DEVELOPMENT OF A PRECISION IRRIGATION CONTROL SYSTEM FOR HORTICULTURAL FOOD CROPS IN TANZANIA

By
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A THESIS PRESENTED TO THE GRADUATE SCHOOL OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE MASTER OF SCIENCE DEGREE
UNIVERSITY OF FLORIDA
2014
To my dear mom Flora, my siblings Ibrahim and Elizabeth, you are always making my life good
ACKNOWLEDGMENTS

I praise and thank almighty God for giving me his blessings and grant me with healthy life to do all my research activities.

My sincere appreciation to the USAID-iAGRI (United State Agency for International Development-Innovative Agriculture Research Initiative) for the financing of my masters studies to the University of Florida (UF).

I am so happy and thank the USAID-Feed-the-future program through the Norman E. Borlaug Leadership Enhancement in Agriculture Program (Borlaug LEAP) at the University of California, Davis for awarding me an outstanding research fellowship to support my research.

My special gratitude goes to the Sokoine University of Agriculture (SUA) for supporting me throughout the two years of my studies as their employee.

I extend my heartfelt gratitude to Prof. John K. Schueller, Prof. Arnold W. Schumann and Prof. Siza D. Tumbo for all their support and advice which facilitated the completion of this study.

I also thank my graduate committee member Prof. Won-Suk Lee for his support and guidance in this research.

Last but not least, I send my special thanks and appreciation to Mrs. Catherine Kilasara at SUA and Mr. Kelvin Hostler at UF for all their technical assistance in the laboratory matters of electronics and instrumentation.
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<td>Citrus research and education centre</td>
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<tr>
<td>DC</td>
<td>Direct current</td>
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<tr>
<td>EM</td>
<td>Electromagnetic</td>
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<tr>
<td>ETO</td>
<td>Evapo-transpiration potential</td>
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<td>HBC</td>
<td>H-bridge chip</td>
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<td>IC</td>
<td>Irrigation controller</td>
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<tr>
<td>LCD</td>
<td>Liquid crystal display</td>
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<td>LEAP</td>
<td>Leadership enhancement in agriculture program</td>
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<td>MC</td>
<td>Master controller</td>
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<td>MC</td>
<td>Main controller or master controller</td>
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<td>PCB</td>
<td>Printed circuit board</td>
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<td>PIC</td>
<td>Peripheral interface controller</td>
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<td>PICS</td>
<td>Precision irrigation control system</td>
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<td>SDI</td>
<td>Serial digital interface</td>
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<td>SUA</td>
<td>Sokoine university of agriculture</td>
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<td>TAHA</td>
<td>Tanzania horticultural association</td>
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<td>TAPP</td>
<td>Tanzania agricultural productivity program</td>
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<td>TBL</td>
<td>Tiny bootloader</td>
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<td>TDR</td>
<td>Time domain reflectometer</td>
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<tr>
<td>TDT</td>
<td>Time domain tensiometer</td>
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<td>UF</td>
<td>University of Florida</td>
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<td>USAID</td>
<td>United states aids for international development</td>
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<td>WC</td>
<td>Water controller or slave controller</td>
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Abstract of Thesis presented to the Graduate School of the University of Florida in Partial Fulfillment of the Requirements for the Master of Science Degree

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By

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August 2014

Chair: John Schueller
Cochair: Arnold Schumann
Major: Agricultural and Biological Engineering

As the Tanzania population grows, scarcity of resources such as water and electricity will pose a great risk to horticultural crop production and society activities. Precision irrigation presents a great opportunity to save water and energy in agriculture. The current off-the-shelf machines used to control water are incompatible to Tanzanian conditions, very expensive, delicate, or do not have enough features.

This study proposed a precision irrigation control system (PICS) prototype design and implementation that can be used in African countries, particularly in Tanzania. The PICS is a solar-powered control system that uses low cost electronic devices to automate drip irrigation and to determine when to irrigate and how much to irrigate. The hardware and software of the PICS were designed, integrated, and constructed in USA and then in Tanzania.

Under testing, the PICS worked properly and achieved a high level of reliability and maintainability. The controller is a high tech tool that can be programmed wirelessly using a laptop and the data can be downloaded using any android based smartphone. The wireless technology incorporated can be used to transfer instant data of rainfall and
soil moisture content. The system updates its data every four minutes (but can be
reprogrammed). The system automates data cleaning while collecting instant
information of the soil moisture, temperature, humidity and rainfall. It can store data at
least for seven days.
CHAPTER 1
INTRODUCTION

Precision farming provides tools and techniques that can be utilized for the modern development of farming activities in Tanzania. Tanzania has to prove itself competitive with the high yield and high quality crops using modern technology provided through precision farming technology. Precision agriculture is the crop production management technique using localized conditions. Schueller (1992) discusses that this management of crop production according to localized conditions is variously known as spatially-variable, site-specific, soil-specific, precision, or prescription crop production. Precision agriculture can be profitable, avoid wastes and save the surroundings by appropriately using agricultural inputs. Precision agriculture provides services in almost all sectors of agriculture but this study concentrates on precision irrigation. In most of the semi-arid places, water is now a scarce factor for crop production.

Precision farming can provide instant information regarding the field conditions. This information is quite necessary for instant variable rate application or offline application. It provides support for decision support management, even for future decisions when you are not using the proposed control system. Casadesus et al., (2012) reported that for supporting a precise and low labor management of irrigation, they proposed and depicted an algorithm that coordinates seven tasks which can be automated: (1) estimation of irrigation needs, (2) adaptation to a particular irrigation setup, (3) execution of the schedule, (4) soil and/or plant monitoring, (5) interpretation of sensor data, (6) reaction to occasional events and (7) tuning the algorithm to irrigation needs. Also, Casadesus et al., (2012) proposed an approach for automated irrigation scheduling which combines a feed-forward estimation of irrigation needs by water
balance method with a tuning mechanism based on feedback from soil or plant sensors. It provided a common basis that could be configured to support different irrigation strategies and user preferences. Khriji et al. (2014) reported that the challenge always is to create an automated irrigation system which can simultaneously reduce the water waste and be cost effective. In this study feed-forward estimation will be done using real-time control based upon feedback from soil sensors. The water-balance method is replaced and soil moisture readings from the sensors estimate the irrigation.

Software can be updated or apps downloaded in programmable devices such as phones to extend capabilities, fix errors, or improve performance. This irrigation control system will have such a technique where a farmer can update the software and change the algorithm to one that is up-to-date while using the same device. The PICS software which is android-based uses Wi-Fi technology to connect to the phone. It displays soil moisture content and control information. The updates of the android software can be found and downloaded directly from the internet and be installed to the phone.

**Background**

Approximately 70% of the people in Tanzania earn their living either directly or indirectly from agriculture. However, most of these farmers face great challenges due to the lack of reliable markets, dependency on seasonal rains, poor infrastructures, the cost of farm inputs and finally, ignorance of the modern farming skills such as precision agriculture. These challenges greatly affect horticultural crops production in the country.

Mashindano et al., (2013) reported regarding the horticultural market in Tanzania. Horticulture market value chain development is one of the specific positioning choices made by Tanzania in its national policy framework 1. According to these agricultural related national policy frameworks, Tanzania intends to promote the
horticulture value chain for the purpose of sustainably contributing to increased production, employment and income generation to resolve poverty in Tanzania. Horticultural products have the potential of creating a strong industry in Tanzania, but the industry has been given less attention, which is disquieting given the existing potential in production and the growing world market demands. Horticulture products are among the main export oriented crops, mainly from part of the northern zone of Tanzania (Arusha, Kilimanjaro regions) where the field survey of their study was conducted, but also in many other regions such as Coast, Morogoro (where main experiments of this study took place), Iringa, Mbeya, Manyara, and Tanga.

Horticultural crops that are grown in eastern, southern and northern zone regions that include Arusha, Kilimanjaro, Tanga, Morogoro, Dodoma and Iringa includes onions, beetroots, okra, carrots, tomatoes, sweet peppers, potatoes, spinach, shallots, leeks, cabbages, watermelons, hot peppers and others. Since it is a big industry, Tanzania horticultural association (TAHA) was formed to develop and promote the horticultural industry in Tanzania to become more profitable, sustainable, and participate more effectively in the development of horticultural crops production.

Sergeant (2004) reported that Tanzania has exported a range of traditional agricultural plantation crops, for example coffee, tea, cashew and sisal for many years. The Tanzanian horticultural export sector is generally regarded as having started in the 1950s with the production of bean seed for selling in Europe, mainly through the Netherlands. Perishable horticultural exports to Europe started in the 1970s, when attempts were made to follow Kenya’s lead in this area. In the mid-1980s, a cut flower industry was established and this was followed by the development of a cuttings
industry based on chrysanthemums. More recently, there have been a number of more specialized investments, for example in propagation of hybrid vegetable seeds, higher value fruits and cut-flowers other than roses. Therefore, Tanzania has a relatively broad-based, if still small, horticultural and floricultural industry focused on supplying the European market. Since the late 1980s and early 1990s, there has been an increasingly important horticultural trade to neighboring countries. Most prominent are sales of onions, tomatoes, potatoes and oranges to Kenya. This trade is predicated on Kenya’s inability to satisfy its rapidly increasing market demand from its own production and imports from Tanzania have made up this shortfall.

Still the horticultural industry is continuing to grow as time passes. The foreign exchange generated by the horticulture industry has increased from USD 46.7 million per annum in 2006/07 to USD 112.6 million in 2008/09 and USD 127.7 million in 2010/11 (Mashindano et al., 2013 and MAFSC 2012). It is still continuing to increase in the years 2011-2014.

