Review of intelligent sprinkler irrigation technologies for remote autonomous system

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Abstract: Changing of environmental conditions and shortage of water demands a system that can manage irrigation efficiently. Autonomous irrigation systems are developed to optimize water use for agricultural crops. In dry areas or in case of inadequate rainfall, irrigation becomes difficult. So, it needs to be automated for proper yield and handled remotely for farmer safety. The aim of this study is to review the needs of soil moisture sensors in irrigation, sensor technology and their applications in irrigation scheduling and, discussing prospects. The review further discusses the literature of sensors remotely communicating with self-propelled sprinkler irrigation systems, distributed wireless sensor networks, sensors and integrated data management schemes and autonomous sprinkler control options. On board 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. Communication systems such as cell phones, satellite radios, and internet-based systems are also available allowing the operator to query the main control panel or base computer from any location at any time. Selection of the communication system for remote access depends on local and regional topography and cost. Traditional irrigation systems may provide unnecessary irrigation to one part of a field while leading to a lack of irrigation in other parts. New sensors or remotely sensing capabilities are required to collect real time data for crop growth status and other parameters pertaining to weather, crop and soil to support intelligent and efficient irrigation management systems for agricultural processes. Further development of wireless sensor applications in agriculture is also necessary for increasing efficiency, productivity and profitability of farming operations.

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1 Introduction

There has been a vast growth in the demand for water which is proved to be a cause of concern in irrigating agricultural fields. Agriculture is the major user of fresh water, and consumes 70% of the fresh water, i.e. 1500 billion m^3 out of the 2500 billion m^3 of water is being used each year[1-4]. It is estimated that 40% of the fresh water used for agriculture in developing countries is lost either by evapotranspiration, spills or absorption by the deep layers of soil beyond the reach of roots. The problem of agricultural water management today is widely recognized as a major challenge that is often linked with development issues. Many freshwater resources have been degraded by agricultural activity, through over-exploitation, contamination with nutrients and salinization[5-8]. Different methods of irrigation are in use like drip irrigation, sprinkler irrigation, etc. to tackle with the water wastage problem in traditional methods like flood irrigation and furrow irrigation[9-13].

Productivity of agricultural fields varies for many reasons. The variability includes topographic relief, changes in soil texture, tillage and compaction, fertility differences, localized pest distributions and various irrigation system characteristics[14-18]. The effects of different sources of variability on management can be additive and interrelated. In this regard, recent advances in communications and microprocessors have led to the general implementation of site-specific water application systems by self-propelled and linear move sprinkler irrigation systems[19-22]. Designing of a suitable site-specific irrigation system could be complicated and challenging because it needs to address many causes of the variations existing in each field including the system capabilities that may be needed in achieving 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 several researchers[23-27]. McCarthy et al.[28] 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

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across a range of crop management and environmental conditions. The authors concluded that while the 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 crop irrigation. 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 analysing and interpreting the data from real time data networks, remote sensing, irrigation monitoring systems, agronomic and other information used to provide direction and implement of basic commands[29,30]. 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[31,32].

Vast simulation models or integrated approaches were used to evaluate alternative irrigation management options across a range of crop and environmental conditions[33-35]. These integrated approaches require the integration of various sensor systems (on the irrigation machine and in the field), hardware, 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[36].

In this research, the techniques used to gain information about autonomous sensor irrigation management technologies will be explained, which includes information collecting using wireless sensor networks, remote sensor connection, data management schemes and target controlling. There are rare reviews on the topic of autonomous sensor irrigation management in the existing literature and this study aims to fill the gap and provide a more up to date and thorough review, featuring many new developments in irrigation management and an extension to the application of latest sensor technology in agricultural engineering. The relationship of the sections of this review paper is as illustrated in Figure 1.

2 Remote access and communications

This section mainly focuses on the components used for remotely controlling or monitoring sprinkler irrigation systems through computers and accessories. Many of these methods 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[37,38].

