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A Low Cost Automatic Irrigation Controller Driven by Soil Moisture Sensors

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Abstract – **A substantial percentage of farmers in Southern Africa, including Zimbabwe, rely on rain for most of their farming activities but there are areas which are entirely dependent on irrigation water to produce viable crops. Water-saving agricultural practices and sound water management strategies are therefore required to ensure viability of the farming industry in those places that receive less rain. The study aimed at developing an automatic irrigation controller which is low cost and reliable for a low income farmer. The controller uses signals from the soil to schedule irrigation and was made from cheap and off the shelf components from our laboratory stores and local electronic retail shops. The heart of the controller circuit was the PIC Microcontroller 16F872 that uses only 35 instructions for programming in assembly language. Two dielectric capacitance sensors (0.20 m ECH$_2$O probe, Decagon Devices, Inc. Pullman, WA USA.) connected to the controller circuit, were used to measure the dielectric constant of the soil in order to determine its volumetric water content and hence the need to irrigate. Most of the low cost irrigation controllers that are locally available are ON/OFF type and these cannot give optimal results in terms of irrigation costs and crop yield. We determined that using our controller we could produce compatible results with other watermark methods for scheduling irrigation at lower costs (The total cost of other materials excluding the landed cost of the capacitance sensors and labour for populating the pc board was US$36). We also managed to provide calibration data for soil water based irrigation control in the clay-loam soils of Northern Harare using the capacitance sensors.**

Keywords – **PIC Microcontroller, Permittivity, Baseline Values, Soil Moisture Sensor.**

I. INTRODUCTION

During a growing season with normal rainfall, supplemental irrigation may be necessary to avoid moisture stress, particularly during the blossom and fruit bulking period, which can result in lack of fruit set, reduced fruit size, sunburn fruit, and a lack of uniform ripening [1]. In many places of the world, irrigation has become a very important component of crop production. In cotton for example, studies have shown that proper timing of irrigation is an important production factor and that delaying irrigation can result in losses of between USD 62/ha and USD 300/ha [2], [3]. Automation of irrigation system has the potential to provide maximum water use efficiency by monitoring soil moistures at optimum level [2], [4].

In general, methods of irrigation scheduling can be classified as plant, soil, or climate-based, or combinations. Crop water status and the amount of supplementary water needed can be assessed by measuring soil moisture and plant physical response to water stress [5].

Among the above mentioned irrigation scheduling techniques commonly used, the soil-based technique involves indirectly measuring the soil moisture quantity in the crop root zone by use of soil tensiometers or dielectric probes. A soil water sensor is an instrument which, when placed in a soil for a period of time, provides information related to the soil water status of that soil [7]. Tensiometers can be used to determine 20% to 25% depletion of the available water capacity and then calculating the amount required to bring the soil moisture back to field capacity. [1] and [6] tested quite a number of soil water sensors representing eight sensor types, including neutron probe, electrical capacitance, electrical resistance, TDR (time domain reflectometry), and heat dissipation with carefully controlled soil water contents.

The performance of soil moisture sensor systems related to soil water content has also been reported by among others [13], [14] and [15]. As water supplies become scarce and in some cases polluted, there is a need to irrigate more efficiently in order to minimize water use, and efficient water management plays an important role in irrigated agricultural cropping systems [9]. An automatic irrigation control system is a potential solution to optimize water management by sensing soil water conditions and site-specifically controlling irrigation sprinklers or drip lines [9]. A wide range of technologically advanced soil moisture sensors for efficient irrigation scheduling exist [10], but the cost of these sensors combined with the control units are beyond the reach of an ordinary farmer in most developing economies.

The automatic irrigation system performance has been enhanced by use of microcontroller resulting in reduction of circuit design complexity and cost whilst also making it easy to upgrade [16]. There are a lot of advantages in developing microcontroller based circuits for irrigation scheduling as these are readily and cheaply available in most electronics shops the world over. Many sensors and auxiliary components are designed to interface directly with microcontrollers, simplifying circuit design and modification [8].