Furthermore, in Tanzania, there is a program to give assistance to the farmers on farming techniques so as to increase production yield conducted by the Tanzania Agriculture Productivity Program (TAPP) funded by USAID. Considering drip irrigation techniques as more effective, TAPP decided to install the systems in Tanzania. About 100 drip irrigation systems were installed in most parts of Tanzania and more will be installed in future. These irrigation systems use a pre-planned scheduling to irrigate by using the evapotranspiration rate of the zone, state of development of the crop and type of the soil. With water usage, 1 acre (assume 22m by 184m land) of drip irrigation with single line and 1 litre/emitter/hour, then 37 lines of length 184m will be required for
planting 60cm by 60cm spacing. This means approximately 11346 plants will be connected to the drip lines. Hence, 11346 litre/hour will be required for all plants. This demands approximately 11 m³/hour of the water applied per acre of the land. Also, this can be determined by the TAPP program of ETO, which uses evapotranspiration calculated from a trusted meteorological station and a determined factor of the crop (KC), plus the flow of drip lines. Using experience, the farmers are recommended to apply about 22000 litres for two hours or 33000 litres for three hours per acre. Basically, the above irrigation specification is applied for most of the horticultural crops planted in Tanzania. It also needs a technician or farmer to control manually the irrigation and hence increases the cost of production. Also these services are provided by TAPP and later on the farmer will be allowed to continue with his/her farming activities alone.

In TAPP Production manual volume 3, TAPP_USAID, the importance of good irrigation was emphasized. If the irrigation isn’t good, but with an excellent fertilization then poor yields will be the result, but instead if there is excellent irrigation and okay fertilization then very good crop yields will be achieved. Good irrigation is more important than fertilization and that is why time should be dedicated in proper irrigation. Therefore, this study concentrated on irrigation and the development of an automatic control system specifically for irrigation.

Basically, horticultural crops farmers need a more advanced hassle-free controlled irrigation system so as to protect them from loss of quality due to lack of water or diseases due to high humidity. Nevertheless, to my basic knowledge, there are no commercial available automatic irrigation controllers with all the necessary features
for horticultural crops production in Tanzania; and which are energy-efficient, cheap in price, and durable for harsh remote rural environments.

**Purpose of the Research**

It was proposed to design an advanced irrigation controller for precision irrigation in Tanzania. The system is designed to be able to monitor soil moisture using sensors, data-loggers and software algorithms and then to control drip irrigation.

In this research, an attempt was made to develop a precision irrigation control system that can control water using whatever different algorithms that can be programmed. It can be programmed to meet precision irrigation parameters in irrigation scheduling of deciding “when” and “how” to apply appropriate amount of water in the field.

Rowson and Amin, (2010) defined “Scheduling” and “Monitoring” program of irrigation. The “Scheduling” program computes the right amount of irrigation deliveries based on crop water requirements. The “Monitoring” program gives information on the uniformity of water distribution and the shortfall or excess.

Ortega et al., (2005) indicated that the right amount of daily irrigation supply and monitoring at the right time within the discrete irrigation unit is quite essential to improve irrigation water management. Proper irrigation scheduling can reduce irrigation demand and increase productivity. A large number of tools are available to support field irrigation scheduling, from in-field and remote sensors to simulation models. Irrigation scheduling models are particularly useful to support individual farmers and irrigation advisory services.

Using the information provided from several sensors it is possible to calculate the right amount of daily irrigation supply. In the result of this research, controllers use this
technique to calculate the right amount of irrigation requirements and then initiate the irrigation.

Culibrk et al., (2014) discusses alternative methods of precision irrigation using satellites. The satellite data of interest for the precision irrigation is primarily data relevant to the water cycle, hydrology and meteorology and provided by missions aimed at gathering such data.

**Statement of the Problem**

The horticultural food crops industry faces a competitive market in the world that needs quality products for export across the continents. Africa in general has a lot of land that needs water which is now quite scarce. Many horticultural crops will have difficulty surviving water scarcity. Generally, the following facts can be presented:

1. Horticultural food crops yield in Tanzania is primarily limited by insufficient quantity of water and nutrients required for optimum growth.

2. Horticultural food crops quality is significantly affected by traditional and cultural methods used by horticultural farms in Tanzania.

3. It’s evident that the current decrease in production of horticultural food crops in Tanzania has been attributed to unfavorable weather conditions especially poor rainfall in most growing areas.

4. Increasing the quality of Tanzanian horticultural food crops will have a great impact in the world market compared to the current situation.

5. Drip irrigation has already proved very successful for optimum production of high value horticultural crops such as ball peppers, grapes and tomatoes in Tanzania.

6. Current methods and instruments of precision agriculture may not be suitable for Tanzania or they may need special modification to apply in Africa.

7. Therefore, small holder farmers of horticultural food crops need an affordable and effective method to be deployed in their farms.
Mafuta et al. (2013) discussed the cost and effectiveness of the off-the-shelf controllers. Off-the-shelf irrigation controllers are usually expensive and not effective in managing scarce water resources.

**General Research Hypotheses**

The following facts are assumed to apply: poverty can be reduced and the quality of life improved in Tanzania by improving horticultural food crops production

Secondly, quantity, quality, and profitability of horticultural food crops production can be significantly improved through improved irrigation techniques

Last but not least, computerized precision agriculture and drip irrigation can significantly improve irrigation and production of horticultural food crops.

**Objectives**

The main goal of this research project is to develop and implement a precision irrigation control system in Tanzania. Therefore, the following are the specific objectives of this research project;

Firstly, develop a robust computerized irrigation controller that will automatically supply drip irrigated horticultural crops with the optimum amount and frequency (timing) of water.

Secondly, develop software algorithms for the irrigation controller to automatically adapt to changing soil conditions in order to minimize user intervention and maximize resource use efficiency and horticultural crops yields.

Lastly, implement and evaluate the performance of the irrigation controller in a real-world horticultural crop in Tanzania.
Satisfying these objectives will demonstrate the achievement of the goal to develop and implement a precision irrigation control system in Tanzania.
CHAPTER 2
LITERATURE REVIEW

Precision farming also known as site specific farming aims to manage production inputs over many small management zones rather than over large zones. It is difficult to manage inputs at extremely fine scales, especially in the case of the horticultural crops farming system in Tanzania where the most of the farms are less than 5 acres. However, site-specific irrigation management can potentially improve the overall water management in comparison to conventional irrigated areas of thousands of acres. A critical element of the irrigation scheduling is the accurate estimation of irrigation supplies and their proper allocation for the actual planted areas. All irrigation scheduling procedures consist of monitoring indicators that determine the need for irrigation. The final decision depends on the irrigation criterion, strategy and goal. Irrigation scheduling is the decision of when and how much water to apply to a field.

Whelan and McBrantley, 2000, and Hadley and Yule, 2009 explain that spatial variability must be correctly characterized for effective site-specific management. If this is not possible, then the “null hypothesis” of precision agriculture applies, i.e., uniform rate application is more appropriate than variable rate application. Spatial differences in soil moisture are likely to be one controlling factor influencing yield, but if they cannot be realistically modelled they cannot be addressed.

Water availability is the major constraint to crop production in different parts of the world. Due to water demand for rapid industrialization and high population growth, the share of water for agriculture is going to be reduced in the coming decades. The further scarcity of irrigation water for crop production, therefore, should be checked for sustaining the food supply through efficient water conservation and management.
practices even in high rainfall areas (Panigrahi et al., 2012; Panda et al., 2004). The amount of water applied is determined by using a criterion to determine irrigation need and a strategy to prescribe how much water to apply in any situation. The right amount of daily irrigation supply and monitoring at the right time within the discrete irrigation unit is essential to improve the irrigation water management of a scheme (Rowson and Amin, 2010).

Irrigation can then be scheduled whenever the soil water content is depleted to a management allowed level (previously set threshold value). Alternatively, a soil water potential sensor can be used to schedule irrigation whenever the soil water potential reaches a previously set threshold. The use of soil water content sensors is gaining vast support in developed countries like the United States of America. The U.S. Department of Agriculture in 2009 awarded the White River Irrigation District in Arkansas $4.45 million to install water measurement and monitoring technology, which includes soil water content sensors (Varble et al., 2011; NRCS, 2009). The governments of the developing countries governments are being urged to support precision irrigation as it has proved to be very successful in developed countries.

Fortes et al., 2004 discusses that many computerized tools have been used for scheduling irrigation deliveries and improving irrigation project management. The possibility for easily creating and changing scenarios allows the consideration of multiple alternatives for irrigation scheduling, including the adoption of crop specific irrigation management options. Scenarios may include different irrigation scheduling options inside the same project area applied to selected fields, crops, or sub-areas
corresponding to irrigation sectors. This allows tailoring irrigation management according to identified requirements.

The irrigation scheduling alternatives are evaluated from the relative yield loss produced when crop evapotranspiration is below its potential level (Fortes et al. 2004).

Ortega et al., (2005) reported that irrigation scheduling is the farmers decision process relative to “when” to irrigate and “how much” water to apply at each irrigation event. It requires knowledge of crop water requirements and yield responses to water, the constraints specific to the irrigation method and respective on farm delivery systems, the limitations of the water supply system relative to the delivery schedules applied, and the financial and economic implications of the irrigation practice (Smith et al., 1996). Irrigation scheduling models are particularly useful to support individual farmers and irrigation advisory services.

Irrigation scheduling is considered as a vital component of water management to produce higher irrigation efficiency under any irrigation system, as excessive or sub-optimum irrigation both have detrimental effects on productivity parameters of many crops, including okra (Aiyelaagbe and Ogbonnaya, 1996). Moreover, scheduling irrigation is influenced by many complex factors such as soil, crop, environment, water supply and cultivation practices. Thus, it is essential to develop an efficient irrigation scheduling under prevailing local conditions. Various methods based on estimated crop evapotranspiration rate (Jaikumaran and Nandini, 2001), ratio of irrigation water to cumulative pan evaporation (Aiyelaagbe and Ogbonnaya, 1996; Batra et al., 2000), open pan evaporation rate (Singh, 1987; Manjunath et al., 1994) and soil moisture
depletion (Home et al., 2000 and Aiyelaagbe and Ogbonnaya, 1996) are widely used for scheduling irrigation in okra. This study used okra for field testing and evaluations.

Although soil water status can be determined by direct (soil sampling) and indirect (soil moisture sensing) methods, direct methods of monitoring soil moisture are not commonly used for irrigation scheduling because they are intrusive and labor intensive and cannot provide immediate feedback. Soil moisture sensors can be permanently installed at representative points in an agricultural field to provide repeated moisture readings over time that can be used for irrigation management. Special care is needed when using soil moisture devices in coarse soils since most devices require close contact with the soil matrix that is sometimes difficult to achieve in these soils. In addition, the fast soil water changes typical of these soils are sometimes not properly captured by some types of sensors (Irmak and Haman, 2001; Muñoz-Carpena et al., 2002; Muñoz-Carpena et al., 2005).

