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DESIGN AND TESTING OF A MULTI-DEPTH SOIL TEMPERATURE SENSOR ARRAY INTENDED AS A CANDIDATE IRRIGATION SCHEDULING TOOL

Lillian Glaeser

Biological Engineering Program

Biological and Agricultural Engineering Department

College of Engineering

University of Arkansas

Undergraduate Honors Thesis
Abstract

A crucial measure in the advancement of water conservation and sustainable agricultural strategies is increasing efficiencies of irrigation systems. Because of the lack of availability of affordable, durable, and scalable soil moisture monitoring devices, this thesis proposes a low-cost, multi-depth soil temperature sensor array as a candidate for monitoring soil moisture content and guiding farmer’s irrigation scheduling. Propagation of diurnal temperature waves through soil is dependent on the thermal diffusivity of the soil, which can be determined by examining temperature waves at different soil depths. Thermal diffusivity is dependent on several factors, though, in undisturbed soil, water has the largest impact on changes in thermal diffusivity. Therefore, it is hypothesized that a multi-depth temperature sensor array can be used as an indirect method of measuring soil moisture content.

The main goal of this thesis was to test the ability of prototypes of the sensor array to collect consistent, repeatable multi-depth temperature; it was hypothesized that a coefficient of variation (CV) of 10% or less could be achieved in temperature readings at a given depth from multiple, adjacent probes. A prototype was designed using a list of design objectives, and a standard method of prototype construction was developed. Eight prototype probes, all fabricated with the same processes, were tested in two different locations in order to observe the repeatability between their measurements. The collected data demonstrated expected behavior, such as increased amplitude damping and phase lag with increasing depth.

The temperature data at a given depth for each plot had a maximum CV of 3.0%, indicating a successful level of repeatability of the sensor arrays. Sinusoidal nature of some residuals, although small (generally less than 0.3-0.4 °C), could represent error introduced by imprecise depth placements; therefore, further design effort to improve the construction process that ensures better precision could be helpful. These devices appear to have the potential to be developed into inexpensive soil moisture sensors.
1. Introduction

Many areas in the United States demonstrate an unsustainable dependency on and demand for water resources for irrigation. For example, in Arkansas, the third leading irrigation state in the US, irrigated agriculture accounts for 80% of extracted water; the high levels of groundwater withdrawal in the state have led to a depletion of groundwater, reducing water availability and increasing water pumping costs (USDA ERS, n.d; National Institute of Food and Agriculture, 2018; Adams, 2018). Irrigation, if not well managed, can have negative environmental impacts, such as ecological degradation and farmland erosion (Frenken, 1997). Therefore, to mitigate the environmental effects caused by irrigation, strategies to improve irrigation water-use efficiency, and to reduce the quantity of water used for irrigation, are needed.

Quantitative awareness of the water needs of agricultural fields can allow farmers to make better-informed irrigation scheduling decisions that increase irrigation efficiency and therefore conserve resources, decrease harmful environmental effects of irrigation, and increase agricultural profitability. Real-time, quantitative awareness of the water requirements of a field can be achieved through the installation of a network of soil moisture sensors. A network with sensors located throughout an agricultural field can enable farmers to understand the spatial variability of water needs in their field; this knowledge can be used to irrigate only areas that need water, therefore preventing overwatering. Waiting to irrigate at the correct soil moisture threshold will provide maximum opportunity for rainfall capture, while still ensuring that crop yields are not reduced. However, appropriate soil moisture sensors are needed for a sensor network to be feasible. There are several commercially available soil moisture content sensors for monitoring for irrigation; however, these options are often expensive and have difficulty expanding to use in large-scale irrigation efforts.

This thesis explores a potential low-cost device that farmers could use to monitor their soil moisture content and create more informed irrigation schedules. The device is a temperature sensor
array intended to be placed in the soil; it consists of cross-linked polyethylene (PEX) pipe combined with four thermocouples positioned at varying depths from the surface (5, 10, 15, and 20 cm) and crimped in place.

The indirect measurement of soil thermal diffusivity used by the proposed device is based on the way thermal diffusivity affects temperature propagation through the soil. Cyclic surface heating and cooling (associated with diurnal solar radiation) causes temperature waves to propagate from the surface of the soil to layers below. Soil thermal diffusivity affects both the amplitude and time lag of temperature waves as they propagate deeper through the soil. Thermal diffusivity is thought to mainly vary with soil texture, bulk density, and water content. In undisturbed soil, soil texture and bulk density remain relatively constant in comparison to water content, which can constantly change due to infiltration, evaporation, and addition of water from sources like rain or irrigation (Xie, 2018). Therefore, it is believed that thermal diffusivity values, determined through the behavior of temperature waves at multiple depths through the soil, can be used to estimate the water content of soil.