A microcontroller is a device which integrates a number of the components of a microprocessor system onto a

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single microchip and these are, the central processing unit for performing arithmetic and logic functions, memory for storage of both dynamic data and program code, parallel digital input and output ports for communication with outside world, timers for event timing and analogue to digital converters for transforming the analogue electrical signal into a digital signal that can be processed by the microcontroller chip. The amount of memory, operating speeds, and other features associated with a microcontroller, varies between different microcontrollers which come with very low prices of about US $2 and US $3 as noted by [17]. A microcontroller is designed to control hardware through user written software programs, thus eliminating the need for building complex hardware circuits for performing control functions. There are virtually hundreds of choices of microcontrollers today ranging from 8 bit to 32 bits, which are available to suit different projects and products, but only a handful of microcontrollers stand suitable if we consider various constraints like cost, complexity and availability.

PIC Microcontrollers which are made by Microchip are today the world's most popular microcontroller family because of their very optimum combination of cost, complexity, features and availability. These small microcontrollers can be programmed to carry out a vast range of tasks. They can be programmed to time irrigation events in agriculture, or to control a production line in the industry and much more. They are found in almost any modern electronic device that one can think of. A simple program is written using a computer, and then downloaded to a microcontroller which in turn can control a target device. PIC microcontrollers (Programmable Interface Controllers) are quickly replacing computers when it comes to programming control devices.

There are mainly two types of controllers that are normally used to schedule irrigation, and these can be open loop or closed loop controllers. Open loop controllers are designed to take input and to compute output for the system accordingly. It does not have feedback to determine whether the desired output is achieved or not. On the other hand closed loop controllers (as the one used in this design), is based on pre-defined control concept and utilizing feedback from controlled system in some manner [11], [12].

This paper looks at the design of an inexpensive microcontroller-based system that could determine the soil moisture status for a given crop in the field. The main objectives of this research were:

- To design and construct a controller that is low cost, reliable and affordable by the low income farmer.
- To provide calibration data for soil water based irrigation control in the clay-loam soils of Northern Harare.

II. MATERIALS AND METHODS

A. *Circuit Design and programming*

Generally the circuit was developed with the PIC16F872 as the core component of the control unit. The other materials used in the design were mostly passive and a few active components found cheaply in our departmental stores at the University and also from local shops, two dielectric capacitance sensors (0.20 m ECH$_2$O probe, Decagon Devices, Inc. Pullman, WA USA.) which measured the dielectric constant of the soil in order to determine its volumetric water content using equation 2. The dielectric constant (proportional to permittivity) of water is much higher than that of air or soil minerals (Water has a permittivity of about 80, while the value for soil minerals is around 4 and air is 1, and this high value for water results in relatively large changes in the permittivity of soil when the water content changes). Ability to make as many measurements as we wanted (even after 30 minutes) over a long period of time was possible with minimal battery usage as the ECH$_2$O probes have a very low power requirements and high resolution.

The total cost of other materials excluding the landed cost of the capacitance sensors and labour for populating the pc board was US$36. Including the sensors and labour, the total cost of the control unit would come to approximately US$156 compared to importing compatible complete units which would land at not less than US$200. A summary of the cost of materials used in this design is given in table 1 below. The microcontroller used, PIC16F872 Microchip Technology, Inc., (Chandler, Ariz.) is 28-Pin, 8-Bit CMOS Flash Microcontroller with 10-Bit analogue to digital converter (A/D). We opted for PIC16F872 microcontroller because of a number of reasons which include

- Its power saving sleep mode and low power consumption(typically less than 2 milliamperes at +5V and a frequency of 4 MHz) as this would save battery power
- We could also perform in circuit programming in the field if need arose to change baseline values, although we had not utilized this feature in this current design
- Only 35 single word instructions to learn and use makes programming in assembly language simple. Assembly language was used here for the simple reason that we felt comfortable writing our code in the native PIC Microcontroller's language, although other simpler high level languages could be used.
- The purpose of the microcontroller is mainly to react on changes in its surrounding. Instead of checking each pin or bit constantly, the microcontroller delegates the waiting function to a specialist signal called an INTERRUPT which will react only when something attention worthy happens and then informs the Controller.
- The 10-bit analogue to digital converter also allows for 10 bit resolution of the incoming voltage signal from the soil moisture sensor.