Meron et al., (2001) discussed the use of tensiometers to automatically irrigate apple trees. It was noted that spatial variability was problematic when the tensiometers were installed 30 cm from the drip irrigation emitters. Smajstrla and Koo (1986) discussed the problems associated with using tensiometers to initiate irrigation events in Florida. Problems included entrapped air in the tensiometers, organic growth on the ceramic cups, and the need for re-calibration. Torre-Neto and Schueller (2000) successfully used instrumented tensiometers in a precision agriculture system to irrigate groups of four or five citrus trees. Muñoz-Carpena et al., (2005) found that both tensiometer- and GMS-controlled drip irrigation systems for tomatoes saved water when compared to typical farmer practices. Dukes et al., (2003) used a commercially
available dielectric sensor for lawns and gardens to control irrigation on green bell pepper (*Capsicum annuum* L.). They found 50% reduction in water use with soil-water-based automatically irrigated bell peppers when compared to once daily manually irrigated treatments that had similar yields; however, maximum yields and water use were on the farmer treatment that was irrigated 1-2 times each day.

Blonquist Jr *et al.*, (2006) discussed recent advances in electromagnetic (EM) sensor technology have made automated irrigation scheduling a reality using state-of-the-art soil moisture sensing. Estimates of water content based on electromagnetic (EM) measurement provide real time, in-situ measurements at a relatively affordable cost. Estimation of water content using EM sensors is based on the ability of sensors to measure the real part of the dielectric permittivity (e), or an EM signal property directly relating to e. e directly relates to volumetric soil water content (u) owing to the e contrast of soil constituents; e_a = 1, e_s = 2–9 and e_w = 80; where the subscripts a, s and w represent air, solids and water, respectively. (Blonquist Jr *et al.*, 2006; Qualls *et al.*, 2001; Paul, 2002; Leib *et al.*, 2003) demonstrated the potential of EM sensors in irrigation scheduling. The ACCLIMA sensors used in this study are based on the EM measurement techniques of time domain tensiometers (TDT).

Muñoz-Carpena *et al.* (2005) stated that water supplies become scarce and polluted; therefore, there is a need to irrigate more efficiently in order to minimize water use and chemical leaching. Recent advances in soil water sensors make the commercial use of advanced technology possible to automate irrigation management for vegetable production. However, research indicates that different sensors types may
not perform alike under all conditions. Reductions in water use range as high as 70% compared to farmer practices with no negative impact on crop yields.

Simonne et al. (2008) explained the importance of using drip irrigation in farming activities. He depicts both advantages and disadvantages. Advantages include reduced water use, joint management of irrigation and fertilization, reduced pest problems, simplicity, low pumping needs, automation (this research utilized this drip irrigation advantage), adaptation and production advantages. Some demerits mentioned include substantial economic investment, required maintenance, high quality water (water filters should be used) that the water-application pattern must match planting pattern, safety, leak repair costs and drip-tape disposal which causes extra cleanup costs after harvest.

Hedley and Yule, (2009) reported that in order to increase practical functionality of precision irrigation; real-time monitoring, decision and control systems must be developed. This research implements real-time monitoring and scheduling using irrigation algorithms and data loggers.
CHAPTER 3
MATERIALS AND METHODS

Design Criteria for the New Irrigation Controller

An irrigation controller (IC) was designed and implemented using several design criteria. The design criteria affected what was built, what was incorporated, and how the system was to be operated. The design includes the IC which is low cost, small, and durable, with low energy requirements. The IC which is self-adjusting, using sensors, loop feedback algorithms and fuzzy logic. The IC requires very minimum attention from farmers. The main function of the IC is to measure the daily water requirements of the crop and respond by applying the correct amount of irrigation water regardless of changing environmental conditions.

The IC created is capable of optimally supplying water to the crop using existing harsh infrastructure and resources (spring, river, lake water, local fertilizers, and available energy sources). The IC is also capable of adapting to the existing resources of the farm without any significant modification or change.

The design included basic data logging and history reporting features that have been incorporated in the IC design. A simple, user-friendly interface of LCD display, and buttons is used to configure the IC, with the remote wireless control and monitoring features with an existing Wi-Fi capable cellular android smartphone or the PC.

Design Procedures Taken

To achieve the goals of this project, the following design procedures were included in the project tasks;

Firstly, an information gathering survey was conducted. This included baseline data collection. Baseline data from horticultural crops farms, existing infrastructure,
energy, water, fertilizer resources, field identification and description of existing horticultural crops production methods were fetched.

Secondly, conceptual design of controller functions / requirements, identification of suitable hardware and design of prototype software / firmware, and enclosure was done. Then, schematic circuit design and testing phase on a breadboard platform (solderless working electronic prototype) for identification of incompatibilities and durability of hardware components was done.

After that, the designing and building the first soldered prototype electronic circuit board, using PCB123 software and tools was carefully done. The PCB was then ordered from the PCB123 Company. Installation of the rugged enclosure design with LCD display, Wi-Fi connection and user input buttons was finally done.

Finally, repetitive and randomly modified continuous (24/7) tests were conducted to evaluate accuracy and reliability of the PICS. This rigorous rapid testing helped to rapidly identify problems early on for debugging, and durability improvement. Android-based software to control the irrigation system was developed to be used for farmers to control the PICS.

**Development Procedures**

The development started earlier in May 2013 and was carried out for a whole year until June 2014. The development procedures were divided into three phases:

**Phase 1 System Development**

1. Identification and purchase of electronic components for the IC, software, latching solenoid valves, tipping bucket rain gauges, flow meters, pressure gauges, soil moisture sensors, temperature/humidity and light sensors, etc. was done.

2. Simple programs for the Microchip PIC MCU to read a keyboard, display information on a LCD, and to log sensor data were developed.
3. Individual part testing continued for all parts/modules of the IC, including; a) Real
time clock b) Serial port for in-circuit programming / debugging c) Serial LCD
display and 12-button keypad d) EEPROM memory for data storage: suggest
Microchip 24AA1025 (128 Kbytes, I2C protocol) e) Soil moisture sensors
interfaced with SDI-12 half duplex serial protocol f) Design oscillator frequency and
sleep modes for lowest power use g) A/D interface for reading analog voltage of
the solar panel h) Pulse counting with I/O pins to read rain gauge and flow meter i)
Solar panel and rechargeable battery power management algorithm j) Solar panel
system design and in-circuit control for charging

Phase 2 Advanced System Development

4. Development of a DC latching valve control driver with H-bridge chips was done.

5. Development of simple feedback control and fuzzy logic methods for the Microchip
PIC was done. These methods were incorporated into the IC for closed-loop
control of irrigation for optimal soil moisture regulation.

6. Construction of the first version of the IC printed circuit board was done. Up to this
point, only breadboard had been used for development.

Phase 3 System Deployment

7. Addition of Wi-Fi and smart phone capabilities was done and both were tested.

8. Installation of IC and all other components to automate the irrigation for the okra
plants was done.

9. Testing and tuning the IC in the okra irrigation system in Tanzania was finally
done. Also, adjustment and tuning the feedback control and fuzzy logic algorithms
for the okra irrigation system was done continuously until a fine control was
obtained.

Design of the Irrigation Control System

The control system is based on a feedback control loop. The water is balanced in
the depletion zone near the water availability upper limit. The water is provided in a
controlled manner that allows the plants to always have enough, but not excess water. It
should be noted that this control system is an electronic device that needs more
knowledge of electronics and programming. It has two main parts; the main controller
(MC) and water controller (WC). See the Figure 3-1. The MC is the master controller
that has been connected with all the sensors while the water controller or slave
controller is connected only with the solenoid valves. This allows two major activities of
the IC to be controlled differently. Also, this simplified approach allows ease debugging
of any problems that arise.

The main controller (MC) consists of all the other subparts and it acts as the
master in the master-slave configuration of two main PIC microcontrollers. The
moisture, flow, rain gauge, humidity and temperature sensors report to it. Since the
solenoid valves needs to be controlled based upon the message feeds from the main
controller, then the slave needs to be off all the time except it is requested to turn on or
off the latching solenoid valves. This design reduces power usage. The wireless module
is connected to the main microcontroller for the smart communication of IC with smart
devices such as laptops and Android phones. It is crucial that this IC needs to send
information it has collected to the smart devices that will allow further processing of the
information for post decision management. The main controller is connected to a time
keeper module and a memory unit. The time keeper module is a separate part from the
main controller but sends time information to it. The MC needs the time to schedule the
irrigation. The memory unit is used to keep information needed for further processing. It
is crucial that data can be downloaded from the IC for analysis. Also, the system is
connected to solar panel system that is providing full power to the system. This is
essential since the system will be used in farmers’ fields where no electrical power is
provided. See Figure 3-2 for a more advanced conceptual diagram of the IC.

The water controller (WC) is the slave unit of the master MC. It acts upon
requests from the MC. It is always OFF unless turned on by the MC. The WC is the one
that is listening and answering to the MC. It then controls the H-Bridge chips (HBC). The HBC chips can direct the voltage in either direction to open or close the latching valves.

The latching solenoid valves need to be controlled using 12 volts. They also draw significant current to open/close the valves about 135mA. The PICS operates on 5V regulated voltage. Hence, this present voltage is not enough to operate the valves. Some means of boosting voltage is required. If the supplying solar cells operate at 12V then no need for boosting. But if the system is connected to economical solar panels that produce less than 12V, boosting is required to operate the valves. Experiments have shown that latching valves can actually operate at least 7V but the drawn current is significant.

In case, the voltage is not enough then voltage booster was connected (See Figure 3-3) to uplift the voltage from 7V to 12V. The input voltage is provided through MC connected to MOSFET and 5V input. This connection allows the voltage booster to be on only when it is required to switch on or off the latching valves.

Sensors Module

The MC has ports for digital sensors such as flow, pressure, light, humidity, rain gauge and soil moisture sensor. Each sensor port was built in the system using the requirements needed for the specific sensors such as resistors, capacitors, diodes and power supply.

