Hardware-based Agriculture Maintenance System

Precision agriculture is a relatively new and expanding field from which emergent technologies have proven to increase crop yields with reduced water usage (Gutierrez et al. 2014, Dinh Le and Ho Tan 2015). The implications of these technologies on developing economies situated in areas prone to drought and pests are positive (Mafuta et al. 2013). Crop production and maintenance in the Caribbean context is an activity of paramount importance in the effort to increase regional food security and to reduce food import bills (FAO 2013). Irrigation and fertigation of crops incurs most of the cost operation through crop cycles. Over-irrigation and over-fertigation wastes limited water resources and expensive fertilisers in addition to adverse effects on crop yield. Inadequate irrigation and fertigation also reduces production. Optimum crop production can be achieved by monitoring soil conditions and taking appropriate and precise actions to maintain optimum conditions. The Hardware-based Agriculture Maintenance System is a scalable field programmable gate array (FPGA) implementation for remote crop monitoring and maintenance.

The report describes the design and development of the minimal constituent parts of the scalable wireless sensor network (WSN): the master administrator node and the slave sensor node. The nodes communicate over general packet radio service (GPRS) using GSM modems.

The functions of the slave node include the following:

1. Monitoring soil moisture and soil pH
2. Allowing the administrator to set moisture thresholds using a keypad and 14-segment display interface
3. Transmitting warning signals to the master node when moisture values move out of administrator defined values
4. Initiating irrigation actuators at the command of the administrator node.
5. Halting irrigation when moisture levels return to values within administrator defined thresholds.
6. Informing the administrator node that the issues have rectified

The functions of the master node include:

1. Allowing the administrator to start and irrigation session in response to low moisture using a keypad interface
2. Displaying warning messages on a 14-segment display
3. Identify sensor nodes by a unique ID.

The problem

Literature review

The following subsections will explore the recent trends and methodologies for implementing field and greenhouse irrigation management and monitoring systems based on Wireless Sensor Networks (WSN’s) as described in the available literature. This discourse begins with a short introduction to the subject of precision agriculture - its origins, rationale and relevance. The review progresses into a discussion and comparison between different WSN applications and topologies encountered in the literature. In the subsequent subsection, the irrigation control schemes in the decision support systems will be compared. An overview of FPGA technology in WSN applications will be explored in the penultimate subsection as to justify its use in PA. In its conclusion, this section will summarise the findings concisely and set the basis for the methodology of the Hardware-Based Agricultural Monitoring System (HBAMS).

Precision Agriculture (PA)

The mid-1980’s saw the implementation of newly available technologies for efficient application of fertilizer to farmland. Techniques were developed to increase crop yield by varying fertilizer blends and application rates with reference to data obtained from aerial photography, satellite imaging and periodic soil tests. These techniques became known as site specific crop nutrition management and with them, the advent of Precision Agriculture (PA) (Robert 2002). In the early 2000’s the widespread proliferation of precision agriculture was limited by socio-economic and technological factors(Robert 2002). Over the last decade, advancements in technology have made implementation of new solutions more viable and sustainable. There have been developments that have yielded sensors for real time, in situ measurements of soil moisture; the devices require little to no calibration, a significant limiting factor in the past. As of late, dedicated and robust Ion Specific Field Effect Transistor (ISFET) probes for in situ measurement of soil pH, pNH4, and pNO3 have been developed (Joly et al. 2017). Crop site monitoring is becoming more affordable and practical with the ubiquity of wireless technologies for real-time data acquisition and the growing array of sensors for obtaining various metrics. The metrics delivered by the data acquisition system can be fed into a Decision Support System (DSS) to determine corrective measures for optimal crop production. PA has proven its potential to increase crop yields and water savings and therefore increase food security and revenue from agriculture.

Wireless Sensor Networks

Recent developments in precision agriculture employ Wireless Sensor Networks (WSNs) and smart actuators for data acquisition, crop monitoring and irrigation. WSN’s were originally developed for military applications for object tracking, identification and tracking. Today, WSN’s have also been developed for industrial control, analysis of vital parameters (medical), and data acquisition for predictive modelling of environmental conditions in ecological systems (de la Piedra, Braeken, and Touhafi 2012). A Wireless Sensor network consists distributed sensor units called nodes. These nodes may communicate to a central control device which may drive actuators and/or accumulate data for transmission to a database or administrator. The design and implementation of wireless sensor networks vary according to the requirements and constraints of the users.

