MAKERERE UNIVERSITY

COLLEGE OF AGRICULTURAL AND ENVIRONMENTAL SCIENCES

SCHOOL OF FOOD TECHNOLOGY, NUTRITION AND BIOENGINEERING

DEPARTMENT OF AGRICULTURAL AND BIOSYSTEMS ENGINEERING

BACHELOR OF SCIENCE IN AGRICULTURAL ENGINEERING

DESIGN OF AN ACOUSTIC SOIL MOISTURE SENSOR TO MEASURE OVER A RELATIVELY LARGER COVERAGE

BY

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A PROJECT REPORT SUBMITTED TO THE DEPARTMENT OF AGRICULTURAL AND BIOSYSTEMS ENGINEERING IN PARTIAL FULFILMENT FOR THE REQUIREMENTS OF THE AWARD OF BACHELOR OF SCIENCE IN AGRICULTURAL ENGINEERING OF MAKERERE UNIVERSITY.

May, 2025

ABSTRACT

Water is among the resources that have to be managed if the world is to achieve Sustainable Development Goal 6; Clean water and sanitation. One of the means of managing water in agriculture is through the use of smart irrigation practices. However, these are not without their limitations, one of which is limited area of coverage of most sensor systems employed currently. The objective of this study was to address this limitation by design, assembly and operationalization of a sound-based soil moisture sensor. The principle and design of the sensor was based on earlier models identified through literature review. Components were identified and assembled in a workshop, and field tests were carried out at Makerere University Agricultural Research Institute Kabanyolo. Calibration was done on-site dependent on soil characteristics obtained by literature review. Readings were visualized for comparison for consistency with existing models. Post-testing, the prototype was able to achieve a 90% (1 meter) increase in the coverage as compared to watermark and tensiometer sensors (0.05m to 0.1m), with potential for even greater distances upon transmitter modification. The study thus presents an opportune candidate for deployment of a wide-area coverage sensor on agricultural fields for soil moisture monitoring and integration with smart irrigation systems. With appropriate modifications, this system could easily be applied to rural and remote areas, with a lower number of units per area of field.

DECLARATION

I, Nannozi Agnes Ketrah, declare that the work presented in this report is my work and it has not been presented to any other higher institution for the awarding of marks.

Signature: ……………………………………

Date: …… 26th …. May …. 2025 ………

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ACKNOWLEDGEMENT

I am so grateful to God for the resilience and the ability to accomplish this project proposal and every person that has been part of this academic journey.

Also, words cannot explain how grateful I am to my supervisors, Eng. Dr. Wanyama Joshua and Dr. Erion Bwambale for the academic support, the inquiries made towards my project that have kept me thinking outside the box so as to come with reasonable work. Their weekly review of the work progress kept me working tirelessly and hence the time completion of the required report and presentation. Special thanks to the financiers of this project, without which this project would not have been possible.

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LIST OF ACRONYMS

GDP	Gross Domestic Product
gsms	Gamma Soil Moisture Sensor
IDE	Integrated Development Environment
IoT	Internet of Things
MEMS	Micro-Electro-Mechanical Systems
MUARIK	Makerere University Agricultural Research Institute Kabanyolo
TDR	Time Domain Reflectometry

CHAPTER ONE: INTRODUCTION

1.1 Background of the Study

Agriculture is among the leading Gross Domestic Product (GDP) contributors for Uganda's economy (URA, 2025) and having massive potential for further increase. However, agriculture in Uganda is mainly subsistence in nature and characterized mostly by low technological inputs that result in low yields, substandard production and utilization of Uganda's true agricultural potential. Precision agriculture, which is a farming technique that uses advanced technology such as sensors to monitor and observe field variations for the purpose of improving crop performance and environment quality, has the ability to improve the agricultural potential (Tyronese *et al*., 2008) in Uganda. This technique is technology enabled and is achieved through integration of different technologies that work together to achieve set operations and management principles and of recent, been has also been used to integrate automation in irrigation systems. The technologies consist of a sensing component to detect changes in environmental variables which inform a control circuit/decision system (Pramanik *et al*., 2022). These work to activate or deactivate a water valve, controlling the water distribution through the system. The system then works to adjust, using Internet of Things (IoT) and other technologies to control soil moisture levels in a continuous self-regulating cycle.

As mentioned, these systems employ the use of sensors to detect changes in soil moisture and other soil parameters. Conventional sensor types include tensiometers, resistive moisture sensors, capacitive moisture sensors, nuclear moisture sensors, heat-pulse moisture sensors, hygrometric water sensors, optical and spectroscopic moisture sensors, and not forgetting the gravimetric soil moisture determination method (Hardie, 2020; Ling, 2004; Su, Singh, & Baghini, 2014).

Tensiometers measure soil moisture by determining the tension or suction the soil exerts on water, it is an inexpensive method and it is easy to develop and maintain although they measure limited range of area and require special calibration (David, 1986). Resistive soil moisture sensors measure soil moisture by detecting changes in the electrical resistance between two metal probes inserted into the soil, this method is relatively inaccurate with a limited lifetime. Capacitive soil moisture sensors determine soil moisture by measuring changes in the dielectric permittivity of the soil, this makes the accurate and able to measure at different depths but these are expensive and the ionconcentration in them can affect the measurement. The gravimetric soil moisture determination method is the indigenous method used to test soil moisture, it is accurate and easy to calculate but again this method is not suitable for rapid and in-situ measurements and yet very destructive to the environment (Gorthi *et al*., 2020).

To overcome these limitations, this study proposed a device for cost-effective and wide measurement of soil moisture using the acoustic amplitude in the soil. For a technique to be suitable for soil moisture monitoring measurement in agricultural fields, it should be affordable, provide fast results, and enable direct in situ measurements of moisture in the topsoil (Hardie, 2020; (Meisami-Asl *et al*., 2013). The acoustic method of determining soil moisture is non- invasive and can provide real-time, in situ measurements without disturbing the soil. This method is also less affected by soil salinity or the presence of chemicals, making it more reliable in diverse agricultural conditions compared to conventional methods of determining soil moisture. This method also enables the measurement of soil moisture content over a larger volume of soil compared to other methods previously reported (Meisami-Asl *et al*., 2013), that is in conventional measurements, the sample area may be too limited to accurately reflect the variations across the test plot (Sabatier *et al*., n.d.).

1.2 Problem Statement

Soil moisture monitoring is important in agriculture, it enables optimal water usage in the agricultural fields which in turn improves crop yields, and enables conservation of the water resources available. However, there are a number of sensors which include; capacitive sensors, resistive sensors, tensiometers, watermark sensors, time domain reflectometry and many other types of sensors, yet, they have significant limitations which hinder their operation and effectiveness in the diverse agricultural environments.

Tensiometers measure soil moisture by detecting the tension or suction force required for plant roots to extract water from the soil, these have a limited range of operation and require special calibration (Gorthi *et al*., 2020). Capacitance sensors measure the dielectric constant of the soil to determine moisture content, but these are highly sensitive to soil type and are affected by soil salinity since the increased ionic content in the soil alters its dielectric properties, leading to inaccurate moisture readings (Wobschall, 1978, as cited in Gorthi *et al*., 2020). Resistance-based sensors operate by detecting changes in electrical resistance as soil moisture varies, these are prone to degradation and corrosion over time, especially in saline or alkaline soils, which reduces their reliability and their life in general (Gorthi *et al*., 2020).