The goal of this thesis is to design, build, and test a prototype of the temperature sensor array to determine if the probes can collect consistent multi-depth soil temperature data in the field. For many types of field data, where there is inherent variability of soil physical properties, an acceptable level of coefficient of variation among replicate measurements of 10% or less would be considered reasonable. It is hypothesized that the soil temperature variation among replicate measurements at a given soil depth, using the newly designed probe, will exhibit a coefficient of variation of less than 10%. If successful, this device could be further developed, along with needed signal processing techniques, into a low-cost, low-power, scalable soil water monitoring system which could serve as an irrigation scheduling tool to give farmers a better understanding of the water needs of their fields and create more efficient irrigation scheduling decisions.
2. Literature Review

2.1 Irrigation concerns

Irrigation is a major contributor to water use in the United States, with agricultural irrigation comprising 42% of freshwater withdrawals (USGS, 2020). Irrigated agriculture accounts for 80% of extracted water in Arkansas, the third leading irrigation state in the US, demonstrating substantial irrigation demands for water resources (USDA ERS, 2019; National Institute of Food and Agriculture, 2018). Irrigation is also an important factor for agricultural profits in the state, as, according to the National Agricultural Statistics Service, the value of Arkansas irrigated cropland is $1,300 more per acre than non-irrigated cropland (National Institute of Food and Agriculture, 2018).

Although irrigation is a common and ingrained part of agriculture in the United States, it is known to have numerous damaging environmental effects. Irrigation can cause degradation of irrigated land through salinization, alkalinization, waterlogging, and soil acidification; this damage can impede a field’s ability to further produce crops (Sonneveld et al., 2016). Surface irrigation sourced from rivers and streams can impair water quantity and quality to downstream ecosystems, causing ecological degradation. Over-irrigation and subsequent tailwater discharge can introduce agrochemicals into water systems, causing harmful repercussions such as eutrophication that can be toxic to wildlife (Dougherty, 1995; Frenken, 1997). Large scale irrigation can also cause groundwater depletion, as observed in the Delta region of Arkansas, where reliance on groundwater has led to significant depletion (Adams, 2018). This groundwater depletion is of concern and is expected to worsen; if no intervention occurs, water demands will continue to grow and unsustainable groundwater use will further compound until groundwater reserves are no longer a viable option for irrigation (Scanlon, 2012). These impacts affect not only the welfare of our ecosystems but also the prosperity and viability of our agricultural systems. For example, in Arkansas, groundwater depletion has led to an increase in costs associated with
pumping water for irrigation, reducing agricultural profits for irrigated land (Adams, 2018). Strategies to reduce the quantity of resources used for irrigation are needed to mitigate these rising issues.

Informed irrigation scheduling can increase irrigation efficiency, allowing farmers to reduce the quantity of water they use for irrigation while improving crop yields and reducing operational costs (USDA ERS, 2020). To create efficient irrigation scheduling strategies, an understanding of the available water in the field is necessary. This can be achieved with the use of soil moisture sensing devices; however, fewer than 10% of agricultural irrigators implement soil or plant moisture sensing devices, demonstrating a marked lack of quantitative irrigation awareness – a valuable tool to guide water use efficiency (USDA ERS, 2019).

Understanding the water needs and available water in a field can be complex. A typical field exhibits spatial variability of characteristics, such as topography and soil type, that affect soil water content (Lara, 2018). Therefore, different sections of a field may require different irrigation requirements. Currently, one of the most common irrigation practices is to adjust irrigation rates to satisfy the needs of the driest regions of the field, then apply the same irrigation scheme to the entirety of the field. This results in an overuse of resources that increases costs and the negative effects of irrigation (Lara, 2018). Knowledge of the spatial variation of water needs in their fields can allow farmers to adjust their irrigation scheduling to balance the need to prevent over-irrigation in areas that still have adequate water reserves while preventing inadequate irrigation in other areas and preserving yields. Better knowledge of the spatial variation in soil water can also help the farmer to delay irrigation until the targeted threshold so that rainfall can be better utilized (e.g., it might rain on a given day that irrigation is suitably delayed thereby canceling that particular irrigation event).