Long An University of Economics, and Industry, Vietnam, developed a system architecture for precision agriculture which consists of network solar powered nodes that measure moisture, windspeed, temperature and humidity at various points on plots of land (Dinh Le and Ho Tan 2015). The wireless sensor nodes (WSN) in the field communicate live data to a central wireless management node to which they are assigned. The central node, the Wireless Management Node (WMN) transmits the accumulated data from sensor nodes to a control centre 1 – 7km away via an antenna. The WMN also drives actuators based in response to readings received from WSN in accordance management policies communicated to it form the control centre. The collected data is uploaded to a web server make it available on the internet. Dinh Le and Ho Tan (2015) also described the formulation of management policies and decisions based on accumulated environmental data using a Dynamic Bayesian Network to accurately forecast environmental conditions. Dinh Le and Ho Tan (2015) present a comprehensive and scalable data acquisition system and their results from field tests shed light on the usefulness of WSN’s for data acquisition and data prediction.

Gutierrez et al. (2014) described a different approach crop WSN monitoring and irrigation compared to Dinh Le and Ho Tan (2015). Their Automated Irrigation System Using a Wireless Sensor Network and GPRS Module (Gutierrez et al. 2014) consisted of multiple Wireless Sensor Units (WIU) connected to a Wireless Information Unit (WIU) over a Zigbee protocol (IEEE 802.15.4 WPAN). The WIU accumulates information from the WSU’s and transmits moisture and temperature data to a web server using an internet protocol over GSM. The WIU communicated with the GSM module over an RS232 serial connection. The accumulated information is stored on solid state memory driven by a microcontroller. This information can be viewed in real time from a website. This is in contrast to the system described by Dinh Le and Ho Tan (2015), which includes a data prediction module and measures four environmental parameters. Gutierrez et al. (2014) did not have a control centre for the system they implemented, instead, the web application used for monitoring the change in parameters with time and the time spent irrigating can be used to set the thresholds for automatic irrigation by the WIU. Relays for opening valves are actuated using optical isolators. The design objective of this network is to acquire data for administrators and allow them to act based on this data.

A system for autonomous monitoring and irrigation of crops was a proposed by Bhanu, Hussain, and Ande (2014). The system implemented was microcontroller based, with the decision support system implemented by sensor network. This system consisted of control software implemented on a wirelessly integrated PC for initiating irrigation, however, a DSS was also embedded into the sensors themselves. This decentralized WSN featured autonomous communication between nodes to for cooperative scheduling of irrigation. This smart WSN communicates with a base station to receive soil specific information or to communicate unexpected events. The irrigation run times were varied by the network in response to changing air humidity and soil moisture. The authors demonstrated their system using two sensor nodes monitoring two different zones. The nodes were interfaced with two moisture sensors and acted based on the average of moisture level recorded from the two sensors. The design objective of this network was autonomous and intelligent monitoring and irrigation by the network. The decentralized topology makes this system distinct from the others encountered during the literature search.

The network implemented in the research article Successful Deployment of a Wireless Sensor Network for Precision Agriculture in Malawi (Mafuta et al. 2013) bears semblance to those employed by Dinh Le and Ho Tan (2015) and Gutierrez et al. (2014). The Mafuta et al. (2013) approach consists of three types of nodes, the coordinator node accumulates data and forwards accumulated data to a gateway node, this gateway node also . In contrast to the systems (Gutierrez et al. 2014) and (Dinh Le and Ho Tan 2015), Wireless Sensor Network for Precision Agriculture in Malawi does not feature an internet component. SMS was the chosen protocol for transfer of moisture and temperature information to administrators due to limited funding. Software installed on administrator PC’s is used to enter the incoming SMS data into a MySQL database and displayed to the administrator using a PHP script. The sensor nodes were an open sources solution from a commercial supplier with Zigbee (IEEE 802.15.4) wireless technology. Water conservation in the context of this project was important and to that end, design elements seen in Bhanu, Hussain, and Ande (2014) were employed concerning irrigation run time. The choice of communication protocols shows consideration of the economic environment in the field of operation - SMS is cheaper than IP.

Irrigation Control Schemes

The primary objective of precision agriculture is optimal use of resources. An appropriate irrigation control scheme is a required to rectify adverse soil conditions and to halt irrigation when optimal conditions have been restored. Soil is over irrigated when water is added beyond field capacity (FC). Field capacity is the moisture level of the soil after excess water has been drained out. Soil will not hold water beyond its field capacity

Bhanu, Hussain, and Ande (2014) described their sensor calibration procedure and control scheme development. The team obtained soil samples of various types, which they dried and weighed. The researchers calibrated the sensors by adding known volumes of water to the soil samples and recording the responding voltages output from the sensors. The authors also processed the data from their initial soil tests to develop an irrigation control scheme using numerical methods.