Humidity Sensor

A digital relative humidity and temperature sensor RHT03 was selected to be incorporated in system. According the manual (http://dlnmh9ip6v2uc.cloudfront.net/datasheets/Sensors/Weather/RHT03.pdf accessed on 28-May-2014), RHT03 output is a calibrated digital signal. It applies an exclusive
digital-signal-collecting-technique and humidity sensing technology, assuring its reliability and stability. Its sensing elements are connected with an 8-bit single-chip microcontroller.

The Maxdetect manual states that every sensor of this model is high precision, capacitive type, temperature compensated and calibrated with the calibration-coefficient saved in one time programmable memory. It is small in size, low power consumption and long transmission distance (100m) enable the RHT03 to be used in many applications. Figure 3-4 shows how the RHT03 is connected.

The power supplied should be between 3.3 and 6V DC. When power is first supplied to sensor no instructions should be sent to the sensor within one second to pass the unstable status. The user will only be required to connect the wires to the ports available (Note: MCU is main control unit, humidity sensor is RHT03, power +5V is $V_{cc}$ and ground is GND).

**Pressure Sensor**

The MSP 300 series pressure transducer is used for the IC. According to the Measurement Specialties, Inc (the manufacturer), MSP300 manual (http://www1.futureelectronics.com/doc/MEASUREMENT%20SPECIALTIES/200149-03.pdf accessed on 28-May-2014) the MSP300 is suitable for measurement of liquid or gas pressure, even for difficult media such as contaminated water, steam, and mildly corrosive fluids. See Figure 3-5.

The transducer pressure cavity is machined from a solid piece of 17-4 PH stainless steel. The standard version includes a 1/4 NPT pipe thread allowing a leak-proof, all metal sealed system. There are no O-rings, welds or organics exposed to the pressure media. The durability is supposedly excellent. It measures pressure up to
10kpsi or 700 Bar and give output in form of mV or amplified voltage output. It provides high accuracy output at maximum temperature range with standard cable from -20°C to +105°C.

However, in this experiment, this sensor catches rust very fast as it was observed in the field. The rust will make it permanently sticking to the pipes. This proves that the sensors are not that much suitable for outdoor applications.

**Rain Sensor**

A model TX32U rain sensor ([http://www.lacrossetechnology.com/tx32/manual.pdf accessed on 29-may-2014](http://www.lacrossetechnology.com/tx32/manual.pdf)) measures the rainfall and sends the information to the MC. According to the manufacturer, La Crosse Technology, for best results the rain sensor should be securely mounted onto a horizontal surface about 1 m or higher above the ground and in an open area away from trees or other coverings where rainfall may be reduced causing inaccurate readings. Leaves and other debris must be removed from the rain sensor. Excess rain must not collect and store at the base of the unit but can flow out between the base and the mounting surface.

The sensor was placed more than 1.5 m above the ground and in a free space area to avoid any external disturbances. See Figure 3-6. This allows correct rainfall collection in the field. Due to size of the field being small, then rainfall measurement accuracy will not be affected by rainfall spatial variability.

The amount of rain is determined by counting bucket tips. The calibration showed that each count corresponds to 0.02in (0.508mm) of rain. I verified this with laboratory tests. Detections of bucket tips go to the MC which interprets and stores the information.
Soil Moisture Transducer

An Acclima SDI-12 Soil Moisture Transducer was used. The Series SDI-12 transducer is a Digital Time Domain Transmissometer (TDT) that measures the permittivity of soils by determining the propagation time of an electromagnetic wave transmitted along a waveguide through the soil. Chavez et al. (2011) reported that under laboratory and field conditions, the factory-based calibrations for the TDT sensor accurately measured volumetric soil water content. Therefore, the use of the TDT sensor for irrigation water management seems very promising. Using a Watermark sensor was also considered. Laboratory tests indicated that a linear calibration for the TDT sensor and a logarithmic calibration for the Watermark sensor improved the factory calibration. According to laboratory tests, the TDT’s factory-recommended calibration performed very well with errors less than 1.2±3.9%. In the case of the Watermark (electrical resistance) sensor, the factory-recommended equation, evaluated with measured soil water content from a corn irrigated field, in average overestimated soil water content by 11.2±12.6%. Blonquist Jr., (2006) concluded that the Acclima Digital TDT sensor is an EM-based water content sensor that when compared to other EM (electromagnetic) sensors was shown to provide exceptional apparent permittivity ($K_a$) measurement accuracy at a reduced cost. The sensor can be employed to schedule irrigation via connection to custom irrigation controllers and conventional irrigation timers.

Blonquist Jr., (2005) reported that the Acclima Digital TDT sensor has the potential to offer a more affordable alternative sensor to others (Tektronix and Campbell). The Acclima Digital TDT Sensor frequency bandwidth and permittivity estimates based on travel time measurements compare quite well to those of the...
Tektronix TDR and Campbell Scientific TDR100. The Acclima Digital TDT Sensor has the advantage over TDR in that signal transmitting and sampling hardware is located in the sensor head negating cable losses. TDT is also advantageous in that one way travel time reduces signal attenuation in the sample (assuming sensor rods are the same length). Blonquist Jr., (2005) said although the Acclima Digital TDT Sensor is presently geared for closed-loop irrigation control, where excavation is necessary for installation, refinement of the rod geometry for insertion (and perhaps conversion to a TDR measurement) will likely rank this TDT method alongside its TDR counterpart as an accepted laboratory and field standard for determining soil water content.

Marble et al., (2011) evaluated the performance of three soil water content sensors (CS616/625, Campbell Scientific, Inc., Logan, UT; TDT, Acclima, Inc., Meridian, ID; 5TE, Decagon Devices, Inc., Pullman, WA) and a soil water potential sensor (Watermark 200SS, Irrometer Company, Inc., Riverside, CA) in laboratory and field conditions. The CS616/625, 5TE and Watermark sensors were strongly influenced by fluctuations in soil temperature, while the TDT sensor was not influenced. The TDT sensor stayed steady while taking readings even in relative high fluctuations in soil temperature. When irrigating, temperature fluctuations are common hence being steady is quite an important feature.

The TDT sensor used in this research is produced by Acclima closed loop irrigation systems. According to the manufacturer’s manual (http://acclima.com/wd/aclimadocs/agriculture/SDI-12%20Sensor%20User%20Manual.pdf accessed on 28-May-2014), the Acclima Series SDI12 soil moisture transducer uses the industry standard SDI-12 interface for
communicating with a data recorder or other SDI-12 equipped controlling device. The SDI-12 communications standard is digital serial data communications hardware and protocol standard based on 1200 baud, ASCII character communications over a three-wire bus. The SDI12 Series is compliant with Version 1.3 of the SDI-12 standard.

Furthermore, the manufacturer’s user manual (2008) (http://acclima.com/wd/aclimadocs/agriculture/SDI-12%20Sensor%20User%20Manual.pdf accessed on 28-May-2014) states that the absolute moisture content of the soil is calculated from the permittivity using the Topp equation (Topp et al., 1980). The transducer can be commanded to produce both the bulk permittivity and the moisture content of the soil. The accuracy and stability of the Series SDI12 is obtained through a patented hardware and firmware system that digitizes the returned waveform and then uses proprietary digital signal analysis algorithms to extract the real propagation time and distortion parameters of the returned wave. High accuracy is achieved over a wide range of soil temperatures and electrical conductivity. In the SDI12 series the resolution of the digitized waveform is 5 picoseconds permitting a small transducer to report very high resolution data. From the extracted distortion parameters the transducer calculates and reports the electrical conductivity of the soil. The permittivity and soil moisture measurements are compensated for temperature. The transducer also reports soil temperature. The Figure 3-7 shows a SDI-12 Soil Moisture Transducer installed at SUA field site.

The sensor is buried at the irrigation root zone of the crop. The sensor will read more accurate when it is near the emitter that gives water to the plant. The sensor will sense water available to plant if placed near the stem of the crop. Many horticultural
crops such as okra develop with short roots which have a limited root zone. Placing the sensor further away might hinder instant control of irrigation systems as signals will consequently vary from plant water requirements. The placement distance and pattern should be the same for all the placed sensors to obtain consistent and reliable control.

Variations in soil type and condition, adjacent land use, shading, and drainage patterns can all cause a sensor to read an unrepresentative soil moisture content, which can result in too much or too little irrigation. If one area does not represent the average condition of the (soil moisture sensor) SMS-controlled area, SMS placement in that location should be avoided. If the sensor probe (such as TDT) is long, flat, and has exposed rounded wave guides (steel rods), it should be installed horizontally and with the wide side facing up (St. Johns River Water Management District, 2008).

Varble et al. (2011) states that the digital TDT and the 5TE (measures soil moisture, soil temperature and bulk electrical conductivity EC) sensors performed better at each treatment at site. They conducted an experiment to compare different sensors and the TDT. Varble et al. (2011) used four statistical measures to arrive to the conclusion. The four statistical equation were computed to compare and evaluate each equation-predicted (P)_v value with the observed (O)_v value derived from gravimetric soil samples taken from the field and laboratory soils. These equations are defined by Willmott (1982) and include the coefficient of determination (R^2), mean bias error (MBE), root mean square error (RMSE), and the index of agreement (k).

Installation of the sensor probe is basically the heart of the automatic control systems. Variations will eventually produce on differences that may hurt control or bring wrong information that will induce irregularities within the irrigation root zone. High
supply of water will bring problems to the plants since high moisture increases the risks of diseases and pests. High supply also wastes precious water. Low supply of water will wilt the plant. Wilting crops that are in flowering stage will cause adverse impacts to the yields.

This SDI-12 sensor allows easy integration with the microcontroller which is the main controller (MC). Requests using SDI-12 commands can be interpreted by both the MC and the sensor. This mutual working allows correct information from the sensor to be transmitted to the MC. The string received has all the information but the MC will trim the whole information and allow only percentage moisture content to be stored in the system.