As mentioned already, the PIC16F872 microcontroller was programmed using low level assembly language. MPLAB, also called an Integrated Development Environment (IDE), was the single integrated environment used to develop code that would be loaded into the PIC microcontroller. It is a software program that runs on a PC (Windows or Linux) to develop applications for Microchip microcontrollers and other signal controllers. After a

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successful assembling the program, we then used Real PIC Simulator 1.3 to simulate the program before downloading it to a PIC microcontroller (*Real PIC Simulator is the fastest software simulator targeting the Microchip baseline and mid-range flash based PIC microcontrollers like the one used in this design*). Simulating the program on screen, allowed us to correct faults making sure our program worked properly before downloading it into the microcontroller. This meant that our circuits could be tested before manufacturing. WinPIC software was used for downloading the hex code into the microcontroller via a cheaply assembled laboratory programmer circuit. The computer with the hex code was connected to the PIC microcontroller programming circuit via a parallel port on the computer. A 9 pin male connector lead connected the computer to the programmer circuit, allowing the transfer of the program to the PIC microcontroller Integrated circuit (IC). After the simulated and working hex code had been loaded into the PIC microcontroller IC , the 9 pin male connector lead was then disconnected and the microcontroller unplugged from the programmer circuit into the PIC microcontroller circuit which could now be used independently.

Table 1: List and cost of circuit components for the In Circuit Programmer

Item Number	Quantity	Description	Unit Cost US$	Total Cost US$
1	1	pc board	3.00	3.00
2	1	Enclosure	2.00	2.00
3	3	resistors 4.7k, 0.25w	0.05	0.15
4	3	resistors 10k, 0.25w	0.05	0.15
5	2	resistors 3.3k , 0.25w	0.05	0.10
6	1	capacitor 330μF, 25v	0.30	0.30
7	1	capacitors 10μF, 25v	0.20	0.40
8	1	LEDs, green	0.30	0.30
9	1	1N4006 diode	0.50	0.50
10	1	1N4012 diode	0.35	0.35
11	2	BC557 pnp Transistor	0.50	1.00
12	1	7812 voltage regulator	0.80	0.80
13	1	7805 voltage regulator	0.80	0.80
18	2	rubber grommets 10mm	0.30	0.60
19	3	bolts + nuts size 15mm	0.10	0.30
20	0.25m	thin stranded cable	0.10	0.30
			TOTAL	**11.05**

Table 2: List and Costs of circuit components and sensors for the Irrigation Controller

Item Number	Quantity	Description	Unit Cost US$	Total Cost US$
1	1	PIC16F872 Microcontroller	3.00	3.00
2	1	Microcontroller base	0.50	0.50
3	2	pc board	3.00	6.00
4	1	Enclosure	4.00	4.00
5	1	5v dc relay	2.50	2.50
6	8	resistors 390Ω, 0.25w	0.05	0.40
7	2	resistors 100Ω, 0.50w	0.05	0.10
8	1	resistors 2.2k , 0.25w	0.05	0.05
9	4	resistors 470Ω, 0.50w	0.05	0.20
10	3	resistors 1k, 0.25w	0.05	0.15
11	2	capacitors .022μF	0.20	0.40
12	4	LEDs, 2green & 2red	0.30	1.20
13	1	4 Mhz crystal	2.00	2.00
14	1	1n4006 diode	0.50	0.50
15	1	BC547npn Transistor	0.50	0.50
16	2	4026 cmos 7-segment drivers	1.50	3.00
17	1	dual 7-segment display	2.50	2.50
18	4	rubber grommets 10mm	0.30	1.20
19	6	bolts + nuts size 15mm	0.10	0.60
20	1	Universal DVD power board, 5v	6.50	6.50

B. Experimental Set-up and Circuit Operation

The microcontroller was programmed to acquire a voltage signal (corresponding to soil moisture level) from sensor 1 at input RA0/AN0 which would be converted to a digital value by the internal A/D converter before storage in register 1. The microcontroller would then acquire a second voltage signal from sensor 2 at input RA1/AN1 which would again be converted to a digital value as done with sensor 1 before being stored in register 2. The interval between reading successive values for sensor 1 or sensor 2 was 2 minutes but this could be adjusted if need be, via a software interface. The microcontroller sends a 50 millisecond 2.5-VDC excitation signal to each of the capacitance probes through a 2.5-V voltage regulator driving a circuit providing excitation-voltage.