Mafuta et al. (2013) employed a sensor that measured Soil Moisture Potential (SMP) as opposed to Volumetric Water Content (VWC). The researchers chose a lower threshold of 50% FC and upper threshold of 10% FC. The upper threshold was chosen to compensate for the delay between added water and changes in measured water content. This was a simplistic approach to avoiding overshoot of FC, however, Mafuta et al. (2013) went on to recommend a more robust control scheme to avoid exceeding the FC of the soil. The researchers proposed an irrigation control system that calculates an irrigation time interval based on the current SMP of the soil, irrigates for that estimated time interval, then hibernates for an interval. When the hibernation interval expires, the proposed system should conduct the process again – with a shorter calculated irrigation interval. When FC is attained, irrigation is halted.

The system implemented by Gutierrez et al. (2014) initiated irrigation automatically for a fixed time interval (35 minutes) when temperature rises above a predetermined temperature threshold or when the moisture level fell below a threshold. Irrigation was pre-empted the moisture level rose above user defined threshold. This method of irrigation control is less sophisticated than what was proposed by Bhanu, Hussain, and Ande (2014) and Mafuta et al. (2013), however, the authors reported water savings of 90% and 60% compared to traditional methods on two separate sites.

FPGA Implementation of Wireless Sensor Networks

Microprocessor based implementations take precedence in the field of WSN’s but FPGA technology features functionality that addresses some of the key challenges that engineers face in the field of WSN development and precision agriculture by extension. Field Programmable Gate Arrays are Programmable Logic Devices (PLD) that can be electrically programmed in the field to become any kind of digital circuit or system (Farooq, Marrakchi, and Mehrez 2012). FPGA’s are pre-fabricated silicon devices that generally consist of configurable logic blocks (CLB’s) distributed in grid pattern with various interconnections made possible by programmable routing interconnect. A CLB typically consists of four Basic Logic Elements (BLE’s). BLE’s consist of 4-input Look-Up tables (LUT’s) are implemented using a network of 2-input multiplexers. The input terminal of the multiplexer networks are connected to SRAM cells that are to logic HIGH or LOW when the FPGA is programmed. Different combinations of inputs to the LUT assign the value of different SRAM cells to the LUT output, these mechanisms allow a BLE to perform any 4-input logic function. I/O block situated on the periphery of the matrix of programmable interconnect and CLB’s facilitate interfacing with other devices. The combination of programmable interconnect and configurable logic realises a device whose behaviour and functionality can be modified after its fabrication (Farooq, Marrakchi, and Mehrez 2012). The most common programming technology used FPGA’s is SRAM. SRAM is volatile, and the configuration is lost when the device is disconnected from the power source. EEPROM or flash memory is an alternative to SRAM, is more area efficient (SRAM requires 6 transistors to store one bit as opposed to 1 in EEPROM) and is non-volatile, but has a finite number of write cycles as opposed to SRAM’s near infinite write cycles (Farooq, Marrakchi, and Mehrez 2012).

There are variety of sensors available on the market today, and new developments in field probe technology for long term in-situ measurements (Joly et al. 2017). The challenge to engineers of WSN’s are the various proprietary and open-source interfaces that these sensors use. Companies tend to manufacture their probes and sensors to interfaces with specific data loggers. The lack of reconfigurability in sensor nodes and data-loggers makes it difficult to use a wide range of specialised sensors on a common WSN platform (de la Piedra, Braeken, and Touhafi 2012). Changing sensors in an existing microcontroller based WSN or adding a new type of sensor to the network would require sensor nodes to be taken offline for firmware upgrades. A field may have tens or hundreds of sensor nodes, the process of upgrading them will be very time consuming. In the case of precision agriculture, land administrators wishing to optimise agricultural DSS by measuring more specific indicators of soil health like pNO3­, pNH4­ will find it necessary add or upgrade these sensors to their networks when they become available on the market. Partial reconfigurability of FPGA systems makes it possible for several sensor interfaces to be supported and reconfigured remotely, without interfering with sensor connectivity (de la Piedra, Braeken, and Touhafi 2012).