Implementation of a network of soil moisture sensors throughout an agricultural field can provide this spatial water information. However, considering currently available soil moisture sensor
options, this can be impractical for farmers to implement due to several factors, such as expensive investment costs.

2.2 Commercially available soil moisture sensors

There are several soil moisture measurement tools commercially available to farmers. Typically, these sensors measure either soil water tension or volumetric water content (VWC). These sensors are often expensive and unsuitable for large scale agricultural applications.

When soil water becomes less available, roots must exert more tension to extract it; tension sensors (tensiometers) measure this soil water tension. These sensors can provide an indication of when plants experience water stress and require irrigation. Because these sensors do not directly measure volumetric water content within the soil, they cannot provide a direct estimation of volumetric water reserves available in the soil; this is disadvantageous for creating irrigation schedules (University of California Agriculture and Natural Resources, 2020), unless the sensors are calibrated for the individual soil.

The VWC sensors directly measure water content, so they can be useful for irrigation scheduling. Commercially available VWC sensors include neutron probes, capacitance probes, time domain reflectometry (TDR) probes, and frequency domain reflectometry (FDR) probes. Neutron probes are typically expensive and contain radioactive isotopes, therefore requiring licensing by the Nuclear Regulatory Commission. The high cost and radioactive nature of these probes makes them generally unsuitable for use in large scale agricultural monitoring. Capacitance probes measure the dielectric constant of a soil volume, which can indicate the VWC of soil when calibrated properly; these sensors require a power source to operate. They can be relatively inexpensive but are sensitive to salinity, temperature, and other soil properties. Inexpensive versions of these sensors often come in short lengths, meaning these sensors can only determine the moisture content of a limited depth of soil. The
TDR and FDR probes also measure the dielectric constant of a soil volume, though they have a more complex process of measurement. These devices are very accurate, representative of a larger area than capacitive sensors, and less sensitive than capacitive sensors to the presence of salt, but they require complex and expensive equipment, therefore reducing their viability as candidates for large-scale, commercial soil moisture monitoring (Department of Primary Industries and Regional Development, 2020; University of California Agriculture and Natural Resources, 2020).

Each of these soil moisture sensors has disadvantages that hinder their suitability for use in large-scale agricultural operations. It is believed that a sensor that uses soil temperature behavior to determine soil moisture content can be designed, with the advantages of being low-cost, durable, low-power, and scalable to large commercial agricultural operations.

2.3 Soil temperature behavior

Temperature propagation through soil is a complex process involving several modes of heat transfer. Heat typically moves through soil through conduction, convection (movement of water), radiation (at the surface), and evaporation-condensation processes. Conduction is typically the predominant mechanism of heat flow in the soil below the surface. During dry conditions (when irrigation decisions are relevant), convection heat transfer due to water (liquid and vapor) movement is known to have a relatively small effect on temperature propagation. Water phase changes can have a significant effect on the heat transfer process of soils due to latent heat changes caused by evaporation and condensation in the soil (Farouki, 1981).

Solar radiation intensity varies in both annual and daily cycles; these cycles of radiation warm the soil surface and cause conductive heating and cooling of soil layers. This creates periodic annual and diurnal trends in soil temperatures that are discernable at a constant depth. The soil at the surface tends to have larger deviations from the mean temperature that translate to temperature waves of decreasing
amplitude and increased time lag for soil at greater depths. Annual temperature patterns penetrate deeper into the soil than diurnal temperature patterns due to their lower angular velocity, so diurnal trends are superimposed onto the overall annual cycle (Costello and Braud, 1989). The properties of these temperature waves are dependent upon the thermal properties of the soil, namely thermal conductivity, volumetric specific heat, and the ratio of the two: thermal diffusivity.

2.4 Soil thermal diffusivity

Thermal diffusivity is the ratio of thermal conductivity and volumetric specific heat. Soils with larger thermal diffusivity values are more capable of conducting heat and, therefore, temperature waves can penetrate deeper with less lag than soils with smaller thermal diffusivity values (Costello and Braud, 1989). The thermal conductivity of soil mainly varies with density, texture (particle size composition), and moisture content (Xie, 2018). Other factors that can affect soil thermal diffusivity include mineral content and organic carbon content. Though changes in soil structure like density and porosity can occur naturally as the soil dries or fills with water, this thesis assumes the density, texture, mineral content, and organic carbon content of undisturbed soil at a given spatial location to remain relatively constant (Farouki, 1981). With this assumption, water content is the largest contributor to variation of thermal diffusivity values in undisturbed soil, enabling the use of changing thermal diffusivity values to be reflective of soil moisture content.