These limitations make existing soil moisture sensors less reliable across a wide range of soil conditions, leading to inconsistent irrigation management and suboptimal water use. To address these challenges, developing a soil moisture sensor based on acoustic principles offers a possible solution. Acoustic sensors can measure soil moisture by analyzing sound wave propagation through the soil, which is less affected by soil type, salinity, and other environmental factors. This method could provide more accurate and durable moisture detection, especially in harsh or varying soil conditions, offering a more reliable tool for precision agriculture.

1.3 Objectives of the Study

1.3.1 Main Objective

The main objective was to design a relatively low-cost soil moisture sensor that measures over a relatively larger area using acoustic waves.

1.3.2 Specific Objectives

i. To develop a software program that operates the acoustic moisture sensor system.
ii. To identify appropriate components and assemble a functional prototype of the acoustic moisture sensor.
iii. To evaluate the performance of the prototype under field conditions.

1.4 Research Questions / Hypothesis

i. How accurately does the acoustic sensor measure soil moisture?
ii. How does the acoustic sensor fair with conventional soil moisture sensors?

1.5 Significance of the Study

The acoustic sensor will increase the area over which soil moisture can be measured in the different fields. This could potentially be used to cover a wider area with fewer units, reducing hardware costs and maintenance. Being able to cover a wider area with fewer units could potentially increase the scalability of smart irrigation systems possibly increasing their application in agricultural settings, improving productivity.

1.6 Conceptual Framework

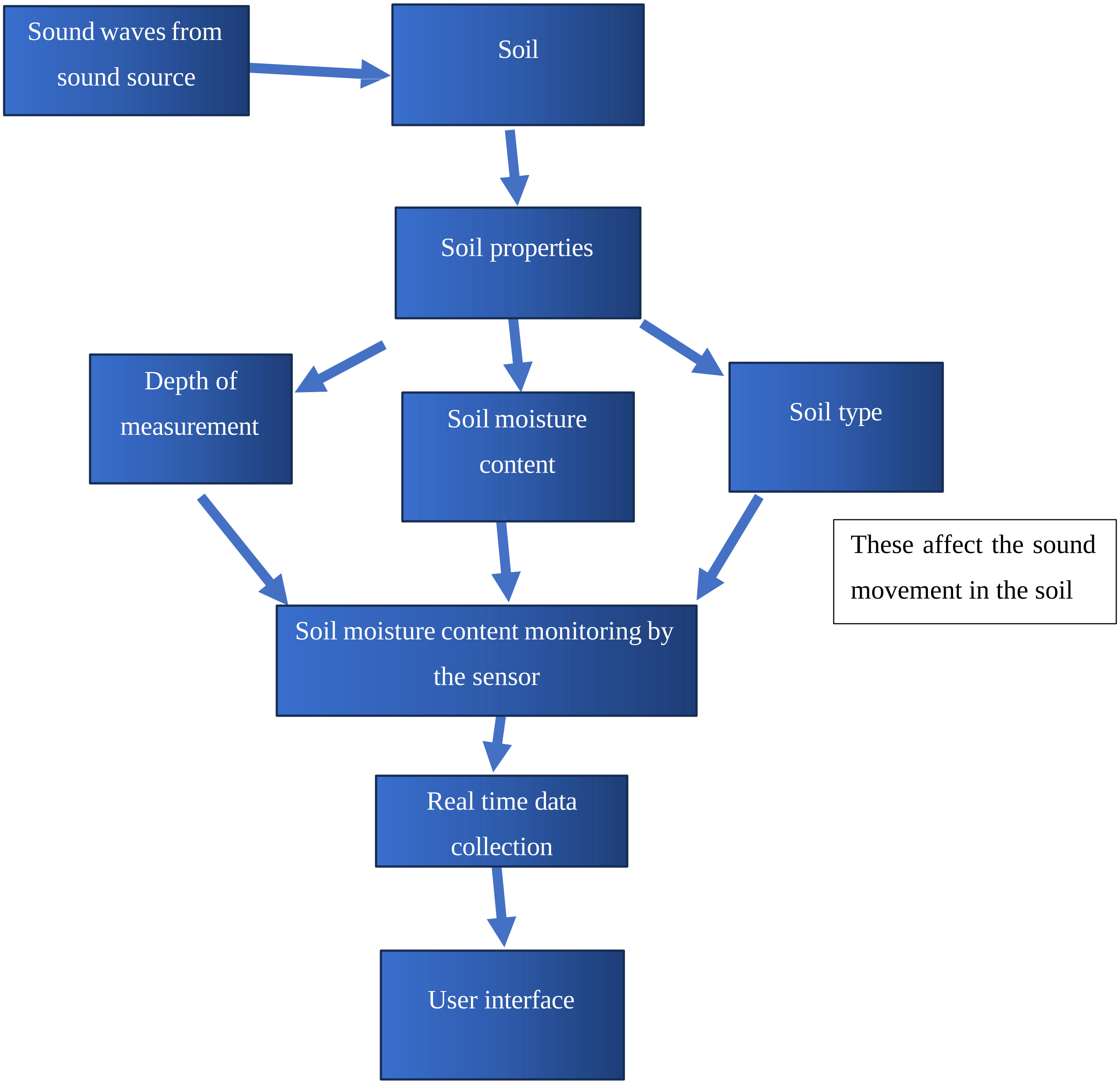

Figure 1-1: Conceptual framework for the sensor prototype development

CHAPTER TWO: LITERATURE REVIEW

Introduction

Soil moisture monitoring is important for effective agricultural practices, especially in irrigation systems where the water usage of the crops directly affects the crop growth, health and yields. Conventional methods of measuring soil moisture such as, the capacitive sensors, resistive sensors, time domain reflectometry (TDR), tensiometry, neutron scattering methods and many others present a number of challenges. These challenges include; limited range of measurement, need for calibration, high costs, maintenance demands, and limited accuracy especially in heterogenous soils (Meisami-Asl *et al*., 2013; Sabatier *et al*., 1990).

Considering the growing need for precision agriculture, there is a need for a more efficient, cost effective and reliable method for soil moisture detection. One of the emerging solutions is the use acoustic soil moisture sensors. Acoustic-based soil moisture sensing offers the potential to overcome some of the limitations associated with conventional methods by using sound waves to detect moisture content. This method is less invasive and can be designed to function in a variety of soil conditions with minimal calibration.

Importance of Soil Moisture in Agricultural Fields

Soil moisture influences almost all plant physiological processes and this makes it an important factor in the plant health and growth. This is because of its indirect and direct influence or bearing on the growth and development of plants. The soil can exhibit three conditions regarding soil moisture, and whichever condition prevails determines the health of the crop, to either the agriculturalist’s delight or dismay. The availability and therefore lack of, of soil moisture has significant implications on crops, especially in critical stages of the plant’s development. These critical stages are found to be those periods with marked fluctuations in transpiratory water loss as a result of atmospheric conditions, and both internal and external factors (Singh & Singh, 1936). In agriculture, this is essential if irrigation interventions in such critical stages are to have the best possibility of having a positive contribution toward both crop yield and growth.