The SDI-12 sensors respond by using their specific identification numbers (IDs). This is a crucial design since it allows only one pin of the PIC microcontroller to communicate with several sensors. In this research, experiments were carried using six sensors which were all connected to one pin of the MC. Each sensor is called using its ID (1, 2, 3, 4, 5 or 6) and then it replies starting with its ID. Hence the MC can control all of them simultaneously.

Sometimes, these sensors might not produce information on time as requested. They can easily be corrupted by disturbances due to electricity supply irregularities. This is common for devices that may have electric variations that halt the chip performance. Any disturbed information becomes unreadable but if read is more error prone information. A sensor failure report is sent if sensor can’t release soil moisture information.
The control of water is dependent on the correct information coming from sensors at the correct time. Whenever the information is not delivered on time the MC is going to miss that particular information. The treatments are based on the 3 sensors. So if readings from all three are missing then no decision is undertaken by the microcontroller. But the good news is that the observation shows that more than 90% of the readings were correctly collected. This will be analyzed more in the Discussion chapter of this document.

Another good thing about this particular sensor is that it works over a wide range of input voltage from 5V-15V. This range provides a good opportunity at the design level and creates a room for wide range of control. This provides great security to the equipment which is the most expensive equipment in this study followed by pressure sensor. Damage to this sensor would cause a great loss to the farmer. In real field applications fewer moisture sensors are recommended in the field. And the placement of the sensor for great quality results becomes a great challenge to the grower.

**Bill of Materials**

This section presents the bill of materials that were used to construct precision irrigation control system. See Table 3-1.

Table 3-1. Bill of materials

<table>
<thead>
<tr>
<th>Type of the component</th>
<th>Model of the component</th>
<th>The manufacturer/retailer of the component</th>
<th>Number of units</th>
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<td>Pressure transducer</td>
<td>MSP300</td>
<td>Measurement Specialties</td>
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<td>Digital TDT sensor</td>
<td>SDI-12</td>
<td>Acclima</td>
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<td>TX32U</td>
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<td>RHT03</td>
<td>Maxdetect</td>
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<tr>
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<td>Model of the component</td>
<td>The manufacturer/retailer of the component</td>
<td>Number of units</td>
</tr>
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<td>------------------------</td>
<td>--------------------------------------------</td>
<td>-----------------</td>
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<td>Roving Networks</td>
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<td>transistors(PNP)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capacitor ceramic</td>
<td>101,102,103,104</td>
<td>Sparkfun electronics</td>
<td>8</td>
</tr>
<tr>
<td>Printed circuit board</td>
<td>Custom design</td>
<td>PCB123 company</td>
<td>1</td>
</tr>
<tr>
<td>Resistors</td>
<td>1k, 4.7k, 10k</td>
<td>Sparkfun electronics</td>
<td>15</td>
</tr>
<tr>
<td>Keypad 16 button</td>
<td>4x4 keypad</td>
<td>Sparkfun electronics</td>
<td>1</td>
</tr>
<tr>
<td>Liquid crystal display</td>
<td>20x4 LCD</td>
<td>Newhaven company</td>
<td>1</td>
</tr>
<tr>
<td>(Serial enabled)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LED super bright</td>
<td>COM-00531</td>
<td>Sparkfun electronics</td>
<td>1</td>
</tr>
<tr>
<td>white</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mini push button</td>
<td>COM-00097</td>
<td>Sparkfun electronics</td>
<td>1</td>
</tr>
<tr>
<td>switch</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polyethylene water</td>
<td>1000L model</td>
<td>Chemi and cotex industries Limited</td>
<td>1</td>
</tr>
<tr>
<td>tank</td>
<td></td>
<td>Balton ltd and Netafirms company</td>
<td></td>
</tr>
<tr>
<td>Drip irrigation pack</td>
<td>250m2 Netafirm unit</td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>
Precision Irrigation Control System (PICS) Design and Implementation

In this section, the design and implementation of the PICS is discussed. The design is the formulation of the printed circuit board (PCB) and the implementation focused in incorporation of all parts of the PICS. Before this formulation, a breadboard design was made in the laboratory. This is the testing design in which each item was installed on a breadboard and then tested for functional capabilities. Figure 3-8 shows a breadboard design.

The breadboard design was then formulated in PCB software. All the parts with the circuits as discussed above were incorporated to design a printed circuit board. The design was done using professional software known as PCB123 version 4 design suites. The red lines indicate upper connections and the blue lines indicate bottom connections. See Figures 3-9 and 3-10. The labeling is done within the PICS PCB software. The PCB is designed 4.5 inch by 6 inch in size. Two boards were ordered, each of which costs 75.04 USD. Figure 3-11 shows a received board.

The PICS PCB was populated with all the devices needed as shown in Figure 3-12. A soldering machine was used to solder each part carefully. After, soldering the PICS system, the arrangement of the PICS with other parts such as voltage booster, batteries pack, keyboard and LC display was made. Figure 3-13 shows the PCB with all items mounted in a small box for weather protection.

The PICS was taken for testing to a small field at the crop museum on the main campus of Sokoine University of Agriculture. Figure 3-14 shows it installed in the field. At that location it was connected with all the sensors and valves.
The PICS software is installed inside the master controller. The software is designed to control all the processes required to execute feedback control of the control system.

Symbols seen in the flowchart Figure 3-15 are more elaborated in the following section as the PICS commands.

The PICS Commands

The PICS is instructed using commands. The software program inside the MC communicates with all the sensors and the slave microcontroller. This design was essential as it allows any third party designer to design wireless controlling program through any device of choice such as windows-based or iOS-based or Android-based. Simply any operating software application can be developed to work with the PICS. These commands act like an interface between the PICS and connected wireless devices like phones and laptops. When these commands execute they represent a certain message that can be interpreted using external devices. For example, when * is sent to the wireless device, it means that the PICS machine is actually alive and it is running. Also, it sends the current date and time to the wireless device. This allows the farmer to make a change if the time is not correct. Collection of data will be merely useless if all the information is recorded with the wrong time. See Table 3-2.

Table 3-2. The PICS commands and their meanings

<table>
<thead>
<tr>
<th>PICS command</th>
<th>Meaning</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>*</td>
<td>PICS is alive and working</td>
<td>Working machine</td>
</tr>
<tr>
<td>#</td>
<td>Reset</td>
<td>It is going to reset the machine and restart</td>
</tr>
<tr>
<td>PICS command</td>
<td>Meaning</td>
<td>Remark</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------------</td>
<td>------------------------------------------------------------------------</td>
</tr>
<tr>
<td>0</td>
<td>Reset the memory record</td>
<td>It is initiated after pressing # where you make the system to start recording data in previous used memory. Usually, it is initiated after R has been utilized.</td>
</tr>
<tr>
<td>S</td>
<td>Settings request</td>
<td>The machine will display the settings and allows the farmer to make any changes</td>
</tr>
<tr>
<td>R</td>
<td>Recorded data retrieval</td>
<td>This command will request the machine to display all the data recorded before last reset instruction was sent</td>
</tr>
<tr>
<td>F</td>
<td>Sensor 1 readings</td>
<td>When F is received, the machine will request readings from soil moisture sensor number 1. Two readings will be retrieved: soil temperature and moisture</td>
</tr>
<tr>
<td>G</td>
<td>Sensor 2 readings</td>
<td>When G is received, the machine will request readings from soil moisture sensor number 2. Two readings will be retrieved: soil temperature and moisture</td>
</tr>
<tr>
<td>H</td>
<td>Sensor 3 readings</td>
<td>When H is received, the machine will request readings from soil moisture sensor number 3. Two readings will be retrieved: soil temperature and moisture</td>
</tr>
<tr>
<td>J</td>
<td>Sensor 4 readings</td>
<td>When J is received, the machine will request readings from soil moisture sensor number 4. Two readings retrieved: temperature and moisture</td>
</tr>
</tbody>
</table>
Table 3-2. Continued

<table>
<thead>
<tr>
<th>PICS command</th>
<th>Meaning</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>Sensor 5 readings</td>
<td>When K is received, the machine will request readings from soil moisture sensor number 5. Two readings will be retrieved: soil temperature and moisture.</td>
</tr>
<tr>
<td>L</td>
<td>Sensor 6 readings</td>
<td>When L is received, the machine will request readings from soil moisture sensor number 6. Two readings will be retrieved: soil temperature and moisture.</td>
</tr>
</tbody>
</table>

**Windows-based Application for Windows (Tiny Bootloader)**

Programming of the microcontrollers needs a compiler and programmer. The PIC microcontroller is programmed wirelessly and it does not need the programmer which is expensive. Instead, the compiler will be used to compile the program that will be loaded to the microcontroller wirelessly. This process works seamlessly with the PICS environment allowing upgrades of the PICS software to be carried easily.

According to tiny PIC bootloader website (http://www.etc.ugal.ro/cchiculita/software/picbootloader.htm accessed on 21-May-2014), a bootloader is a program software that stays in the microcontroller and communicates with the PC (usually through the serial interface). In this case, the PICS is connected through Wi-Fi but still the PC will need to be configured with the virtual port of the Wi-Fi so that it can have a serial interface needed for bootloader operations. The bootloader receives a user program from the PC and writes it in the flash memory, then launches this program in execution. Bootloaders can only be used with those
microcontrollers like the 18F series that can write their flash memory through software. Most of the PIC microcontrollers are capable of being written to their flash memory. The PICS system uses the Microchip’s 18F4585 microcontroller as the main controller (MC). The bootloader itself must be written into the flash memory with an external programmer. The programmer used in this research was the Melabs U2 Programmer. In this case it could be done only once but if it happens that the bootloader has been corrupted then the operation needs to be executed again. In order for the bootloader to be launched after each reset, a "goto bootloader" instruction must exist somewhere in the first four instructions; There are two types of bootloaders, some that require that the user reallocate his code and others that by themselves reallocate the first four instructions of the user program to another location and execute them when the bootloader exits. The PIC 18F4585 microcontroller can easily be loaded with the bootloader and programmed seamlessly using the Wi-Fi connection at the microcontroller. The microcontroller is connected to the wireless module using the RX and TX pin of the PIC microcontroller. These pins have been used because they can communicate synchronously and asynchronously easily. Using tiny bootloader (TBL) software as demonstrated in the Figure 3-16, the MC was loaded with the program. The loading will involve turning off (resetting) the pin 1 of the 18F4585 for few seconds and release so that the program can be loaded to after the boot loader codes. In order to work with wireless the TBL will need to connect to port. The VirtualSerialPorts software (See Figure 3-17) was used to create a virtual serial port for wireless connection to the system. The COM2 port is connected through Internet protocol (IP) address 10.251.25.199 (The Wi-Fi module is programmed to use this IP address. It can be
changed) using transport control protocol (TCP). The baud rate is set to 9600 bits per second.

