigate even if the control system failed) to regulate the amount of water to be applied. Each of the thirty zones were turned on or off by individual custom-built zone controllers that were tied to a computer through a spread-spectrum radio modem (900 MHz FreeWave Technologies Inc., Boulder, CO). The individually addressable controllers were tied together through a 2-wire RS-485 bus (current based) along the pivot lateral. The individual controllers could also monitor RS-232 devices such as digital compasses or pressure transducers. Positioning was done with two inexpensive, field-calibrated electronic compasses at the first and last tower of each machine that indicated the machine's position to within ±2 meters at the edge of the field.

A computer in the farm office communicated with the pivot controllers as well as an on-site weather station (every hour) via the radio modems. The office computer had various simulation (plant and machine operation) models, the GIS data bases, current soil water status data, climatic data and developed real-time "management maps" or prescriptions, and applied these depending on the position of the center pivot in the field. Real-time data from field weather stations, rain gauges and electronic soil water sensors were also read via additional spread-spectrum radio modems and used by the computer as part of the decision process.

Achieving the prescribed irrigation amount in a management zone was done by cycling the sprinklers on and off at selected intervals over a period of time. Based on the specific rotator sprinkler head characteristics, delays in valve closing and opening, and machine speed, a 250-second cycle time interval was used to control application depths. Thus, a total off time of 50 seconds out of every 250 seconds resulted in 80% of maximum application depth (this could be 5 off times of 10 seconds each or whatever other criteria were used). This control system theoretically allowed application depths ranging anywhere from 0 to 100%, realistically, however, these changes could be made in about 5% increments.

A PC-DOS based center pivot irrigation simulation model (CPIM) was developed, tested, and linked to the GIS (Evans et al., 1993) used by the control system. The CPIM model was calibrated for the specific sprinkler packages and hydraulic characteristics of individual center pivot system. This was necessary because the implementation of an optimum irrigation water application rate map required precise delivery of water to specific field locations. The computerized control was based on the results (e.g., the required nozzle flows) from the hydraulic model, which calculated the actual water applications to each area. A site-specific irrigation scheduling program was written that utilized the output from CPIM and included uniformity considerations (Han et al., 1996).

Washington Commercial PLC Control System

On a large commercial farming enterprise, Harting (1999) installed a precision irrigation control system specifically designed for a central cluster of pressure control valves, shut-off valves, fertilizer storage tanks, and fertilizer injectors located within the triangular area between three adjacent circles. The cluster also contained the electrical panels for on/off and speed control for each of three center pivot machines. From the control valves, pipelines went to each of the three center pivot systems. The control system has been installed on two center pivots for two years and another center pivot system for one year. Three other machines have been modified to allow for control of the sprinklers only within the span between the pivot and the first tower.

The control system was composed of off-the-shelf programmable logic controllers, electric solenoid valves, and hydraulic valves. Both electric compass systems and differential GPS (beacon corrected) units were used to determine machine position in the field with the GPS system the preferred alternative. The sprinklers were controlled in groups or banks of four sprinklers. The sprinkler groups were pulsed on and off to reduce the amount of applied water, in a duty cycle of one minute.

The cluster control system controlled all of the center pivot functions including rotation direction, end tower speed, over-watering timer, positioning, first and second stage timing functions, fertilizer control, and control of the chemical tank agitators. A modular human-machine interface (HMI Siemens OP 17) was used as an interface for the main programmable logic controller (Siemens 314 or 315 PLC). A proprietary communications protocol (Siemens CP342-5 Profibus) provided a link to the remote PLCs. The "on" time for each sprinkler group was sent to another PLC (Seiments 215-DP) on the first or second tower which split the run times between the sprinkler groups controlled by itself and the PLC on the next-to-the-end tower. A multi-conductor cable connected one controller to several control valve groupings on other towers, reducing the need for controllers on each tower.