A circuit to generate an excitation signal of 50 milliseconds was made from a 555 timer operating in a monostable multi-vibrator mode. The two values from both sensors were added together (i.e. register 1 and register 2) before dividing this sum by 2. A comparison of the quotient against the threshold for clay-loam soil would give decision on whether or not to irrigate. If the voltage returned from the probe is below a user set threshold then the controller through pin RB1, triggers irrigation via an energized DC relay whose closed contacts allows 24-VAC signal to power the irrigation solenoid valve that drives either drip lines or sprinklers in the field. If the average signal from the sensors goes above the threshold value, then the DC relay becomes de-energized and cuts off the 24-VAC signal that in turn will disable the irrigation solenoid valve, culminating in a no irrigation event.

Each time that the microcontroller makes a decision to irrigate, it updates the display screen, i.e., it increments the displayed value by 1. By so doing, the microcontroller keeps track of the number of irrigation events that occur. All irrigation events lasted for the same time duration. Knowing the emitter rate, R, (which was 600ml per hour per emitter multiplied by the number of emitters for 10mm drip lines) , and that each irrigation event lasted about 10 minutes, (denoted T in this case), and having got the number of instances of irrigation (from the display), N, we managed to calculate the amount of water used for irrigation. If we let T_t be the total time when the emitter was actually emitting water, then T_t would be given by T x N. If W is the total amount of water used for irrigation, then $\boldsymbol{W=T_t \times R}$. Calculation of the amount of water used for irrigation using the seven segment display was necessary in order to compare with other tried and tested water metering mechanisms.

As seen in figure 2, the controller can be powered by either a 5-VDC battery which provides unregulated voltage or by the power from an AC source that will be rectified and regulated to give an output of the same 5-VDC needed to power the microcontroller and other components that operate on this same voltage.

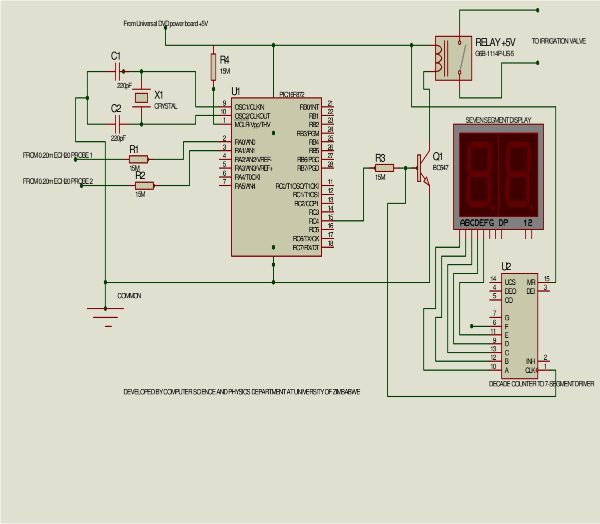

Fig.1. Soil moisture based irrigation controller circuit

Fig.2. Soil moisture based irrigation controller circuit board and the sensors

C. Algorithm

Step1: Acquire input from sensor 1.
Step2: Convert the analog input to digital.
Step3: Retrieve the digital value and store it in register 1.
Step4: Acquire input from sensor 2.
Step5: Convert the analog input to digital.
Step6: Retrieve the digital value and store it in register 2.
Step7: Add the two registers, register 1 and register 2.
Step8: Divide the sum of the two registers by 2.
Step9: Compare the quotient against the threshold and decide whether or not to irrigate.
Step10: Wait about 2hrs and start all over again.