When soil moisture is in its right amounts, that is levels optimal for crop growth, which vary depending on climate, soil and crop type and environmental conditions, it facilitates optimal performance of plant processes. Sufficient soil moisture enables cell turgor maintenance, which is important in positioning of plant structures and stem erection, for proper support in order for plants to receive sunlight. Similarly, it contributes to proper stem elongation, vegetative growth and osmotic balance (Slatyer, 1957). Soils with properly regulated soil moisture content may exhibit a sufficiency in soil organic matter content as the necessary conditions for its formation will have been met. This increases nutrient availability within the soil. Furthermore, availability of soil moisture in right amounts will avail nutrients in solution (such as mineral ions and phosphates) and facilitate their mobility within the soil. Adequacy of soil moisture, as in levels to offset transpiration demand (Singh & Singh, 1936) would result in water not being a limiting factor in photosynthetic production and therefore growth and yield would be maximized (Smith, 1938).

However, insufficient soil moisture levels result in water stress. Water stress results in significant changes in a plant's physiology, by dawning morphological, physiological and biochemical changes to compensate for deficiencies in water content (Mitchell *et al.*, 2013; Lee *et al.*, 2016), that in turn distort proper plant growth. For instance, reduced soil moisture below appropriate levels for extended periods of time may result in fruit, leaf and flower abortion, a phenomenon where plants abscise parts in response to scarcity in resources (Stephenson, 1981), of which water is a proximate cause. Inadequate soil moisture might deny the potential for nutrients to dissolve in solution, and be made available, again limiting plant growth. In addition, low levels of soil moisture may result in incipient wilting which is reversible, and permanent wilting which is unlike the former (Singh & Singh, 1936). This again severely affects yields (through crop losses and die-offs) and quality of produce.

Excess soil moisture whether through over dispensation of water through irrigation, excessive rainfall, flooding or other factors, can affect water stress on crop plants. Flooding results in soil air pores being overrun with water, effectively denying oxygen supply to the roots of plants, causing reduced nutrient uptake, stunted growth, tissue death (root rot ensues) and ultimately crop death. Similarly, it obstructs formation of soil organic matter by facilitating peat formation rather than decay and composition. In addition, nutrient leaching to zones beyond the plant root zone is rampant in soils where soil moisture is in high levels (Morton *et al.*, 1988).

These are all undesirable considering the cost of water for irrigation, climate change related discrepancies in water availability, and the danger too-much withdrawal poses to groundwater sources. It is also worthwhile to note that excess application of water in irrigation to soil results in environmental degradation, through accelerated soil erosion and siltation of water bodies, increase in nutrient in run-off, salinization of soils making them of limited use, and increased likelihood of agrochemicals in waterbodies (Hillel *et al.*, 2008). As such, it is ideal that water applied to soil is optimally controlled through sound scientific management.

Soil Moisture Monitoring and its Importance in Agricultural Fields

Soil moisture monitoring is the process of measuring the amount of water present in the soil for agricultural and environmental management. It is essential that the soil moisture content of the soil, and consequently its supply be managed in a scientifically sound manner. Just like any other living thing, plants need water for healthy growth and production of yield and the water used by plants is found in the soil (Slatyer, 1957).

Water is one of the most abundant resources in the world yet many of the many of the poor and disadvantaged people still lack access to clean and safe water. Much of the water used for agriculture is from rainfall but it is complimentary to the water used for other uses. Pressures on freshwater are rising from the expanding needs of agriculture, food production and energy consumption to pollution and the weaknesses of water management. The agricultural sector is responsible for approximately 70% of global freshwater usage (figure 2-1), and in rapidly developing economies, this figure can rise to as high as 90%. Irrigation and food production are among the largest consumers of freshwater resources, with annual water consumption amounting to roughly 3,100 km³ (World Water Assessment Programme, 2012).

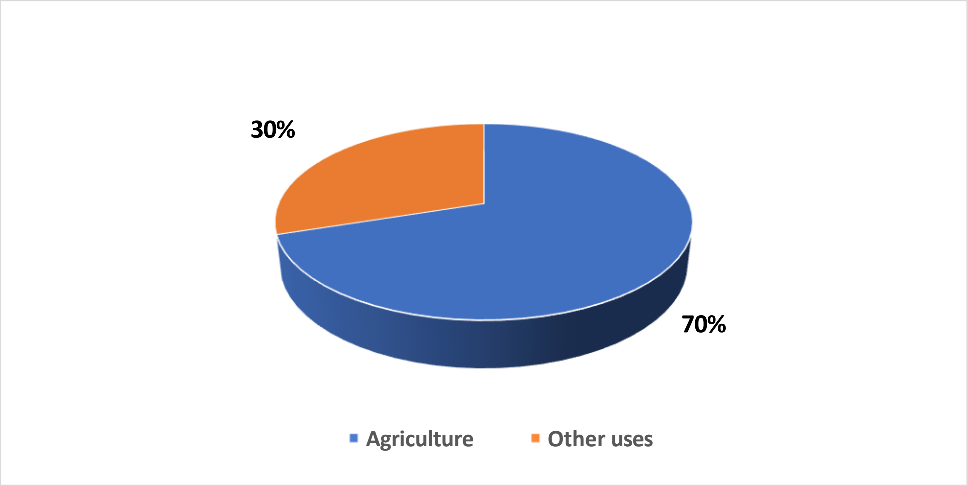

Figure 2-1 Chart showing the global usage of fresh water

According to the World Water Assessment Programme reports (2012), Freshwater is a factor that influences all development initiatives in the world, yet it is increasingly under threat from challenges such as urbanization, excessive consumption, inadequate investment, and lack of proper management. Mismanagement, wastage, and the growing demands from sectors like agriculture, energy, and food production further strain freshwater resources. The current use of freshwater is unsustainable, with insufficient data and fragmented management practices which increases the issue. As uncertainty around water grows, the associated risks are set to intensify. Therefore, there is If we do not take action today to use water as a tool for peace, it could become a significant source of conflict in the future.

Conventional Soil Moisture Sensors and Associated Strengths and Limitations

Soil moisture sensors are devices used to measure the water content or moisture levels in soil. Soil moisture sensors are commonly used in agriculture particularly in irrigation management, in horticulture for greenhouse automation (Ling, 2004), in environmental monitoring at weather stations and in many other ways that may require monitoring of soil moisture. Soil moisture sensors enable to determine when and how much to water plants which are essential aspects of irrigation. To automate this process, various sensors and methods are available to assess when plants require watering (Pramanik *et al.*, 2022). Some approaches estimate water supply by measuring soil moisture levels, others gauge water demand through evapotranspiration rates, while some directly evaluate the plants' water status. Based on the scope of this project, review of a few key soil moisture sensing technologies; other techniques to be explored. Soil moisture sensors include; tensiometers, time domain reflectometry, frequency domain measurement, electrical resistance blocks, gamma ray attenuation sensors, neutron scattering sensors and radiological sensors (Hardie, 2020).