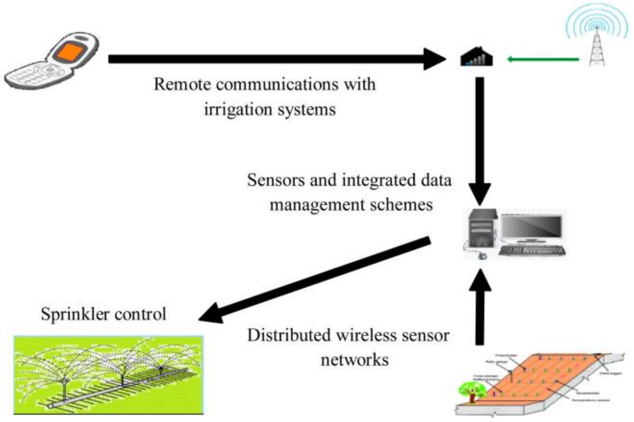

Figure 1 Relationship of autonomous sensor irrigation management technologies

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, application depth, and field position. 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[39-41]. Shock et al.[42] used radio transmission for soil moisture data from data loggers to a central computer logging site.

Researchers from the Department of Soil and Crop Science and Civil Engineering at Colorado State University developed WISE for agricultural producers, irrigation managers, and research scientists[43,44]. The tool resides on a cloud based platform of the environmental risk assessment and management system, and uses the soil water balance (SWB) approach to assist users by providing recommended irrigation amounts for individual fields. Mandatory setup of a field can only be completed on a web browser via a computer. The difficulty of outlining field shapes on a smart phone or tablet prohibits users from using the full version of WISE on those devices; therefore, the mobile version does not possess full capabilities of WISE. Instead, users can easily view their soil moisture profile, irrigations, precipitation, and soil deficit values once the project and field are set up using a web browser on a personal computer[45-47].

The GSM based automated irrigation control system with a gun sprinkler[48,49] was mentioned about using automatic microcontroller based rain gun irrigation system in which the irrigation will take place only when there will be intense requirement of water. Mobile phones have almost become an integral part for serving multiple needs of humans. Mobile phone applications make use of the GPRS feature of mobile phone as a solution for irrigation control system. These systems cover less range of agriculture land and not economically affordable. The system uses GSM to send message and an android app to notify the farmer to overcome under irrigation, over irrigation that causes leaching and loss of nutrient content of soil[50,51].

The GSM based automatic irrigation control system for efficient use of resources and crop planning by using an android mobile phone[52,53] is featured of the water management decision, which is used for monitoring the whole system with GSM (RS-232) module. The system can continuously monitor the water level (water level sensor) in the tank and provide accurate amount of water required to the plant or tree (crop). The system checks the temperature, and humidity of soil to retain the nutrient composition of the soil managed for proper growth of plant. This system is low cost and effective with less power consumption using sensors for remote monitoring and controlling devices which are controlled via SMS with a GSM android mobile phone.

In irrigation control system using android mobile apps and GSM for efficient use of water and power, autonomous irrigation system uses valves with controllers to turn the pump on or off. Farmers can use automation equipment to reduce runoff from over watering saturated soils, avoid irrigating at the wrong time, which will improve crop performance by ensuring adequate water and nutrients when needed[54,55].

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[56,57]. Higher powered, licensed, radio systems (e.g., 5-10 W) with data modems may also be an option but may also be affected by topographic relief. Repeater stations for radio frequency systems can also be quite expensive, especially if there is a need to communicate long distances over diverse topography. These additions to the existing on- board control capabilities of center pivot panels make site-specific irrigation a reality for irrigation zones less than 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-specific information and the cost recovery potential of the cropping system since system costs up to \$20 000 are possible when there are many management zones along the system length.