Thermal diffusivity can be estimated using soil temperature data, and several mathematical procedures have been developed for this purpose (Kirkham, 1972; Lier, 2013). Heat flux density can be described by the one-dimensional form of Fourier’s Law of thermal conduction:

\[ q = -\lambda \frac{dT}{dx} \]  \hspace{1cm} (1)
where \( q \) is heat flux density (kJ m\(^{-1}\) d\(^{-1}\)), \( \lambda \) is the thermal conductivity of the medium (kJ m\(^{-1}\) d\(^{-1}\) K\(^{-1}\)), \( T \) is temperature (K or °C), and \( x \) is distance (m).

When considering heat transport in soils, \( \lambda \) is a function of water content \( \theta \), and an assumption that heat conduction only occurs in the vertical direction (for a semi-infinite, homogeneous solid) can allow \( x \) to be substituted by depth, \( z \) (m). Therefore, equation 1 becomes:

\[
q_{\text{soil}} = -\lambda(\theta) \frac{dT}{dz} \]  

(2)

The heat conservation equation is then written as:

\[
c(\theta) \frac{dT}{dt} = -\frac{dq_{\text{soil}}}{dz} \]  

(3)

where \( t \) is time and \( c(\theta) \) is the volumetric specific heat of the soil (kJ m\(^{-3}\) K\(^{-1}\)). Combining equations 2 and 3 yields the following:

\[
\frac{dT}{dt} = \frac{d}{dz} \left[ \alpha(\theta) \frac{dT}{dz} \right] \]  

(4)

where \( \alpha(\theta) \) is the ratio of thermal conductivity and volumetric specific heat, i.e. the thermal diffusivity. Considering \( \alpha \) to be constant at all depths, equation 4 can be simplified to:

\[
\frac{dT}{dt} = \alpha \frac{d^2T}{dz^2} \]  

(5)
Boundary conditions to solve equation 5 can be defined. First, the surface temperature can be considered (as a simple first estimate) to vary according to a sine wave, as follows:

\[ T(z, t) = T_{avg} + A_0 \sin \left( \frac{t}{\tau} + \varphi \right); \quad z = 0 \]  

(6)

where \( T_{avg} \) is the average soil temperature of a daily or yearly cycle at all depths (K or °C), \( A_0 \) is the amplitude of the surface temperature (K or °C), \( \tau \) is the period of the cycle, and \( \varphi \) is the phase constant.

At large depths, temperature can be assumed to remain constant in time and equal to the average surface temperature. Therefore, a second boundary condition can be defined as:

\[ \lim_{z \to \infty} T(z, t) = T_{avg} \]  

(7)

Solving equation 5 satisfying these boundary conditions presented in equations 6 and 7 gives (Kirkham, 1972):

\[ T(z, t) = T_{avg} + A_0 \exp \left( -\frac{z}{d} \right) \sin \left( \frac{2\pi t}{\tau} - \frac{z}{d} \right); \]  

(8)

where parameter \( d \) is the dampening depth:

\[ d = \frac{r\alpha}{\pi} = \frac{2\alpha}{\omega} \]  

(9)

Assuming a constant thermal diffusivity \( \alpha \) per time- and space-step, equations 8 and 9 can be used to estimate the value of \( \alpha \) from soil temperature observations in time and depth. This can be done
using several different mathematical methods, including an amplitude ratio method, phase lag method, four temperature observation method, and a Fourier analysis method.

The amplitude ratio method employs two temperature amplitudes, $A_1$ and $A_2$, measured during the same interval at two different depths, $z_1$ and $z_2$. From equation 9, amplitude as a function of depth can be shown as:

$$A(z) = A_0 \exp\left(\frac{-z}{d}\right)$$  \hspace{1cm} (10)

By inserting values of $(A_1, z_1)$ and $(A_2, z_2)$, two equations can be obtained with two unknowns, $A_0$ and $d$. Solving for $d$, substituting by its components defined in equation 9, then solving for $\alpha$ gives the final equation for the amplitude ratio method, as follows:

$$\alpha = \frac{\pi}{\tau} \frac{(z_2 - z_1)^2}{\ln(A_1/A_2)}$$  \hspace{1cm} (11)

It has been reported that day to day results from this method can vary greatly (Costello, 1986), perhaps because the assumption that the surface temperature is a pure sinewave is not strictly true.