Tensiometers are devices that measure soil moisture tension that is; they operate like artificial roots that measure how easily plant roots can pick up water from their surrounding media (David, 1986). These devices consist of sealed, water-filled tubes with a porous ceramic tip at the bottom and a vacuum gauge at the top. When placed in the soil at the depth of the plant root zone, water flows between the tip and surrounding soil until equilibrium is established. The tensiometer will be subjected to negative soil water potentials, causing water to move from the tensiometer into the surrounding soil matrix. The water movement from the tensiometer will create a negative potential or suction in the tensiometer cylinder which will register on the recording device. At this point, the moisture tension is displayed on the gauge, indicating the soil's water availability. From the gauge, drier soil has higher tension and wetted soil has lower tension values. If the soil water potential increases, water moves from the soil back into the tensiometer, resulting in a less negative water potential reading (David, 1986). Tensiometers (figure 2-2) offer several advantages and one key advantage is that they are not affected by the temperature of the soil water solution or the osmotic potential, which reflects the amount of dissolved salts in the soil water. this is because salts can freely move in and out of the ceramic cup, hence tensiometer readings remain unaffected by electroconductivity (EC) or soil temperature. Some of the most mentioned disadvantages of the sensor are; its maintenance requirement, where water in the tensiometer cavity needs frequent refilling when tensiometers are used in dry environments where the tensiometer becomes a source of water that seeps out due to drier surrounding soil and its limited range where it operates best at soil moisture tensions near field capacity (Anderson & Burt, 1977; Watson, 1967, as cited in Gorthi *et al*., 2020). Tensiometers do not operate well when the soil becomes extremely dry. This is because excessive air is sucked in through the tip breaking the vacuum seal between the soil and the gauge (Agriculture Victoria, 2024).

Figure 2-2: Irrometer Tensiometer Retrieved from https://esi.com.my/inst-home/irrometer-tensiometer/ on 26 October, 2024

Electrical resistance blocks are soil moisture sensors that operate based on changes in electrical resistance in response to soil moisture levels. They are also known as gypsum blocks and they measure the soil water tension. These sensors contain two electrodes embedded within a block of porous material, gypsum. The electrodes are connected to lead wires that run to the soil surface, allowing readings with a portable meter. As water enters or exits the porous block to reach equilibrium with the surrounding soil, the electrical resistance between the electrodes shifts accordingly. In drier conditions, less water is present, leading to higher resistance between the electrodes. In wetter conditions, more water is present in the block, decreasing the electrical resistance. Resistance meter readings are converted to water tension using a calibration curve(Agriculture Victoria, 2024). Gypsum blocks can be relatively inexpensive, easier to install compared to other types of soil moisture sensors and they also operate over a wider range of soil moisture tensions than tensiometers (Hanson *et al*., 2000.). Although the gypsum blocks have many advantages, they also have disadvantages such as, they tend to deteriorate over time and may even need to be replaced yearly and they are not effective in saline soils (Hanson *et al*., 2000).

Some soil moisture sensors use soil water dielectrics as a principle of operation for example time domain reflectometry (TDR) and frequency domain measurement. A dielectric is an insulating material, and the dielectric constant of an insulator measures the ability of the insulator to store electric energy in an electrical field. The volumetric water content in soil can be measured accurately, quickly, and non-destructively using the dielectric properties of moist soil, avoiding the risks linked to radioactive devices. TDR is a widely recognized method for assessing the impedance and signal path quality in components, interconnections, and transmission lines, it measures the soil's dielectric constant by tracking the movement of an electromagnetic pulse along a waveguide created by two parallel rods inserted into the soil (Technologies, 2024.). At the end of the waveguide, the pulse is reflected, and its propagation speed, which is inversely proportional to the square root of the dielectric constant, can be accurately measured using modern electronics. TDR provides accurate and reliable measurements of soil moisture content, its calibration requirements are minimal (in many cases soil-specific calibration is not needed), it is not affected by radiation hazards associated with neutron probe or gamma-attenuation techniques, measurements are easy to acquire, and the method can deliver continuous soil moisture readings through automation(Principles of Time Domain Reflectometry Time Domain Reflectometry, 2004). According to Ojo *et al.*, (2015), while time-domain reflectometry operates at microwave frequencies in the gigahertz range, frequency domain sensors assess the dielectric constant using a single microwave frequency in the megahertz range. The microwave dielectric probe employs an open-ended coaxial cable and a single reflectometer at the probe's tip to measure both amplitude and phase at a specific frequency. The soil measurements are compared to air and are calibrated using dielectric blocks and liquids with known dielectric properties.

Other soil moisture sensors are based on radiological methods, these include; neutron scattering sensors and gamma ray attenuation sensors. According to Stone *et al*., (1955), the neutron scattering sensors are based on the interaction of high-energy (fast) neutrons and the nuclei of hydrogen atoms in the soil. In neutron soil moisture detection, a probe equipped with a radioactive source that emits high-energy (fast) neutrons and a slow neutron counter (detector) is inserted into the ground. A cable connects the neutron probe to the main instrument electronics, allowing it to be lowered into a pre-installed access tube. Hydrogen nuclei, which have a mass similar to that of neutrons, are at least ten times more effective at slowing down neutrons upon collision than most other soil nuclei. Since most of the hydrogen in the soil is found in water molecules, the density of slow "thermalized" neutrons around the neutron probe is nearly proportional to the volumetric soil water content. The density of the neutron cloud surrounding the probe does not increase indefinitely; instead, it reaches an equilibrium based on the rate at which neutrons are absorbed by the soil. In dry soil, the neutron cloud will be less dense and will extend further from the probe. On the contrary, in wet soil, the neutron cloud will be denser and will extend a shorter distance.

Gamma ray attenuation soil moisture sensors, measure the attenuation (i.e., the decrease in intensity) of the gamma ray beam as it moves through the soil. It utilizes gamma rays emitted by the soil to assess soil moisture content. Natural radionuclides release radiation that is detected by this gamma soil moisture sensor (gSMS). Gamma rays are attenuated by moisture in the soil, so the flux of gamma photons serve as an indicator of the amount of moisture present in the soil (Steven *et al.*, 2020). gamma rays from gamma ray devices are more dangerous to work with than neutron scattering devices, as well as the fact that the operational costs for the gamma rays are relatively high.

Heat dissipating sensors, here the temperature of a porous block is recorded before and after a small heat pulse is applied. The heat flow from the heated point is primarily proportional to the amount of water present in the porous material, meaning that wet material will heat up more slowly than dry material. This change in temperature (or cooling) is measured using a precise temperature sensor at the sensor tip, which is calibrated to the soil water content of the medium (Striegl, 2012). Their operating principle is similar to gypsum block sensors, except they measure thermal conductivity rather than electrical conductivity; and hence, the conductivity of the water is not an inherent problem. The advantages of this type of sensors include; its sensor output is independent of the soil electrical conductivity value, and are usually small in size. The most prominent disadvantage of heat dissipating sensors is their high-power requirement (Valente *et al.*, 2004, Jorapur *et al.*, 2015, as cited by Gorthi *et al.*, 2020).

While the mentioned soil moisture sensors offer useful solution in soil moisture measurements and monitoring, they face several limitations as explained. The challenges faced and gaps posed by the conventional soil moisture sensors highlight the need for innovative approaches such as the acoustic soil moisture sensor, which aims to provide a cost effective, real time and versatile solution for monitoring moisture in agricultural fields.

Acoustic Method in Soil Moisture Monitoring

"Acoustic" can mean "related to sound or sense of hearing", so, acoustic method of determining soil moisture means; the use of sound waves to investigate the moisture in soil. According to Sharma & Gupta (2010), for a technique to be useful for soil water content monitoring in the agricultural fields, it must be affordable, capable of in situ measurement of water content of the soil in the top layer and the effect of the presence of chemicals on the measurement results, should be negligible, yet, most of the methods already in use are not able to achieve all these and sometimes the sample area used in conventional measurements may be too small to represent the variations in the test plot hence it would require a sensor to measure over a relatively bigger area. According to the existing research and experiments, it is possible to overcome these limitations by use of acoustic method in soil moisture determination.