D. Probe Calibration and Installation

The experiment was carried out at the University of Zimbabwe's Computer Science and Physics soil science laboratory. The soil type was a shallow clayey loam of the Kroonstad soil form (Ochric Planosol; FAO) with a high clay percentage (Soil Classification Working Group, 1991). The physical properties of the soil at the site were provided by the Department Agriculture at the University of Zimbabwe. In a separate experiment earlier carried out at the soil site, the threshold digital value (D for PIC16F872) was determined to be 90. A formula linking volumetric water content (VWC) to the corresponding threshold digital value (D, value that corresponds to sensor output voltage after Analogue to Digital Conversion) was required and hence we had to carry out other experiments to determine the relationship. In order to determine the link between sensor output voltage (mv) and D, an experiment was carried out which resulted in a formula of the form:

$mv = m_2D + y_2$ .... (1)

where m_2 and y_2 are the gradient and intercept respectively.

Twelve plastic containers of similar size and dimensions approximately 9cm x 14cm (diameter x depth), were then each filled with oven baked soil of volume 489ml. The soil was sampled at two different locations in the field taking note of root zone depth for most vegetable crops. Samples were collected from 0 to about 20cm depth from two sites in the field. The containers were numbered 1a,2a,3a,4a,5a and 6a for the first set of values, then 1b, 2b,3b,4b,5b and 6b for the second set of values with (75, 85, 90, 95, 100 and 105) millimetres of water added to the first, second, third, fourth, fifth and sixth container for each set respectively. The different volumes of water for each container were measured using a cylinder EMIL GOLD LINE measuring from 30ml to 250ml at intervals of 2ml. Sensor voltages (mv) corresponding to each volume of water added to the soil for each container was measured, documented and volumetric water content for each container later calculated.

Sensor readings for each of the soils in the plastic containers were taken and graphs later plotted for ***vwc*** versus D. See equation 2 below:

$vwc = m_1D + y_1$ ....(2)

where $D = (mv - y_2)/m_2$ m_1 and y_1 are the gradient and intercept respectively.

A digital multi-meter (ES 480A Digital Multimeter, TAIWAN) was used for measuring the sensor output voltages. The probe was installed in each container such that no air gaps were left as these would affect the sensor readings. We also made sure that the soil around the probe was not excessively compacted as this would also equally affect our readings as the soil adjacent to the probe surface has the strongest influence on the probe reading which is a measure of the volumetric water content is. Care was also taken to keep out attenuation on the probe's electromagnetic field by avoiding metal objects as this adversely affects output readings as well. Since we did not have Decagon's Probe Installation Kit to install the probe, we used a small flat bar to make pilot holes in the centre of each soil sample in a container, then inserted the probe into the hole making sure that the entire length of the probe was covered. We made sure there was good contact between probe and the soil by forcing the soil gently toward the probe using the same small flat bar. We also minimized effects on downward water movement by installing the probe flat side perpendicular to the surface of the soil. Figure 3 below shows the 3-wire cable wiring configuration for the capacitance sensor.

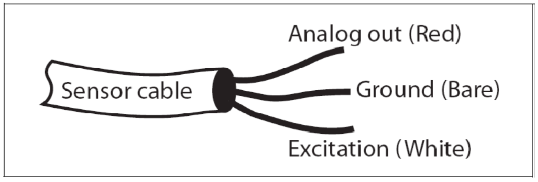

Fig.3. 3-wire cable wiring configuration

III. RESULTS AND DISCUSSION

Figure 4 shows a plot of sensor voltages (mV) against the different digital values of water that yielded a linear relationship between the two, as shown by equation 3 below. The gradient and intercept values from the graph are ***4.808333*** and ***6.472222*** respectively.

$mv = 4.8083D + 6.4722$...........................(3)

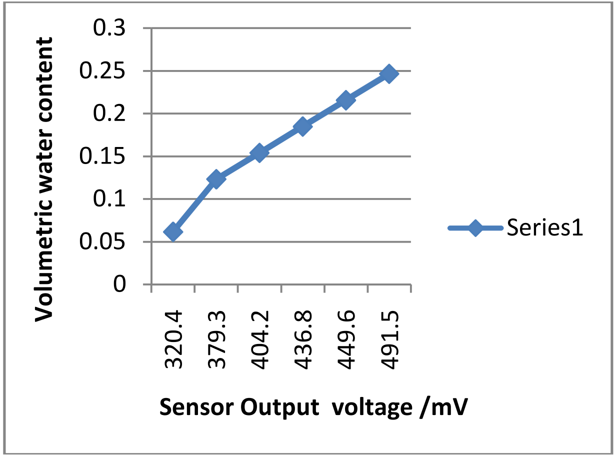

Fig.4. Volumetric water content vs sensor output voltage of soil sample 1.