The next method is known as the phase lag method. It uses the phase lag between sine waves at two different depths to estimate $\alpha$. This is most easily achieved by determining the times at which each temperature wave reaches a maximum (or minimum) value, $t_{m1}$ and $t_{m2}$, at two depths, $z_1$ and $z_2$.

According to equation 9:

$$\frac{2\pi t_{m1}}{\tau} - \frac{z_1}{d} = \frac{2\pi t_{m2}}{\tau} - \frac{z_2}{d}$$  \hspace{1cm} (12)
Equation 12 can be solved to find the final equation of the phase lag method, as follows:

$$\alpha = \frac{\tau}{4\pi} \left[ \frac{z_2 - z_1}{t_{m2} - t_{m1}} \right]^2$$

This method has been shown to be unreliable during periods of clouds because of the existence of two or more relative maxima or minima (Costello, 1986).

A third method is based on four temperature observations at two depths collected during a 24 hour period, with 6 hours between observations. The equation for this method is as follows:

$$\alpha = L \left[ \frac{z_2 - z_1}{\ln \left( \frac{(T_{1,1} - T_{1,3})^2 + (T_{1,2} - T_{2,4})^2}{(T_{2,1} - T_{2,3})^2 + (T_{2,2} - T_{2,4})^2} \right)} \right]^2$$

where $T_{z,t}$ represents the temperature at a depth $z$ and time $t$ and $L$ is a constant of value 12.65 d$^{-1}$ (Horton, 1983).

A final method, which will be used in this thesis, utilizes Fourier Series representation of the surface temperature boundary condition to determine the thermal diffusivity (Costello and Braud, 1989) using multi-depth diurnal soil temperature data. This model considers both the diurnal and annual temperature cycles to create a combined term model. Therefore, the surface boundary condition defined in equation 6 can be redefined to include both components as the superposition of two sine waves, as follows:

$$T(z, t) = T_{avg} + \sum_{n=1}^{\infty} A_n \sin[\omega_n t - \varphi_n] + \sum_{n=1}^{\infty} A_d \sin[\omega_d t - \varphi_d] ; z = 0$$
where $T_{\text{avg}}$ is the average annual soil temperature at all depths (K or °C), $A_a$ and $A_d$ respectively represent the amplitude of the surface temperature for the annual and daily waves (K or °C), $\omega_a$ and $\omega_d$ respectively represent the angular velocities for the annual and daily waves (h⁻¹), and $\varphi_a$ and $\varphi_d$ respectively represent the phase constants for the annual and daily waves. For diurnal modeling, we assume that at a particular day of the year, $T_{\text{avg}}$ at the surface is constant for the day. Because of this, the annual variation is therefore included in this term, so $T_{\text{avg}}$ can be expressed as the daily annual soil temperature and $t$ can be expressed in hours instead of days. Using the boundary conditions presented in equations 7 and 15, a periodic solution of equation 5 can be given as:

\[
T(z, t) = T_{\text{avg, daily}} + \sum_{n=1}^{\infty} \left\{ A_{dn} \exp \left(-z \left(\frac{\omega_{dn}}{2\alpha}\right)^2\right) \times \sin \left[ \omega_{dn}t - \varphi_{dn} - z \left(\frac{\omega_{dn}}{2\alpha}\right)^2\right] \right\}
\]

For each additional term, as the summation index increases, the period of the sinewave becomes shortened, so the angular velocity can be expressed in terms of the angular velocity of the first summation index, or $\omega_{dn} = n \times \omega_{d,1}$. It can be noted that $\omega_{d,1} = \frac{2\pi}{24 \text{ hours}}$.

Temperatures measured at multiple depths, and at multiple sample times across the day, in the field can be modeled using this equation. Nonlinear regression can be performed to determine the unknown model parameters including thermal diffusivity of the soil for a given day. This model operates under a few assumptions and conditions.

It is assumed that soil is a semi-infinite, homogenous, and isotropic solid. While, in reality, soil is heterogeneous on many scales, it has been stated that homogeneity may be correctly assumed when the bulk properties of small units of soil do not vary appreciably in space or in time (Costello, 1986). The degree of homogeneity assumed is relative to the implied precision of the model; for predictions of
higher precision, a high level of homogeneity must be present at a small scale. Non-homogeneity of soil is expected to result in systematic prediction errors of amplitude and phase from the model, which would be visible when examining residual data.

It is assumed that periodicity (the dynamic pattern of soil temperature at the surface is repeated each 24 hour period) is present in soil temperature variations; however, in conditions such as warm spells, cold spells, or sporadic cloud cover, these variations are not periodic, which can affect the viability of the model’s predictions.