Many researchers have explored the propagation of sound waves in soil both experimentally and theoretically. Acoustic waves can deliver information regarding soil physical properties while interacting with the soil (Oshima *et al*., 2015). Brutsaert, (1964), Michael *et al.,* (2002) and Flammer *et al.*, (2001) have theoretically and experimentally established that the velocity of sound in soil is strongly influenced by its moisture content, with sound speed decreasing as the soil becomes more saturated with water. The relationship between the speed of sound in a soil–air–water mixture has also been theoretically examined by Tuncay & Corapcioglu (1996) and Lo *et al*. (2005, 2007). Their analyses yielded conflicting results, with predictions suggesting that the speed of sound in the mixture actually increases as the soil's water content rises. From the experimental work done by Meisami-Asl *et al*., (2013) to investigate the effect of soil water content on the peak amplitude of sound, total power, total harmonic distortion signal to noise ratio, it is evident that the acoustic properties of soil can be calibrated based on its water content.

CHAPTER THREE: MATERIALS AND METHODS

3.1 Study Area

Field tests were conducted at Makerere University Agricultural Research Institute Kabanyolo (MUARIK) located in Nangabo Sub County, Wakiso District within the irrigation plots with preinstalled sensors. Soil characteristics were obtained through literature review.

Soils at MUARIK were characterized as being generally clayey in texture (based on the USDA soil classification) with 52% clay particles predominantly in the lower soil horizons, with sand at 43% and silt with 5% (Okiror *et al.*, 2017).

3.2 Acoustic sensor program development

The code was developed using Arduino Integrated Development Environment (IDE) version 2.3.4. The full working code can be seen in appendix 1. The model utilized in the code is based on the relationship of decreasing velocity of speed with increasing soil saturation by Adamo *et al.* (2004) and Brutsaert *et al.* (1964). The acoustic sensor program was developed to be compatible with Arduino microcontroller systems. The program detects a transmitted signal to return for processing to the microcontroller, for velocity calculation and consequently, moisture content analysis, before displaying output (figure 3-1).

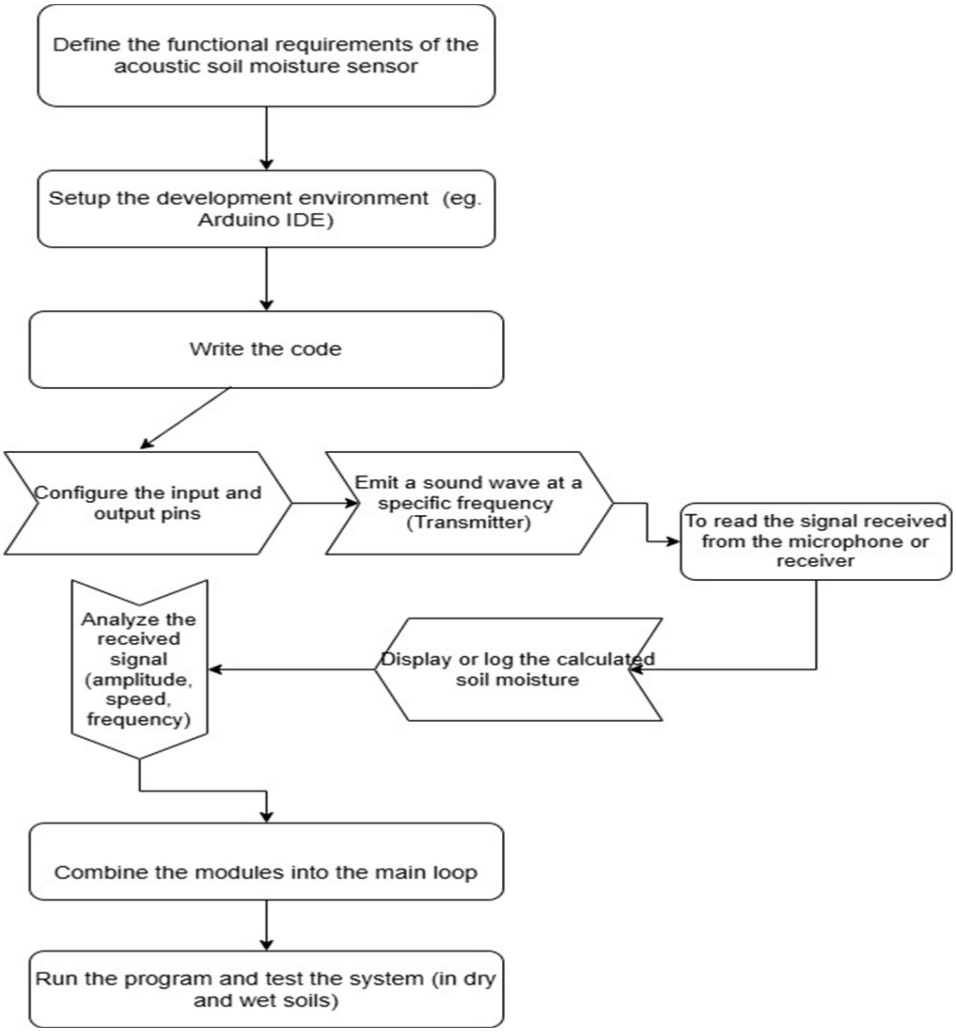

Figure 3-1 Flowchart showing the logic behind the code design

3.3 Assembled a Working Prototype of the Sensor

In the assembly process, it required develop a circuit diagram, and a simple layout of the components required for the sensor development (figure 3-2). The housing components and the components were purchased from different places depending on the prices and availability. The components such as microphone(sound receiver), microcontroller (arduino R3), breadboard, resistors, capacitors, wire cutters, screw drivers, power supply, housing (a wooden material for the prototype) were gathered.