**Android-based Software for Precision Irrigation Control System**

The PICS works very well with the PC but not all farmers will be using a PC at all times. A cellphone app that can work very well with the PICS was developed as a tool. The app needs the wireless capabilities of the android phone. This allows seamless connection between the phone and the PICS. However, this is connection is limited to distance covered by the Wi-Fi networks (less than 100 meters). Longer distances may be covered by using a Wi-Fi extender, but at increased cost to the farmer.

The app (Figure 3-18) was developed with necessary features like reset, collection of data, sensor requests and instant display of the PICS messages while processing the data. These features are quite necessary for farmers in real time applications and to see if any problem is occurring on the farm. Critical operations such as valve operation can be attended instantly. The farmer has the capability to assess the operations and report or attend any problem.

While starting, the app first searches for Wi-Fi connection to the PICS. If there is no connection the app will eventually halt. This operation is quite necessary as the farmer cannot press any button to test connectivity that could send false message to the PICS if accidentally reconnected. The app was developed to fit in 127mm (5in) screen of the Sony Xperia Z running Jelly Bean Android. Hence, it won’t fit in other phones that use different screen size unless it is changed. The app may work but the display won’t fit the screen.

The Basic4android integrated development environment was used to develop the WaterControl software. It is quite user friendly to all the programmers that know the
Basic programming language and who want to program android apps which are java based apps. In fact, Java is a proprietary programming language for the Android applications development.

Changes can be done easily using the Basic4android software used to develop the app. The phone and PC need to synchronize using either a wireless connection or Bluetooth. The connection will give a live display between the two devices and gives an opportunity to simulate the software using the phone or PC. This feature speeds up the development task. The app was used to collect data from the field. The data was then stored automatically in the phone default directory of the app located at android/data/b4a.example/files. The collected data can then be analyzed by using the PC. Instead of requiring a laptop to be carried to the field, a phone saves the data collected from the PICS. The file created has its name written with the date and hour that it was recorded. It is in the format (Data on date_month_hour_minutes.txt) for quick reference. The data collected is very small in size and will not exceed 22KB for 1 week of data collection.

**Testing of the Irrigation Controller (Lab Experiments)**

The PICS was connected to test the control loop at the CREC, Lake Alfred, Florida, USA. A bucket was prepared and filled with the soil. The acclima moisture sensor was then buried inside the bucket. One empty flask was filled with water and connected to solenoid valve. The PICS was allowed to control water instantly as it drains in the bucket. The system was able to control any amount of water to maintain 15% soil moisture content within the bucket.
Testing of the Field Application (Field Experiments)

Study Site

The experiments have been carried out at Morogoro region in Tanzania. Morogoro municipality is located eastern of Tanzania about 210 km inland west of Dar es Salaam city.

Experiments were conducted at the crop museum farms (Sokoine University of Agriculture) latitude -6.84 longitudes 37.65 at an altitude of 400 meters above mean sea level. Figure 3-19 downloaded from the google maps shows the site location at the crop museum. These farms are coordinated by crop science department at SUA.

During the study period, different planting dates were used within a 2013-2014 year due to environmental conditions at planting time. The first experiment was taken from 26-October-2013 to 20-December-2013, the second was 06-Jan-2014 to 05-March-2014, the third was from 11-March-2014 to 30-April-2014 and the last one was from 28-May-2014 to present. The first experiment failed due to instrument malfunctioning and power problems. The second experiment failed because aphids pests killed all the plants and hence the experiment was reestablished on 11-march-2014. This third experiment was successful but it happened until the rainy season which started in mid-April interfered. The controller was unable to collect all the required information as expected and hence it was cancelled to allow rainy season to finish.

The experimental design used is a split-plot with six plots arranged in a randomized complete block design. Two treatments were established with each treatment having two replications as shown in Figure 3-20 numbered from 1 to 6. One treatment is the conventional irrigation control treatment and the other one is the PICS controlled treatment. The basis of this experiment is to make comparison between the
two treatments. The yellow plots used are conventionally irrigated while the blue field plots are PICS irrigated. The brown plots are bare lands and were used to randomize the experiment.

In each plot, 4 rows of okra plants were established for evaluation. See Figure 3-21. One drip line was used for each row. Kigalu et al., (2008) reported that the design for one drip line per row produced higher yields than one per two rows of tea. In particular, data presented in the paper clearly demonstrated that drip treatment I2, replacing 50% of the cumulative soil water deficit, with one drip line for irrigating one row of tea produced the highest yields compared with applying either more or less water, and saves water compared to 75% and 100% replacement of soil water deficit. Although, Kigalu researched in tea farms, these facts can be considered to apply to okra and other horticultural crops too. This is the standard drip irrigation layout in Tanzania.

**Okra Crops Used for Testing**

Due to high number of pests that affect other horticultural crops in Morogoro, okra was chosen since it can withstand some challenges of the aphids. This experiment needed a plant that will change with water use rather than diseases. (http://homeguides.sfgate.com/treatment-aphids-okra-35015.html accessed on 24-may-2014) Okra, a cousin to other members of the mallow (Malvaceae) family such as cotton, hollyhock, and hibiscus is a tall-growing, single-stemmed plant that produces edible seed pods. Grown as an annual in home vegetable gardens, okra is started from seed in full sun in well-drained soil. Varieties of okra for the home garden include spineless varieties such as Annie Oakley II, Clemson Spineless, Emerald, Lee and Dwarf Green Longpod. It matures approximately in 50 to 60 days, okra pods grow on
short stalks from the main stem at leaf axils. Both leaves and fruit of okra can be attacked by aphids. Cultural, organic and chemical controls can be used to manage this insect pest. In this experiment, Clemson Spineless variety of okra was used for testing.

**Tank Elevation, Irrigation Installations and Settings**

The drip irrigation system was set. The system provides water to the plants effectively and efficiently, thereby it reduces water loss through evaporation. Also, it is effective in reducing crop diseases such as black spots and powdery mildew. Before installation was done, water source pressure was determined and found that it was too low to provide more than 15psi (103kpa) required by the latch solenoid valve and the water was not reliable for continuous control. The tank was installed at 15 feet (4.6 m) high (See Figure 3-22) to solve this problem and provide more that 18psi (124kpa) pressure. This pressure was enough to supply across the field. The tower is created using local woods that are available in Tanzania. The wood was not treated against wood pests. This simple installation is quite familiar to most farmers in Tanzania. The design is well built and can withstand the weak winds of Morogoro.

It was observed that the flow meters experienced turbulent flow of the liquid caused by the valves upstream that adversely affected the meter readings. The valves and flow meters were installed closely together. This type of installation is quite common in Tanzania but it can bring very wrong readings to the flow meters. The flow meters and the latch solenoid valve need a minimum length of the straight pipe before and after the meter to keep the water in a laminar flow pattern.

Standard good engineering practice is to require ten diameters of the pipe upstream and five diameters downstream. So for the PICS system the 20mm meter size required 200mm upstream and 100 mm downstream.
The piping was modified to meet the length requirements and the flow sensors indicated correctly. Figure 3-23 demonstrates the change that allowed water to flow and be read by the manual flow meters.

**Data Collection**

The most important data that is collected will be the water used for both treatments and percentage of soil moisture. These data will be used to compare the performance of the conventional method and the PICS controlled method. The data and graphs derived are used to evaluate the supply of water to the plants and analyze water usage by the plants. The PICS is expected to have a well-balanced soil moisture control within the field.

**Sensor Calibration Tests**

The experiment was set at the field to test the sensors for performance and similarity. Varble *et al.*, (2011) emphasized the importance of the sensor calibrations. It is apparent that each individual sensor requires unique calibrations for the soil and conditions in which they will operate. It is recommended that field-based calibrations be developed, over laboratory-based calibrations, since field data are more representative of the conditions in which the sensors will operate. This should be done in every season to obtain correct readings.

As it has been stated above in literature review, the acclima TDT sensors expected to be accurate. But testing was conducted to see accuracy in real installations. Figure 3-24 shows the first experiment based on testing the similarity of the sensor readings. The soil was filled with water to saturation and then the PICS collected data every 10 minutes. Also, another test, as shown in Figure 3-25, is done to see the pattern of water percolation in the soil. This test will indicate the operating moisture of
the soil. The operating moisture, here, I refer to the soil moisture available at each depth determined after water percolation.