Figure 5 on the other hand, shows a plot of the sensor voltages (mV) against the different values of volumetric water content. The relationship is also linear if we consider the line of best fit, equation 4 and 5 below. The gradient and intercept values from the graph are ***0.001130416*** and ***-0.296660294*** respectively.

$vwc = 0.00113mV - 0.2967$ ....4.

Expressing vwc in terms D from equation 1 yields equation 3 below,

$vwc = 0.005433D - 0.2894$ ....5.

Equation 3 was the formula we found suitable for use with the PIC microcontroller and the ECH_20 dielectric aquameter sensors.

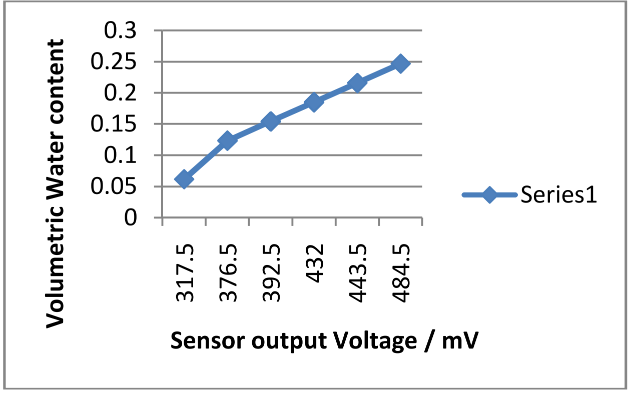

Fig.5. Volumetric water content vs sensor output voltage of soil sample 2.

Figures 6 and 7 show the threshold (D) values versus the sensor voltages for soil sample 1 and 2 respectively. Figure 8 shows a plot of average sensor voltages (mV) of the two soil samples against the different digital values (D). For the three Figures, a linear relationship between the digital values and sensor output voltage was found.

Figure 8, shows the relationships for equation 3 above where the gradient and intercept values from this graph are 4.808333 and 6.472222 respectively.

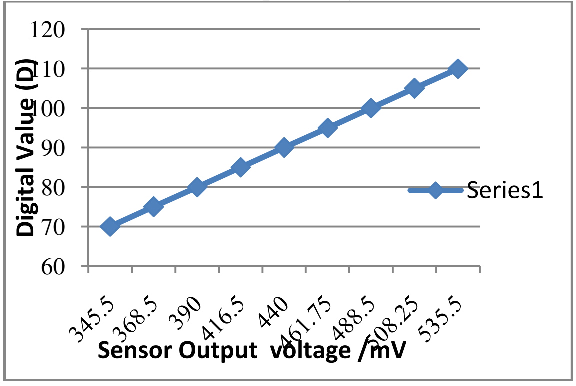

Fig.6. Threshold (D) vs mV for soil sample 1.