Data acquisition, encryption, compression and transmission demands for WSN’s in PA will increase as land administrators increase the environmental parameters they measure to improve their DSS’s. The demands increase sharply if graphical data becomes a requirement. Data processing algorithms are computationally intensive and constitutes up to 80% of the energy demand of a WSN (de la Piedra, Braeken, and Touhafi 2012). Sensor nodes often operate on batteries therefore power consumption is an engineering concern. Low power FPGA’s can be configured to perform these calculations optimally with significant decreases in power consumption compared to microcontrollers. It must be noted that Application Specific Integrated Circuits (ASIC’s) have a smaller footprint and consume less power than FPGAs. The mechanisms and architecture of the FPGAs that make them flexible also increase their size and power consumption. Superiority of FPGA’s compared to microcontrollers with respect to power consumption is seen when low power FPGAs are used to perform more complex calculations such as Fast Fourier Transform (FFT), Haar Wavelet Transform (HWT) (de la Piedra, Braeken, and Touhafi 2012). The most significant advantage of FPGA’s in the field of WSN’s for PA is reconfigurability and rapid prototyping, which will allow engineers to continually adapt and upgrade WSN’s without the recurring economic cost associated with producing ASIC’s or the time and operation cost of upgrading microcontroller firmware. As more low power FPGA’s are introduced to the market and microcontroller-FPGA hybrid systems such as Xilinx Zynq-7000 All-Programmable System on Chips (APSoC) enter the market, the prevalence of FPGA technology in WSNs will increase in PA, Medical and industrial applications.

Application to Project Scope

Lai and Dai (2012) implemented and FPGA based irrigation control system consisting of an irrigation controller and a control panel. The control panel provided a console for administrators with an array of 16 LED’s corresponding to a maximum of 16 irrigation sites. The system was equipped with 12 seven-segment displays and a 4 x 4 keypad. The controller component house the FPGA. The controller actuated 12 relays that energised the solenoid valves enabling irrigation. This system communicated with a computer on which a DSS software application was implemented. An RS232 interface was chosen to interact with the Controller. Modification of the controller’s behaviour was also possible using the keypad. Lai and Dai (2012) also implemented a user accounts system for with password protection. Personnel with the appropriate credentials were able to set the system time of the controller using the control panel. The control panel could also be used to delay, advance, or cancel an irrigation session when prompted by the DSS on through the said control panel. It was possible to manually set irrigation time by entering a desired irrigation volume to the system. Administrators were able to add and delete user accounts and modify passwords from the control panel. A 2-digit scheme was used to enter the different operating modes of the control panel.

In their paper, Lai and Dai (2012) also provided a pictorial description of the relationship between different system modules. Their system architecture featured design elements that proved a suitable reference for this project. The composition of their system has been reflected in in the conceptual block diagrams developed in in the following section. The decision was made to follow the example of Mafuta et al. (2013) in selecting a communication protocol to use in conjunction with GPRS. The simplicity of SMS was preferred over increased complexity IP for the time constraint and limited experience of the designer. Volumetric water content was chosen over Soil Water Potential as the soil moisture metric to be measured, the Vegetronix VH400 probe used by Gutierrez et al. (2014) was well supported by the relevant documentation on the manufacturer’s website. 12-key keypads were chosen instead of 16-key keypad matrices it was deemed sufficient to meet the project. 14-segment displays were chosen as opposed to 7-segment displays to support all alpha-numeric characters. The irrigation control scheme described by Mafuta et al. (2013) was considered to be the most suitable for this application, but it would be impossible to implement with the time constraints of the project.

Methodolgy

The demands of this project required a combination of design and implementation strategies to produce rapid prototypes, identify design errors errors quickly and to swiftly identify and attain key functionalities for the system. The philosophy of the methodology can be summarised as: functionality above all.



Figure 1 Planning the Project

Figure 1 gives the pictorial representation of the planning process. The four last steps are testament the cyclic nature of planning and adaptation as problem is better understood. The sensor node and master node were to be implemented on to Diligent Xilinx Spartan 3 XCS31000 development boards without the guarantee than final design could place and routed to the FPGA’s without exhausting all the available resources. This uncertainty resulted in the adoption of design strategy that eliminated duplication of data as far as possible and the implementation of ROM lookup as far a was practically possible.



Figure 2 Specification and Modelling Methodology Flowchart

The flowchart in figure 2 above generalizes the 3-stage, iterative process employed for specification and modelling of the different modules conceived form the initial conceptual block diagrams in figures 3 and 4 below



Figure 3 Sensor Node Conceptual Block Diagram



Figure 4 Master Node Conceptual Block Diagram

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