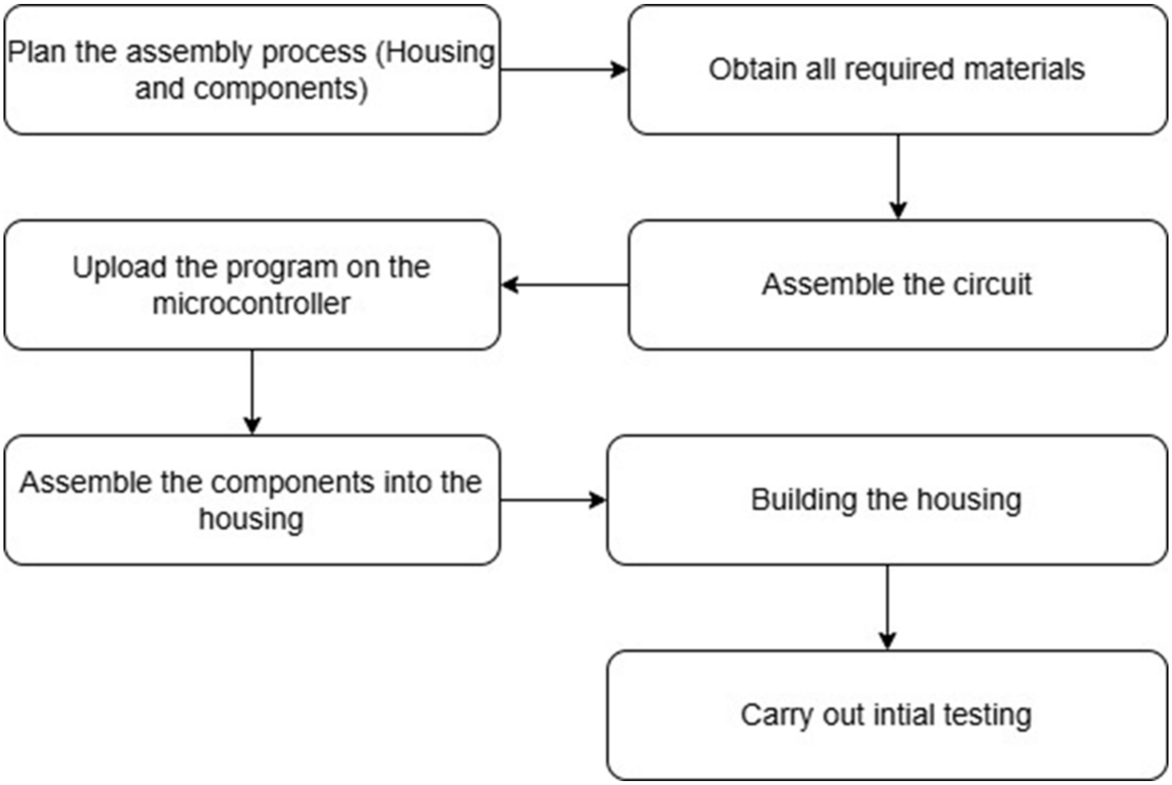

Figure 3-2 Assembly procedure taken

The components (Appendix 2) were assembled following the circuit and the connection was tested. After testing the connections, the program was uploaded to the microcontroller and the basic functionalities were tested. The housing was made by cutting, shaping, creating compartments, attaching the components. The critical parts were sealed with glue to make them water proof temporarily as needed for a prototype (Figure 3-3).

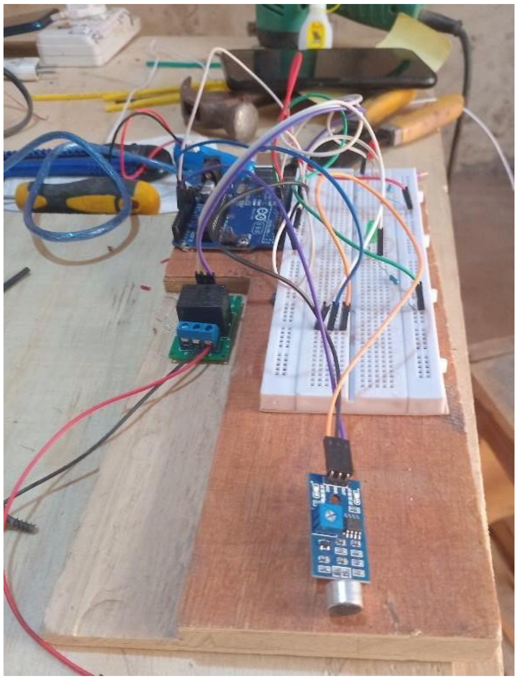

Figure 3-3 Parts assembly housing development in a workshop

The prototype was then be tested in controlled environments that is; dry soil, wet soil, and varying soil moisture levels to observe the signal changes and the calibrate accordingly.

3.4 Prototype Testing

This was done through field tests at MUARIK irrigation plots. It was installed where both parts were buried under the soil about 15 cm from the surface, one meter apart and tested for consistency. Trial runs were conducted to calibrate the microphone sensitivity, and amplitude of the signal from the transmitter. This involved setting the microphone threshold, in a bid to optimize its sensitivity. Final values were adjusted in the code. The plot was irrigated to simulate different moisture levels, so as to get readings at the different levels. Readings from the sensor were recorded for analysis.

CHAPTER FOUR: RESULTS AND DISCUSSIONS

4.1 Sensor Code Development

The code (Appendix 1) was developed based on the requirements of the acoustic sensor, the code checks how wet or dry the soil is using sound waves. A speaker sends a sound, and a microphone listens for it. The time it takes for the sound to travel through the soil tells us how moist the soil is.

At the beginning, the code identifies which parts are connected to which pins and general use of the connected parts: relay to turn the speaker on and off, red LED to light up if the soil is too dry, green LED to light up if the soil is moist enough and microphone (MIC_PIN) which listens for the sound. In the "`setup ()`" part: it prepares all the pins, turns off everything (relay and LEDs), starts the screen and shows a welcome message and also prints messages to the computer's serial monitor (for debugging).

In the "Main loop" part, the commands keep repeating. The code displays "Measuring..." on the screen. It then tries up to 3 times to detect the sound and in each trial, turns on the speaker by switching on the relay, waits for a short moment. Then starts a timer. It then waits to see if the microphone hears the sound. If the microphone hears it, it calculates how fast the sound travelled, the faster the sound, the drier the soil (sound travels faster in dry soil). The code then calculates the moisture level using a math formula (a quadratic equation) (Equation 1). If no sound is heard, it tries again (up to 3 times) and after 3 failed attempts, it shows "System off" and stops running.

$$Moisture\ (\%) = a * v^2 + b * v + c$$

Equation 4.1: quadratic equation

Where: Velocity of sound (meters per second, m/s)

a: Controls the curvature (how much velocity squared affects moisture) as the velocity in dry soil.

b: Scales the linear effect of velocity.

c: Baseline moisture offset as the velocity in saturated soil.

If the signal was detected, it shows the speed of the sound and the estimated moisture percentage. If moisture is 50% or more, it lights up the green LED and shows “Sufficient”. If less than 50%, it lights up the red LED and shows “Deficient”. It then waits 5 seconds so the user can read it.

After showing the result, turns off the LEDs, displays “Ready for next”. It waits a short time before starting another measurement.

4.2 Prototype Layout

The sensor comprises a transmitter (Figure 4-1) and receiving (Figure 4-2) component (Figure 6). The code is uploaded onto the microcontroller making the sensor operable without the need for a personal computer. It is powered by a 6V-1W solar panel, that feeds into a rechargeable battery. Output is displayed on an LCD screen that functions as a Visual Display Unit.

Figure 4-1: Transmitter component

The transmitter consists of a repurposed Bluetooth speaker with a circuit board wired to a relay switch... The transmitted tone is 550 Hz loud enough to be propagated and detected by the sound sensor on the receiver. The receiver consists of a sound sensor connected to an Arduino R3 as a microcontroller. Connected to it also are the relay switch, LED lights for signaling, the LCD screen through a circuit board all in a housing (Figure 4-2). Adamo *et al*., 2004 suggests that modification of the transmitter, which would require more resources, would boost operation distances to up to 2000 metres (2 km) which can be applied to the prototype. This would significantly enhance the sensor's capabilities and application by reducing the number of units required per unit area of agricultural field land. The prototype sensor is able to make measurements over 1 meter's distance (the working distance between transmitter and receiver) comprehensively achieving the main objective of increasing the area over which moisture content can be measured, with the prototype registering a 90% increase in the diameter as compared to available sensors. Being solar powered enables the sensor to be used even in remote areas that may not be supplied with conventional electricity grids and power sources, making it reliable for use in widespread application in the agricultural sector. Additionally, it is a greener alternative since it utilizes renewable energy. The majority of the sensor's components are locally accessible and easily obtainable making it cheaper and easily mass-producible.