Figure 3-1. Kademhe G Fue. Conceptual diagram of the controller. 01-June-2014. Morogoro, Tanzania
Figure 3-2. Kadeghe G Fue. *Advanced conceptual diagram of the controller*. 01-June-2014. Morogoro, Tanzania
Figure 3-3. Kadeghe G Fue. Advanced conceptual diagram of the controller with voltage booster. 01-June-2014. Morogoro, Tanzania
Figure 3-4. RHT03 recommended circuit connections. Reprinted with the permission from Max Detect Technology Co. Ltd, https://www.sparkfun.com (June 20, 2014)

Figure 3-5. The MSP 300 pressure transducer. Reprinted with permission from Measurement specialties, http://www.meas-spec.com (June, 20, 2014)
Figure 3-6. Kadeghe G Fue. *Location of rain sensor and humidity sensor in the field.* 09-November-2013. Morogoro, Tanzania

Figure 3-7. Kadeghe G Fue. *SDI-12 Soil Moisture Transducer at the field experiment treatment.* 26-November-2013. Morogoro, Tanzania
Figure 3-8. Kadeghe G Fue. *The PICS breadboard at the laboratory in CREC*. 10-June-2013. Lake Alfred, Florida

Figure 3-9. Kadeghe G Fue. *Upper part of the PICS PCB*. 30-June-2013. Lake Alfred, Florida
Figure 3-10. Kadeghe G Fue. *The full PICS PCB*. 30-June-2013. Lake Alfred, Florida
Figure 3-11. Kadeghe G Fue. PCB plate received from PCB123 Company. 10-July-2013. Lake Alfred, Florida
Figure 3-12. Kadeghe G Fue. *PCB with all other electronic chips soldered on it.* 23-July-2013. Lake Alfred, Florida
Figure 3-13. Kadeghe G Fue. *PICS with other modules in a weather protection box.* 25-July-2013. Lake Alfred, Florida
Figure 3-14. Kadeghe G Fue. *PICS installed at crop museum*. 23-September-2014. Morogoro, Tanzania
Figure 3-15. Kadeghe G Fue. Flowchart of the PICS software. 25-June-2014. Morogoro, Tanzania
Figure 3-16. Kadeghe G Fue. The tiny bootloader used to load the program to the PICS MC microcontroller. 26-June-2014. Morogoro, Tanzania

Figure 3-17. Kadeghe G Fue. Virtual serial ports software. 20-June-2014. Morogoro, Tanzania
Figure 3-18. Kadeghe G Fue. *The screenshot of PICS android based software.* 26-March-2014. Morogoro, Tanzania
Figure 3-19. Kadeghe G Fue. *Field experiment site at Sokoine University of agriculture latitude -6.84 longitudes 37.65 downloaded from maps.google.com. 23-May-2014. Morogoro, Tanzania*

Figure 3-20. Kadeghe G Fue. *Experimental plot layout. 29-January-2014. Morogoro, Tanzania*
Figure 3-21. Kadeghe G Fue. *Two treatments with three replications Plots*. 10-January-2014. Morogoro, Tanzania

Figure 3-22. Kadeghe G Fue. *Tower elevation and tank installations*. 03-February-2014. Morogoro, Tanzania
Figure 3-23. Kadeghe G Fue. *Straight pipe installations at the site.* 23-February-2014. Morogoro, Tanzania

Figure 3-24. Kadeghe G Fue. *First experiment to test similarity of the sensors.* 11-March-2014. Morogoro, Tanzania
Figure 3-25. Kadeghe G Fue. *Sensor water percolation investigation layout*. 12-March-2014. Morogoro, Tanzania
CHAPTER 4
RESULTS AND DISCUSSIONS

Sensor Calibration Tests

The data were collected and recorded every ten minutes and recorded over a 24 hour period using the layout in Figure 3-24. Figure 4-1 shows the readings which were taken at 8 inches (200 mm) depth in the soil profile. The readings show that the sensors were recording accurately except sensor number 4 which had a significant offset that indicates a problem. This observation indicates that the TDT sensors are accurate in some required sense as we stated before. Sensor number 4 is defective might be proved wrong by the second experiment below where sensor number 4 was kept together with sensor number 3 at a depth of 150 mm in the soil profile.

From the layout in Figure 3-24, 925 sensor readings (data points) were collected for all the sensors. The readings taken within time changes were correlated each to sensor 4. Correlation is representing the degree of linear association between two measured sensor readings. The correlation table verifies that the sensors are strongly correlated since it is above +0.5. See Table 4-1.

Table 4-1. Correlation table for sensor 4 and others in the 1st experiment

<table>
<thead>
<tr>
<th>Sensor number</th>
<th>Sensor 4</th>
<th>Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor 1</td>
<td>Sensor 4</td>
<td>0.93</td>
</tr>
<tr>
<td>Sensor 2</td>
<td>Sensor 4</td>
<td>0.78</td>
</tr>
<tr>
<td>Sensor 3</td>
<td>Sensor 4</td>
<td>0.79</td>
</tr>
<tr>
<td>Sensor 5</td>
<td>Sensor 4</td>
<td>0.81</td>
</tr>
<tr>
<td>Sensor 6</td>
<td>Sensor 4</td>
<td>0.69</td>
</tr>
</tbody>
</table>
In normal sense, 0 indicates no correlation and +1 indicates strong correlation. That means sensor 1 and sensor 4 are strongly correlated while sensor 6 and sensor 4 are more weakly correlated. Taylor (1990) defined correlation coefficient as it is representing the degree of linear association between two measured variables. This shows that sensor number 4 was responding equally with others but it was reading lower values compared to others. Furthermore, Figure 4-1 shows sensor water percolation levels experiment to a depth of 350 mm in the soil profile using the layout from Figure 3-25. 2998 sensor readings were collected by the PICS. Sensor 3 and sensor 4 were kept together since they are average correlated compared to others as represented in Table 4-1.

Sensor 4 has shown that it reads the same as sensor 3 which indicates that the 1st experiment may have given a wrong impression about the accuracy in sensor number 4. Wrong impression may have been caused by wrong sensor placement. The sensor should always be placed careful when buried to the soil profile.

In Figure 4-2, the peak value in 13th March, 2014 at 12:55pm to 2:35pm was caused by slight rainfall. It was not a heavy rainfall so it didn’t destroy the experiment. At different times readings were taken to investigate the speed of water percolation in the soil profile. At -5cm sensor 1 readings, at -15cm sensor 3 readings, at -35 sensor 5 reading and at -35cm sensor 2 readings were used to generate Table 4-2.

Table 4-2. Sensor readings at different depth in different time taken

<table>
<thead>
<tr>
<th>Sensor at depth</th>
<th>12-03-14 16:05</th>
<th>12-03-14 18:25</th>
<th>13-03-14 0:55</th>
<th>13-03-14 8:05</th>
<th>13-03-14 12:45</th>
<th>14-03-14 5:05</th>
</tr>
</thead>
<tbody>
<tr>
<td>-5</td>
<td>40.1</td>
<td>37.1</td>
<td>35.5</td>
<td>35.4</td>
<td>37.4</td>
<td>34</td>
</tr>
<tr>
<td>-15</td>
<td>42.9</td>
<td>40.4</td>
<td>38.8</td>
<td>38.2</td>
<td>39.1</td>
<td>37</td>
</tr>
<tr>
<td>-25</td>
<td>53.4</td>
<td>44.5</td>
<td>42.3</td>
<td>41.5</td>
<td>41.8</td>
<td>39.2</td>
</tr>
<tr>
<td>-35</td>
<td>53.4</td>
<td>53</td>
<td>43.8</td>
<td>44.8</td>
<td>44.8</td>
<td>43.1</td>
</tr>
</tbody>
</table>
The Table 4-2 represents data selected randomly from Figure 4-2 to analyze the optimum soil moisture of the soil. Figure 4-3 represents the graph derived from the Table 4-2.

The red and green straight lines represent the optimum soil moisture obtain at the third day 14-march-2014 at 5:05AM. The water drains more uniform above the 20 cm mark compared to below. The lower parts of the soils retain water for long time. Field capacity is determined when saturated soil is left to drain for 2 to 3 days. At these days we assume that the remaining soil water content represent field capacity. In this case the field capacity is between 35% - 40%. The soil texture is clay loam so the range is acceptable in certain extent. The PICS should maintain that level.

To determine optimum soil sensor position and soil moisture percentage in the soil profile is a very challenging task for researchers and farmers too. Munoz-Carpena et al., (2005) discussed that due to the soil’s natural variability, the location and number of soil water sensors may be crucial and future research should include optimization of sensor placement.

Mafuta et al. (2013) discussed sensor positioning in the root zone for drip irrigated farmland. Sensor positioning in the root zone of the plant is crucial, because it determines the amount of water to be applied during each irrigation event. A sensor placed very deep into the soil allows the irrigation system to apply more water up to that depth beyond plant roots; the water below plant roots is lost through deep percolation. On the other hand, a very shallow sensor promotes light irrigation, consequently, failing to apply water into the root zone and therefore stressing the plants. The results in Figure 4-2 proves that the optimum depth and percentage of water at that depth in
different times. In their study, (Texas Water Development Board, 2004) said maize is a deep-rooted crop with approximate maximum rooting depth ranging from 75 cm to 120 cm depending on the characteristics of the soils like the presence of restrictive soil layers. Accordingly, the study placed the soil moisture sensors at a depth of 40 cm. Morris, (2006) discussed the conclusion that at this sensor depth, about 70% of water uptake by crops takes place; the effective root zone in this case was 60 cm.

Based on those study conclusions, the sensors in the subsequent field experiments placed at about 20 cm depth. The effective root zone of the most of the okra plants grow up to 35 - 40 cm in first 3-4 weeks and then grow further to 2 feet or more. Based on the graph, at the 20 cm depth, the field capacity is more than 35% but less than 40%. This is set to control moisture based on the average root growth.

**Precision Irrigation Control System (PICS) Field Deployment**

After the development of the PICS, field deployment was conducted to see the performance of the system. This experiment is crucial since the performance of PICS in harsh environment is of crucial importance. Recordings of the sensor testing were taken using the PICS though it was not true testing but it proved how it can be designed to calibrate the sensors.

The water-balance control was set at 35% of the soil profile at the depth of 20 cm. Then, the readings were recorded every 20 minutes. In this stage, the machine is trying to control water after every 4 minutes. Balancing of the limits and water uptake should range at the water lower limit as predetermined before. As the water balance control mark is increased, more water is required to maintain and more irrigation is commended. Hence, correct determination of the lower limit and upper limit is of great
importance for farmer to obtain maximum performance to the plant growth while saving water.

Control of water using two limits, lower limit and upper limit is of great importance as it reduces the time used to switch on or off the valves and hence saves water. But this control will give a very rough control when visualized inside while working. Figure 4-4 shows control of water supply to the plants using upper and lower limit. The system will irrigate until it finds that 39% of soil moisture is detected and then it stops to irrigate until depletion is lower than 31%. 31% is not a permanent wilting point. The observation in the table 4 show that the drip irrigated soil using emitters of 0.5 liter per hour will only take about 20-30 minutes to increase more than 10% of soil moisture when the sensors are located 20cm in the soil profile. That’s means only 167 – 250 ml of the water. This observation gave a conclusion that if we irrigate for 4 minutes only then less than 3% of soil moisture will be increased in the soil profile.
Figure 4-1. Kadeghe G Fue. *Sensor similarity test results*. 14-June-2014. Morogoro, Tanzania
Figure 4-2. Kadeghe G Fue. *Water percolation results for experiment 2*. 14-June-2014. Morogoro, Tanzania
Figure 4-3. Kadeghe G Fue. Water percolation graph with respect to time and soil profile depth. 14-June-2014. Morogoro, Tanzania
Figure 4-4. Kadeghe G Fue. *Water balancing at 35% and having +4% upper limits and -4% lower limits (31%-39%).* 14-June-2014. Morogoro, Tanzania
CHAPTER 5
CHALLENGES AND EXPERIENCES GAINED IN THIS RESEARCH

The research had a lot of experiences and challenges that should be considered in advance for future research. The challenges occurred at the lab, field site, system failures and sensor failures.