3 Distributed wireless sensor networks

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. The seamless integration of sensors, data interface, software design, and communications for site specific irrigation control using wireless sensor-based irrigation systems can also be challenging[58]. Electrical power needs are often a major consideration and solar panels are often used. A number of researchers have addressed the issues of interfacing sensors and irrigation control using several different approaches. Shock et al.[42] used radio transmission for soil moisture data from data loggers to a central data logging site where decisions were made and manually changed. Wall and King[59] 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. However, it is often not feasible to have in-field sensing stations that use wires to connect to a base station because of the cost, labour 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. In this regard, 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[60-63].

These are ‘line-of-sight’ (LOS) systems and crop canopies, small trees, and fences can interfere with transmissions. ZigBee is a low-cost, non-proprietary 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[64,65]. Zhang[66] 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 h continuous battery operation and 2-3 s of transmission latency with the increase of communication range. Oksanen et al.[67] used a PDA with Bluetooth to connect a GPS receiver for their open, generic and configurable automation platform for agricultural machinery. Lee et al.[68] 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, and synchronous data collection[69]. 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, and by reducing idle listening and collisions that occur during the medium access to realize power conservation[70,71].

However, reducing quiescent current draw is typically a significant method for impacting battery longevity[72]. Other identified challenges specific to WSNs and agriculture include interference with radio propagation due to crop canopy height[73]. Andrade-Sanchez et al.[74] 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.

Table 2 summarizes the advantages and disadvantages of distributed wireless sensor networks (WSN).

Table 2 Advantages and disadvantages of distributed wireless sensor networks (WSN)

Advantages	Disadvantages	
Allows producers to maximize their productivity while saving water	Power needs are often a major consideration	Interference by vegetation
Provide dynamic mobility and easy relocation and replacement of stations	Provision for ample bandwidth	Synchronous data collection
Coordination of control and instrumentation data is most effectively	Existing inefficiencies in routing protocols	Sensor battery life Radio range
Managed using data networks and low-cost microcontrollers	Electromagnetic interference	Interference with radio propagation to crop canopy height

4 Sensors and integrated data management schemes

In this section, to determine the soil moisture content either in volumetric and gravimetric forms, various techniques can be employed, which can be categorized. These are classical and modern techniques for both the laboratory and in situ measurements. The classical soil moisture measurement techniques include thermo-gravimetric, calcium carbide neutron scattering, gypsum block and tensiometer methods[75-77]. While the modern techniques utilize soil resistivity sensor, tensiometer, infrared moisture balance and dielectric techniques like Time Domain Reflectometry (TDR), Frequency Domain Reflectometry (FDR) capacitance technique, heat flux soil moisture sensors, micro-electro mechanical systems and optical techniques[78,79]. Estimation of water content based on sensor measurements provides real time, in situ measurements at a relatively affordable cost. Soil moisture sensors potentially provide the means to irrigate in accordance with the unique characteristics of a given crop in a given field. These sensors can be used as a ‘stand-alone’ method, or their use can be combined with the FAO method, or they can be used to complement irrigation management based on experience[80].

Automating farm or nursery irrigation systems allows farmers to apply the right amount of water at the right time, regardless of the availability of labor to turn valves on and off. It only allows the user to monitor and maintain the moisture level remotely irrespective of time. If the plants get water at the proper time then it helps to increase the production from 25% to 30%[81,82]. Traditional instrumentation based on discrete and wired solutions, presents many difficulties on measuring and control systems especially over the large geographical areas. If different kinds of sensors (that is, temperature, humidity, etc.) are involved in such irrigation in future works, it can be said that an internet based remote control of irrigation automation will be possible. The developed system can also transfer fertilizer and the other agricultural chemicals (calcium, sodium, ammonium, zinc) to the field with adding new sensors and valves. Cost effective solar power can be the answer for all our energy needs. Conserves electricity by reducing the usage of grid power and conserves water by reducing water losses[83,84].

A conceptual system layout of distributed in-field wireless sensor network (WSN) is illustrated in Figure 2[85]. Farmers can get the real-time information of their farmland by android app or through automatic SMS facility, for better crop management practices. Using this information, the farmers could be advised that when and how much to irrigate.