The precision irrigation control resided in the PLC at the cluster and consisted of three databases and corresponding programs. The control program consisted of several function blocks that were added to the main program as needed. These blocks included: center pivot on/off and direction; end tower speed and hour meters; water control for 2-stage timer applications of water; over watering control; fertilizer control; agitator control; water application; positioning; precision irrigation control; manual operation control; and fault codes. Three PLC counters were used to control the sprinkler groupings. These created 20-second offsets between groups so that all of the sprinklers did not shut off at once, decreasing the possibility of system flow-pressure control valve problems at the cluster point.

The control system compared the position of each sprinkler control group to a map in the memory of the main controller. The program was designed to allow up to 80 individual area definitions per circle with a maximum of 8 treatment areas. Each sprinkler control group operated on a one-minute cycle.

Associated with the treatment area definitions was another database that contained the distance from the center point to the middle of the sprinkler group for each sprinkler bank. This database also contained the total flow rate that the sprinkler group could apply. A third database, accessed through the HMI, contained the application depth percent (treatment) of the base application rate for each individual treatment area. The user entered the percent of the base application rate for each individual treatment area (the first span is semi-independent of this control scheme).

A unique aspect of this project was the use of normally-open Bermad pneumatic valves rather than water-assisted electronic solenoid valves. This was done because the air was much cleaner than the irrigation water, which meant that foreign material did not plug the orifices. Normally-closed electric solenoid valves, placed in banks of five valves, were used to control pneumatic valves.

RESULTS

All of the control systems functioned well and were dependable. Evans et al. (1996b) reported some problems with plugging of water-assisted electric solenoid valves due to dirty water, which required additional screening. Consistently, the most significant reported problems centered around obtaining information to manage the system. The data requirements for variable rate water application are several times greater than for current precision agricultural applications. In warm arid areas, irrigation with self-propelled machines occurs 24 hr/day, 7 days a week throughout much of the season, allowing little time for fine tuning and improvements. Soil water content is dynamic value and the data requirements vary hourly as well as spatially to manage the systems.

The challenges lie in developing criteria and appropriate strategies for integrated water, nutrient, and pest control programs. On-board and field sensor systems are needed to monitor soil and plant conditions for proper management. Further work is needed in the integration of irrigation and fertilizer management under precision irrigation equipment.

Uniformity testing clearly shows that accurate characterization of water application patterns is important in calculating and maintaining records of actual depths applied in any reduced application zone so that each zone can be properly managed over the season, and any yield-reducing conditions avoided. Testing within the control zones have generally shown good uniformity but there is considerable variance under all the precision water application approaches that have been tested. On pulsed systems, the cycling of the valves may contribute to variability in the catch data. In addition to variability caused primarily by wind velocity and direction variations, other compounding factors include the start/stop action of the machine alignment system and time lags between the first sprinkler and the last sprinkler in a control group turning on and off relative to can placement. The operation of pressure regulators, which also have a time lag going from no flow to full flow, can also contribute to the variability. Nevertheless, precision irrigation programs cause average system water application uniformities to decrease only slightly since relatively small areas are affected at any one time, but the decreases are in the appropriate locations for maximum environmental benefit.

It is not known if site-specific irrigation is economically feasible if judged by production alone (Knorr, 1995; Evans et al., 1996b; Evans and Harting, 1999). Based on analyses done so far, it is probably not economically feasible to site-specifically manage only for water and/or nitrogen. Improvements in crop quality on crops such as potatoes coupled with increased yields from lower yielding areas do provide economic incentives. It is expected that there will be some cost savings due to: reduced aerial applications of pesticides (e.g., fungicides), lower seasonal water applications, increased average yields across a field, lower fertilizer use, increased accuracy of chemical applications, and better utilization of manpower, all of which add to the economic returns. In addition, future environmental regulations may greatly change the economic feasibility of the site-specific irrigation control system. Individually, these may not be significant but together may add up to substantial savings that could justify the control system.