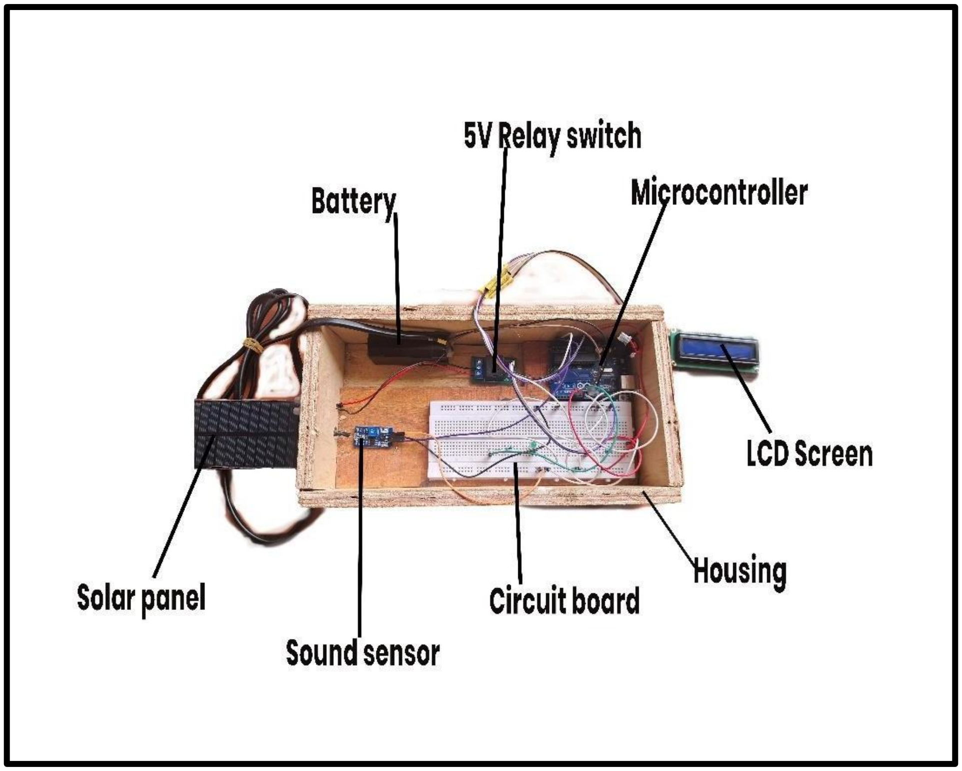

Figure 4-2 showing the assembled prototype with the components displayed

4.3 Schematic Diagram

The connection of the prototype is represented below in the schematic diagram (figure 3). The diagram briefly shows some of the hardware components of the prototype and their connection for receiving and processing sound waves.

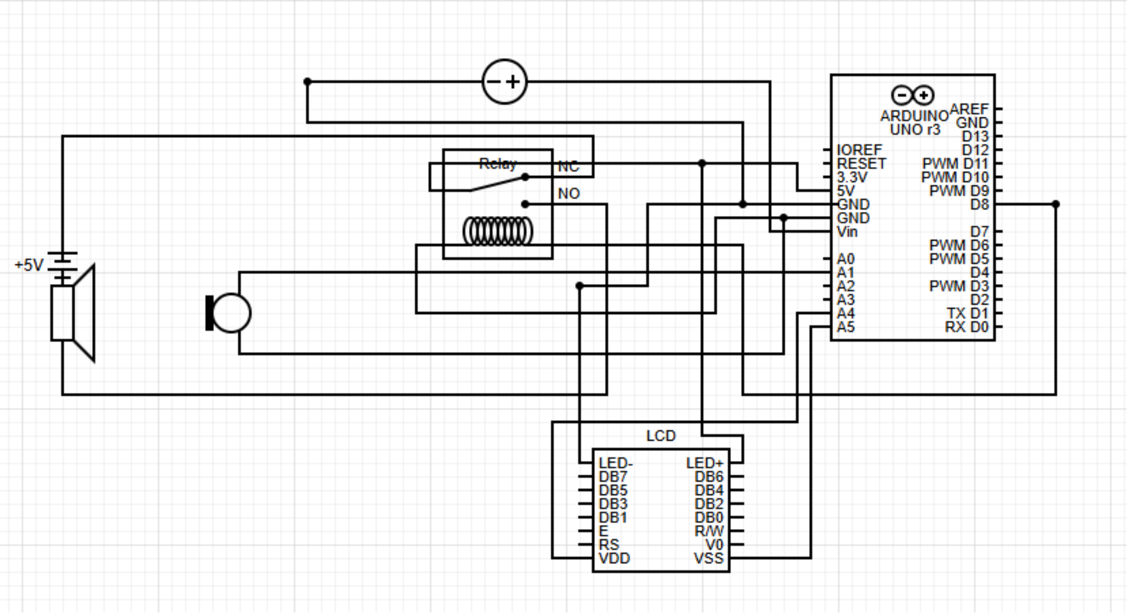

Figure 4-3: schematic diagram of the prototype connections

4.3 Acoustic Sensor Testing

The sensor readings were obtained and represented graphically for visualization (Figure 4.4), showing that the velocity of sound decreases with increasing soil moisture content, fitting the suggested quadratic model. The sensor has demonstrated to be able to consistently apply the models developed by Adamo *et al*., 2004 and Brutsaert *et al*., 1964, enabling it to make real-time in-situ measurements with minimal programming interventions.

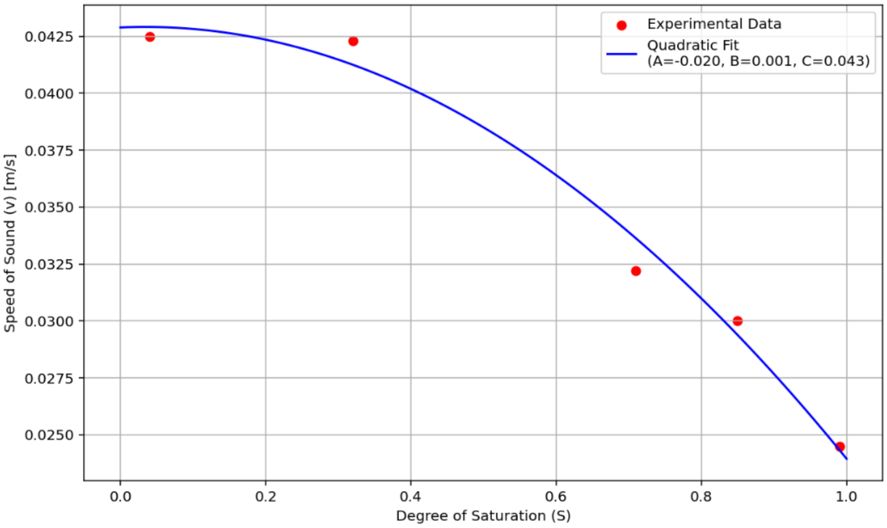

Figure 4-4 showing the relationship between the speed of sound and the degree of the saturation for clay loam soil

Parameters:

S (float or array): Degree of saturation

A (float): Quadratic coefficient (controls curvature)

B (float): Linear coefficient (controls initial slope)

C (float): Offset (baseline speed)

Equation: -0.02 * S**2 + 0.001 * S + 0.043

The developed prototype thus demonstrates that a modern acoustic soil moisture sensor is achievable for making soil moisture measurements, in monitoring field soil moisture conditions in a cost-effective way. The action of the sensor as the literature suggests could also be deployed to investigate other soil characteristics, such as soil porosity and bulk density (Meisami-Asl *et al.*, 2013; Sabatier *et al.*, 1990).