The system was designed to be fully wireless controlled. This has posed a lot of challenges when a wireless module doesn’t work. The system experienced a lot of power failures when the low power solar panel was used. A low power solar panel gives an economic advantage in third world applications but in this system the optimum power was quite difficult to be achieved without random failures.

The PICS sometimes heated the components leading to module failure. Unfortunately, it was twice returned to the laboratory for repair and maintenance. This affected the data collection activity which needs to be continuous without missing.

The needed pressure of the water, 15psi (103kPa) was not available in the initial design. Raising the tank was not initially planned but was necessary during the experiment. The initial tower height of 6 feet (2 metres) was not enough to obtain the minimum pressure required and then it was decided to increase the height up to 15 feet (5 metres) high. Also, water availability is a great challenge to precision irrigation technologies which needs water at all times for deficit irrigation control.

The aphids pests were present and tried to kill a lot of plants. These pests induced irregularity of the plants and hence influenced the results and consumption of water in plants. The experiment number 2 basically failed because all the small plants were attacked by the aphids. The control of the aphids using chemical proved successful in other experiments compared to experiment number 2.
Mafuta et al. (2013) discussed very common challenge in sensor disturbances. It was also observed that there is a high possibility of disturbing the sensors and wires during field work, for example, weeding and other farm activities. In this study, the wires were disturbed; even the drippers were also disturbed. This will eventually induce irregularity in data collection and general control action.

The short period of one year to complete the research has hindered more testing and modification of the system. Also, some of the researches that were disturbed high rainfall in 2014 were not fully carried to validate some results obtain in previous experiments. This has also prevented further research to consumer acceptance of this system in Tanzania. That’s why this research has no user evaluation information or discussions for the system.

Sensor placement is a great challenge for spatially variable irrigation. It is difficult to obtain consistent data that could trigger regular control of irrigation. Placement of the sensors in different locations that are irrigated from the same source of water will bring different readings. This indicates that drip irrigation most of the time irrigates irregularly in the field. The PICS face challenges to compare the readings of the sensors and decide when and how much to irrigate. Figure 4-3 shows what happened when the sensor placement variations. Water from the same source but irrigates differently in the field. While it looks like the sensor 5 and 6 becomes more stable at 28th of March, 2014, the other sensor 4 fluctuates with irrigation control. However, this might be due to either sensor placement or field soil variability. High peaks in Figure 5-1 were caused by high rainfall that happened during the night of 28th March, 2014.
The design of the PICS had some problems. The connection to the PICS is merely wireless and no cable connection capability was made. This had some problems, especially when the Wi-Fi module failed sometimes. The new design should consider inclusion of the RS232 or USB connection.

The system can use the GSM module to connect but the incorporation of latest technologies such as 4G and LTE would increase its communication capability. Distant updates of the database will give flexibilities. The challenge to follow the information at the field using the Wi-Fi or sending the SMS always increases costs to the farmer.

Figure 5-1. Kadeghe G Fue. Sensor 4, 5 and 6 takes readings from the same water supply but in different field. Irrigation irregularities while providing water using the same water source. 14-June-2014. Morogoro, Tanzania
CHAPTER 6
CONCLUSIONS AND RECOMMENDATIONS

The PICS was successful built using considerable low-cost technologies which have demonstrated that low cost control system is possible for developing countries. This new technology prototype can be used for farming in developing countries. Modularity of the PICS using low cost devices in it allows easy replacement.

Results of the experiment showed that the PICS control irrigation using signals from the Acclima TDT moisture sensors. This type of automation has achieved relatively reliable control in terms of moisture at the depth of 20 cm and 35% soil moisture. The machine was able to collect all the data regarding rainfall, humidity and temperature. The data collected had some problems but at least 80% of the data were correct and allowed system control. The experiments showed that effective control is achieved when the system is allowed to control every 4 minutes compared to 20 minutes or one hour control. More precise control is boosted by reducing the time to collect sensor information.

Precision irrigation control system has shown a great potential to African farms applicability. Systems like this will need replications for demo use in African farms. The cost of replicating one unit is still very high, approximately more than 300 USD.

Including the one soil moisture sensor costs, that will bring the cost to about 545 USD (See Table 6-1). This cost is still considerable high for Tanzanian farmers but can be afforded to large scale productions such as grape crops or flowers production who may find it more useful for them. More research is needed to determine and reduce the economic cost of precision agriculture tools. Most of them that are present in the market
cost more than 545 USD for full set and they are very delicate and can be destroyed very easily.

A farmer who cultivates horticultural crops can save from 50% to 70% of water per acre of cultivation. Most horticultural crops are water for three hours in a day and approximately 33000 liters are used per acre. For three months of cultivation then at least 40 days are used to water the plants. 50% of water saved in 40 days of irrigation is about 660 meter cubic of water. In Tanzania, most of the farmers use water from rivers and other alternative water sources. In case they use water supplied from the government authorities then each meter cubic costs about 750 Tshs (for current exchange it is approximately equal to 50 US cents) and the charge increases as days go on. It means they will save at most 330 USD per acre. The farmer who uses PICS for more than 2 acres will see the profit. Even the farmer who uses the PICS for one acre and cultivates for more than two seasons will get the profit.

The instrument has performed very well in the field. The shield used was able to withstand dry and wet seasons and the system was not hurt. The instrument wireless connection was performing well. All the time the system was reachable using both the laptop and phone. The soil moisture sensors were performing very well while in the soil. No any sensor failed during all the tests. The system performance was dependent on the rainfall and humidity sensor also.

The use of mobile smart phone is still very low in Tanzania but the growth is significant and signifies future opportunities. This low usage will limit the adoption of precision irrigation equipment in Tanzania. About three-quarters of Tanzanians can read and write but they are not reading agricultural reports. This is also a limit to the system
adoption in Tanzania. Awareness of the importance of commercial horticultural farming is of great significance in Tanzania. Most of the farmers will adopt precision agriculture if they find more markets in the world market that require quality products.

More research should focus on determination of the minimum cost that farmers could incur to purchase precision agriculture. The cost of the technology always decreases with number of the users. Hence, if more users require the instrument the less the cost it becomes. The government of Tanzania, through the commission of science and technology (COSTECH), should modify the policy of technology transfer to farmers and conduct national search for new technologies that can be improved for small holder farmers. Also, the national fund for advancement of science and technology (NFAST) that is organized by COSTECH should include advancing existing technologies or technologies that were developed in the universities. The government and non-governmental organizations should sponsor practical testing of technologies for the farmers, make sure that technology is transferred to the farmers, and farmers are encouraged to use new technologies. The PICS prototype provides technology advancement in Tanzania. Local production of such systems will give Tanzania an opportunity to be the leading producers of irrigation controls in Africa.

I recommend that new designs should be based on reducing electricity demands so that we can reduce the costs of the solar panel, reduce the system size to be installed in the field, and also, to determine which sensors are effective but cheap for Tanzania. Research should also be done to identify a profitable horticultural crop that needs high attention to the crop water use. It has been reported that grapes need more attention to the water supply to maintain the quality of the fruit.
I recommend that new designs should include data analysis using smart phone particularly android based because the system is already having an app in android phone. Also, the online updating of the PICS software would be good for hassle free updates.

Table 6-1. Cost approximation for the PICS

<table>
<thead>
<tr>
<th>Particulars</th>
<th>Costs ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PICS components</td>
<td>150</td>
</tr>
<tr>
<td>PCB costs (4 pairs)</td>
<td>50</td>
</tr>
<tr>
<td>Wireless Module(RN-XV WiFLy)</td>
<td>30</td>
</tr>
<tr>
<td>PICS weather enclosure</td>
<td>25</td>
</tr>
<tr>
<td>Orbit valve and Orbit Solenoid for battery operated</td>
<td>60</td>
</tr>
<tr>
<td>Solar panel and system battery</td>
<td>35</td>
</tr>
<tr>
<td>Soil Sensors per acre (1 sensor)</td>
<td>175</td>
</tr>
<tr>
<td>La crosse Rain gauge</td>
<td>20</td>
</tr>
<tr>
<td>Total cost of PICS</td>
<td>545</td>
</tr>
</tbody>
</table>
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BIOGRAPHICAL SKETCH

Kadeghe Fue received his Master of Science in agricultural and biological engineering from the University of Florida, USA in the summer of 2014. He studied precision agriculture, information systems and automation. He was sponsored by iAGRI under USAID feed the future program. He received Borlaug LEAP fellowship award in the fall 2013. After then, He received the Pan African Conference on Science, Computing and Telecommunications (PACT) 2014 best student paper award in Arusha, Tanzania for the paper entitled “A Solar-powered, Wi-Fi Re-programmable Precision Irrigation Controller” on 17th July, 2014. Before joining the University of Florida, He received Bachelor of Science in computer engineering and information technology and attained honors degree from the University of Dar es Salaam, Tanzania in October, 2011. Then, He joined Sokoine University of Agriculture in 2011 as the academic staff. He teaches several courses in computer programming languages, networking, microcomputer systems and database management systems. He has supervised more than ten undergraduate students on their special projects in information systems development and others in precision agriculture.

He is a graduate engineer member of the Institution of Engineers Tanzania and American Society of Agricultural and Biological Engineers. He has specialized in applications of computers and electronics in Agriculture especially in area of Precision agriculture, e-agriculture and Software systems engineering. He has published scientific papers in ICT and applications of computers in Agriculture. Also, He does consultancy in software systems development and electronic control systems development to the public and private companies.