FUTURE DIRECTIONS

The ability to vary the application of water throughout a field suggests that water-soluble fertilizers can also be variably applied. Research with precision land applications (Sudduth et al., 1996; Wibawa et al., 1993; Wollenhapt, 1997) has shown that variably applying fertilizers has promise in increasing production. Some variable-rate irrigation systems have successfully variably applied nitrogen over test sites (Camp et at., 1996; Harting, 1999; King and Wall, 1997; Omary et al., 1997). These experiments indicate that to make variable-rate fertilizer application work with pulsed systems, a feed back control system based on measurements from flow meters on both the chemical injection system and the center pivot supply line will be required.

However, a considerable amount of work remains to be done in integrating the site-specific application of fertilizers and pesticides into the precision irrigation management system. Pivot/cluster controls should include constant concentration, variable-rate injection of agrichemicals. Experiments on pulsed systems have indicated that a feedback control system based on electronic flow meters on both the chemical injection system and the center pivot supply line will be required to integrate either constant-rate or constant-concentration fertilizer injection into the pivot control system. This will allow either wedge-shaped applications of different amounts or the use of the irrigation treatment area definitions to variably apply agrichemicals at either a constant rate or at a variable rate based on changes by position and by treatment area. The control programs also need to have automatic record keeping on the amount of water applied through the growing season (flow rate monitoring) and individual treatment area databases as well as times the systems are irrigating, traveling without irrigating, and down for maintenance.

We believe that wide-scale adoption of precision irrigation technologies on self-propelled systems will depend on the development of inexpensive, remote and real-time direct sensing of the soil and/or plant water status that are integrated with communications networks into the control and decision support systems. Soil water levels in each treatment area need to be monitored and used in irrigation scheduling simulations to achieve maximum benefit from a site-specific irrigation control system. Monitoring plant response to environmental stresses offers an opportunity for early detection and low cost remediation of problems before severe yield or quality damage occurs as well as to enhance integrated pest management programs and reduce pesticide costs.

Fortunately, self-propelled irrigation systems provide an outstanding platform on which to mount sensors and devices that communicate with other sensors scattered across a field (i.e., via low power radios or infra-red links) to provide real-time or near-real-time feedback of crop conditions throughout the day to improve crop management and to detect dynamic crop status variation during the season. However, much of the necessary technology for inexpensive soil and plant sensors, multi-spectral scanners, video cameras, and associated software remains to be developed.

Variable frequency drives (VFD's) will allow the machine to travel faster than standard machines and decrease drive train wear. Although these are more expensive than normal constant speed motors, they offer considerable control advantages when placed on every tower. For example, the start - stop action is eliminated, and lap times could be reduced, which would be advantageous for low-volume pesticide applications.

SUMMARY

Self-propelled irrigation systems, such as center pivots and linear moves, are particularly amenable to site-specific approaches because of their current level of automation and large area coverage with a single pipe lateral. In addition to irrigation, however, self-propelled irrigation systems also provide an outstanding platform on which to mount sensors for real time monitoring of plant and soil conditions and interact with the control system for optimal environmental benefits. Basically, all of the current approaches worked well.

The knowledge of soil variability within a field is fundamental to the development of site-specific management areas (Han et al., 1996; Evans and Harting, 1999) because different soils have different water holding capabilities. Thus, the full promise of this technology is somewhat limited by the ability to economically remotely monitor soil moisture in specific areas within a field. To achieve maximum benefit from a site-specific irrigation control system, soil water levels in each treatment area need to be monitored to improve simulation and irrigation scheduling accuracy.

Future environmental regulations may change the economic feasibility of the site-specific irrigation control system. Other regulations that may impact the operation and or development of the site-specific irrigation controls are chemical application restrictions on aerial application of chemicals. For example, in the pacific Northwest, recent changes in the endangered species listing of the various salmon and steelhead fish runs could have a large impact on the economics of site-specific irrigation. In the Southeast, coastal zone management acts may similarly impact economics.

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