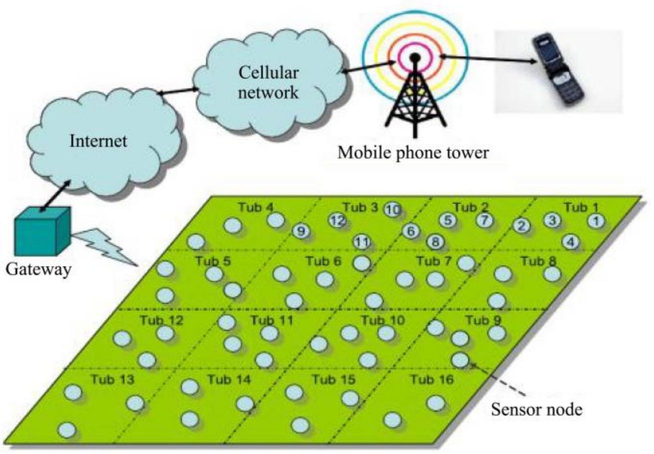

Figure 2 Application of sensor network in field

The system comprises of several components called ‘nodes’. These are smart devices that are used to collect the application oriented data requirements. A sensor network performs three basic functions that is Sensing, Communication and Computation by using hardware, software and algorithm[86]. The nodes perform several roles and the distributed nodes that collect the information are called source node while the node that gathers the information from all source node is called the sink node or the gateway node. The sink node has high computing power. A source node also works as a routing node due to the requirement of multi hop routing. External memory is an optional module that could be needed in case of data storage requirement for local decision making. The in-field sensors monitor the field conditions of soil moisture, soil temperature, and air temperature. All in-field sensory data are wirelessly transmitted to the base station. The base station processes the in-field sensory data through a user-friendly decision-making program and sends control commands to the irrigation control station[87].

Dias et al.[88] developed a new single probe heat pulse sensor (SPHP), which was comprised of only one element, a n-p-n junction bipolar transistor, worked as both heating and temperature sensing elements. Xiao et al.[89] developed a wireless, integrated, frequency domain soil moisture sensor for paddy field (WFDSS) applications in China. This soil sensor was able to measure soil moisture content and water depth at the same time and transmitted the collected data wirelessly to a remote data management center.

5 Sprinkler control options

Center pivot systems, for example, operate on varying topography and often have a range in soil textures present under a single machine. 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[90-92]. 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/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[93-96].

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° 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 with 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[97-99].

The 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[100,101]. 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[102-104]. Normally open solenoids allowed system control with the assurance that irrigation water was applied even if the control system failed. Chávez et al.[105,106] 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 on-board 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[107] and Liu et al.[108] 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[109,110]. Controlling irrigation water application depth can also be accomplished using multiple manifolds with different sized sprinkler nozzles to vary water and nitrogen application[111-113]. 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 like 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 most important 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.

6 Conclusions and future work

Electronic sensors, equipment controls, and communication protocols have been developed to meet the growing interest in site-specific irrigation systems. On-board 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.

However, the limitations reported in reviewed publications about Bluetooth applications in agricultural systems can be solved or alleviated 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. Considering a real need to improve the efficiency of irrigation systems and prevent the non-optimal use of water, the most promising and challenging research direction is to develop intelligent irrigation management systems which will enable farmers and other end users to optimize the use of water; for example, only irrigate where and when it is needed. This would provide site specific and time specific irrigation management to maximize the efficiency of the irrigation so reduce the use of water. This is a very complicated and challenging research topic as crop water productivity is affected not only by the environment and soil but also by what kind of crop and at what a stage. Whenever there is a change in local environment such as temperature and humidity, sensors are required to sense or observe these changes and the irrigation decision making system need to consider these changes and update irrigation strategies accordingly. New sensor or remote sensing capabilities are required to collect real time data for crop growth status and other parameters pertaining to weather, crop and soil to support intelligent and efficient irrigation management systems for agricultural processes. Further development of wireless sensor applications in agriculture is also necessary for increasing efficiency, productivity and profitability of farming operations.

Acknowledgments

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