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

The project has been able to develop a competitive alternative to currently used soil moisture sensors for monitoring soil moisture conditions in agricultural fields. The sensor is presented as a model for development of a higher-range commercial prototype for numerous applications in soil moisture monitoring. The prototype can be used with calibration, in different soil types, though may require modification for more wetter soil environments. The prototype as well can be integrated into smart irrigation systems amongst other uses. Through using solar energy as a power source, the prototype is sustainable and a standalone device by utilizing renewable energy. Therefore, the prototype demonstrates an applicable solution towards increasing the capacity of climate-smart agricultural and efficiency in agricultural projects, increasing food security, whereas minimizing the environmental impact of wasteful irrigation practices.

5.2 Recommendations

The following are some recommendations that would bring even greater relevance to the design and function of the developed prototype;

i. Explore the sensor's operation in a variety of different soil types.
ii. The use of higher-end components to significantly improve its range especially with the transmitter component.
iii. Create understanding with incubator programs to secure funding to further develop the prototype into a commercial prototype for sale.
iv. Review the sensor performance (for example, accuracy) under all possible extreme conditions such as extreme heat and cold to simulate harsh climatic conditions.

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APPENDICES

Appendix 1: Acoustic sensor code

```
#include <Wire.h>
#include <LiquidCrystal_I2C.h>

// Pin definitions
#define RELAY_PIN 8       // Relay control pin
#define RED_LED_PIN 7     // Red LED (moisture deficient)
#define GREEN_LED_PIN 6   // Green LED (moisture sufficient)
#define MIC_PIN A1        // Microphone analog input

// Constants
const float DISTANCE = 1.0;           // Distance between speaker and microphone
(meters)
const unsigned long WELCOME_DELAY = 4000; // Speaker welcome message duration
(ms)
const int MAX_TRIES = 3;              // Maximum attempts to detect signal
const int MIC_THRESHOLD = 500;        // Microphone signal threshold for tone
detection
const float DRY_VELOCITY = 340.0;     // Placeholder: Speed in dry soil (m/s)
const float SATURATED_VELOCITY = 300.0; // Placeholder: Speed in saturated soil
(m/s)

// Quadratic model coefficients (moisture = a * v^2 + b * v + c)
// Replace with calibrated values
const float A = -0.001;
const float B = 0.5;
const float C = 50.0;

//LCD Screen wire set up
//Black = Ground
//Grey = A4
//Purple = A5
//White = 5V
// LCD setup (16x2 LCD with I2C, address 0x27)
LiquidCrystal_I2C lcd(0x27, 16, 2);

void setup() {
  // Initialize pins
  pinMode(RELAY_PIN, OUTPUT);
  pinMode(RED_LED_PIN, OUTPUT);
  pinMode(GREEN_LED_PIN, OUTPUT);
```

```
  digitalWrite(RELAY_PIN, LOW); // Relay off initially
  digitalWrite(RED_LED_PIN, LOW);
  digitalWrite(GREEN_LED_PIN, LOW);

  // Initialize Serial and LCD
  Serial.begin(9600);
  lcd.init();
  lcd.backlight();
  lcd.setCursor(0, 0);
  lcd.print("Soil Moisture");
  lcd.setCursor(0, 1);
  lcd.print("Sensor Starting");
  Serial.println("Soil Moisture Sensor Starting...");
  delay(2000); // Display startup message
}

void loop() {
  float velocity = 0.0;
  float moisture = 0.0;
  bool signalDetected = false;
  int attempt = 1;

  lcd.clear();
  lcd.print("Measuring...");

  // Try up to MAX_TRIES times to detect signal
  while (attempt <= MAX_TRIES && !signalDetected) {
    Serial.print("Attempt ");
    Serial.print(attempt);
    Serial.println(" of 3");

    // Turn on speaker via relay
    digitalWrite(RELAY_PIN, HIGH);
    //delay (1000);
    delay(WELCOME_DELAY); // Wait for welcome message

    // Start timing
    unsigned long startTime = micros();
    unsigned long timeout = 20000; // 20ms timeout for signal detection
    unsigned long endTime = startTime + timeout * 1000;

    // Wait for microphone signal
    while (micros() < endTime) {
      int micValue = analogRead(MIC_PIN);
      if (micValue > MIC_THRESHOLD) {
```

```
        unsigned long travelTime = micros() - startTime; // Time in microseconds
        velocity = DISTANCE / (travelTime / 1000000.0); // Velocity in m/s
        signalDetected = true;
        break;
        Serial.print("Travel Time ");
        Serial.print(travelTime);
        Serial.println("microseconds");
      }
    }

    // Turn off speaker
    delay (2000);            //so that relay doesn't turn off while measuring
causing interference
    digitalWrite(RELAY_PIN, LOW);

    if (!signalDetected) {
      Serial.println("No signal detected");
      lcd.clear();
      lcd.print("No signal: Try ");
      lcd.print(attempt);
      delay(2000); // Wait before retry
    }
    attempt++;
  }

  // Check if signal was detected
  if (signalDetected) {
    // Calculate moisture content using quadratic model
    moisture = A * velocity * velocity + B * velocity + C;

    // Display results
    lcd.clear();
    lcd.setCursor(0, 0);
    lcd.print("Velocity: ");
    lcd.print(velocity, 1);
    lcd.print(" m/s");
    lcd.setCursor(0, 1);
    if (moisture >= 50.0) {
      lcd.print("Sufficient");
      digitalWrite(GREEN_LED_PIN, HIGH);
      digitalWrite(RED_LED_PIN, LOW);
    } else {
      lcd.print("Deficient");
      digitalWrite(RED_LED_PIN, HIGH);
      digitalWrite(GREEN_LED_PIN, LOW);
```

```
    }

    // Serial output
    Serial.print("Velocity: ");
    Serial.print(velocity, 1);
    Serial.println(" m/s");
    Serial.print("Moisture: ");
    Serial.print(moisture, 1);
    Serial.print("% - ");
    Serial.println(moisture >= 50.0 ? "Sufficient" : "Deficient");

    delay(5000); // Display results for 5 seconds
  } else {
    // Max tries exceeded, enter "System off" state
    lcd.clear();
    lcd.print("System off");
    Serial.println("System off: No signal after 3 attempts");

    // Turn off LEDs
    digitalWrite(RED_LED_PIN, LOW);
    digitalWrite(GREEN_LED_PIN, LOW);

    // Enter infinite loop
    while (true) {
      // Do nothing
    }
  }

  // Reset for next measurement
  digitalWrite(RED_LED_PIN, LOW);
  digitalWrite(GREEN_LED_PIN, LOW);
  lcd.clear();
  lcd.print("Ready for next");
  delay(2000); // Wait before next measurement
}
```

Appendix 2: Sensor Components

i. Arduino R3 microcontroller.
ii. Breadboard
iii. Jumper wires
iv. Analog microphone
v. 5V Relay switch
vi. 12.6 inch LCD screen
vii. 15000 mAH Rechargeable LiPo Battery
viii. 6V Mini Solar Panel
ix. A repurposed Bluetooth speaker