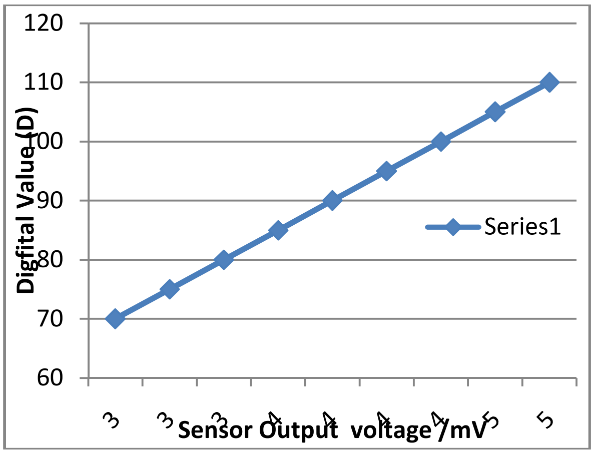

Fig.7. Threshold (D) vs mV for soil sample 2

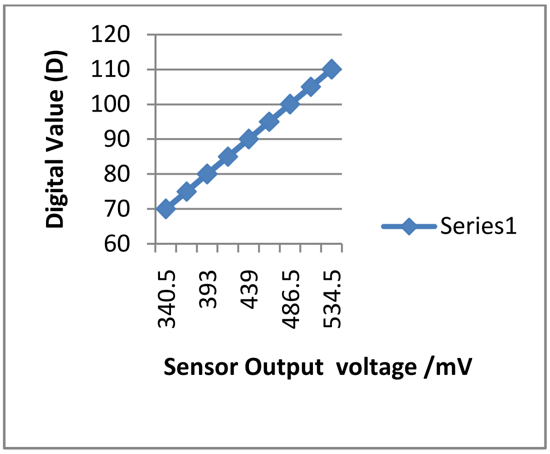

Fig.8. Threshold (D) vs mV average of the two soil samples

E. Equations

Having the data set at hand, the question was on the relationship between the amount of water in the soil and the respective voltages. Different amounts of water were plotted against the respective voltage readings. The scatter plot produced suggests a linear relationship between moisture in the soil and the corresponding voltage. Before the linear trend line was fitted, the following tests were conducted to prove the suitability of the model. The hypothesis was "is there linear relationship between water content and the level of voltage?"

Null Hypothesis: There is no linear relationship

Alternative Hypothesis: There is linear relationship

Level of significance: *5%*

Test statistic: r = Pearson's product moment correlation coefficient

Rejection criterion: Reject the null hypothesis if $r > t$ at 0.025 and (n-2) df

Table 3: Water volume against sensor volt

Water (ml)	70	75	80	85	90	95	100	105	110
Mv1	340.5	367	393	417.5	439	463.5	486.5	511.5	534.5
Mv2	350.5	370	387	415.5	441	460	490.5	505	536.5
Average(mv)	345.5	368.5	390	416.5	440	461.75	488.5	508.25	535.5

From the calculations using the data set above we obtain:

- ✓ *r(mv1)= 0.999756*
- ✓ *r(mv2)= 0.998227*
- ✓ *r(average)= 0.999743*
- ✓ *r(vwc sample1)= 0.993882*
- ✓ *R(vwc sample2)= 0.9958133*
- ✓ *and t crit=0.12*

Since $r > t$ crit for all r, we reject the null hypothesis at 5% level of significance.

IV. CONCLUSION

In this study we developed an automatic irrigation controller that uses signals from the soil to schedule irrigation. The controller was made from cheap and off the shelf components from our laboratory stores and local electronic retail shops. We determined that using our controller, we could get optimal results in terms of irrigation costs which compared favourably to other local grower methods for scheduling irrigation. Research in the field of automated irrigation systems has shown promising results in water savings, as reported by [19] who found a 50% reduction in water use in pepper plants using soil water based automatic irrigation system in comparison to daily manually irrigated treatments.

The main objectives of the research were generally achieved. We managed to design and construct a controller that is low cost (in-terms of electronic components), reliable and affordable by the low income farmer.

Programmable Microcontrollers, like the PIC16F872, are today the world's most popular microcontroller family because of their very optimum combination of cost, complexity, features, availability and allowing for simple connection and operation of peripheral components. These small microcontrollers can be programmed to carry out a vast range of user defined tasks like timing of irrigation events in agriculture, as was done in this project. The total cost of other materials excluding the landed cost of the capacitance sensors and labour for populating the pc board was US$36. Including the sensors and labour, the total cost of the control unit would come to approximately US$156. The number of sensors required depends on characteristics of the soils found in the field, although in this case we opted to use two dielectric sensors. We also managed to provide calibration data for soil water based irrigation control in the clay-loam soils of Northern Harare using the capacitance sensors.

Although we did not go on to field evaluate the control unit on any particular crop, further work is required to repeat this type of investigations and future work should focus on the impact of this method against other available grower based methods on yields and water use efficiencies for a Galina tomato crop at our University farm.

The amount of moisture in the soil and the voltage read from the sensors are strongly linearly dependent and therefore can be modelled by a linear model $y = mx + c$.

Furthermore, the fitted model was tested for goodness of fit using the r-square value. The obtained value for r-square was 0.88. This means that about 88% of the data is being explained by the model hence our model is good enough to explain the relationship.

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