Movement of soil moisture affects the thermal properties of the soil and can transfer energy in the form of sensible and latent heat. The effects of this mass transfer are not included in the model equation, so in circumstances where significant movement of water through the soil is present such as directly after a rain event or irrigation, estimates for thermal diffusivity may be miscalculated.

Finally, energy transfer caused by evaporation and condensation of water vapor can cause an apparent increase in the thermal conductivity of air spaces in the soil, changing the value of thermal diffusivity. Heat conduction is the only explicitly incorporated mode of heat transfer in this model; however, the effects of water vapor diffusion can be included by utilizing apparent thermal diffusivity, which includes the vapor diffusion component with thermal conductivity, instead of the normally-defined thermal diffusivity.

In summary, the applicability of this model is dependent upon the following: temperature variation must be periodic in nature, which can be achieved by analyzing consecutive days of clear weather or consistent diurnal temperature profiles; sufficient homogeneity must be present relative to the desired temporal and spatial precision of temperature; and there must not be significant movement of water in the soil, which can occur due to precipitation, irrigation, drainage, or other causes.

The consequences of these dependencies are that this model cannot reliably be used to find thermal diffusivity in certain circumstances, such as during inconsistent weather, or directly after causes
of water infiltration (such as rain or irrigation) occur. This latter consequence is dismissible for the application of this thesis; if a field has recently received water, it is unlikely that farmers will be making immediate irrigation scheduling decisions.

2.5 Soil temperature measurement techniques

For this model to be utilized, it is important to collect accurate temperature data at precise depths. Several temperature sensors suitable for soil temperature measurement exist. Three of the most common instrument types are nonelectric thermometers, thermocouples, thermistors, and resistance temperature devices (RTDs) (Logsdon, 2008).

Nonelectric thermometers are the simplest type of soil temperature sensor and include liquid-in-glass and bimetallic types; they operate using the properties of thermal expansion in liquids and solids. These sensors are not for use in unattended dynamic measurements, making them inappropriate for long term, dynamic data collection.

Thermocouples are a common tool used for soil temperature monitoring; they consist of two insulated wires of dissimilar metals soldered together at one end to create a measuring junction. The other end of the wire, known as the reference junction, is connected to a measuring device. When a temperature difference occurs between the measuring and reference junction, a small voltage is generated. This voltage increases proportionally with the temperature difference between junctions and, therefore, can be used to determine the relative temperature difference between the junctions. Relative temperature information is determined, so an independent measurement of the temperature of the reference junction is needed in order to determine the absolute temperature of the measuring junction. Several types of thermocouples exist, constructed out of different metal alloys. The type of thermocouple used dictates the limits of error the thermocouple has. The most commonly used thermocouple type for soil temperature measurement is Type T, which is formed by joining copper with
a copper-nickel alloy known as constantan. Thermocouples have many advantages; they are inexpensive, durable and don’t require electrical excitation. Thermocouples can also be small in size, have fast response times, and are relatively stable and reproducible. Ultimately, thermocouple accuracy is dependent upon the method used to separately measure the reference temperature.

Thermistors are ceramic semiconductors that measure temperature through variable resistance values, which change depending on the temperature present; they are considered the most sensitive temperature sensors currently available. Unlike thermocouples, thermistors cannot be easily constructed from bulk materials. Thermistors require an excitation voltage to determine their resistance; because of this, the selection of a proper thermistor and excitation voltage is important to avoid heating the thermistor and altering temperature readings. These devices are also more prone to calibration drift than thermocouples (Logsdon, 2008). Providing sensor excitation only during (and just prior to) any temperature measurement sample event will help to conserve power consumption in battery operated systems.

The RTDs measure temperature based on increased resistance values of metal with increased temperature. An electrical current is transmitted through the metal RTD element, then the resistance of the element is measured with an instrument. These sensors have very high accuracy and good sensitivity but are one of the most expensive options and consume relatively large amounts of power (Soltero, 2016).
3. Sensor Design

The main objective was to design a low-cost sensor array that could measure daily temperature fluctuations accurately at multiple depths. Specifically, the design objectives for the sensor array were:

- Low-powered
- Representative of temperatures measured at relevant soil depths
- Consistent and precise in depth placement
- Minimally disturbing to the surrounding soil
- Relatively inexpensive cost per device
- Safe to operate without a special license

**Low-powered.** A low-powered device would require less energy input, potentially reducing operational costs over time for large-scale agricultural operations. To create a low-powered sensor, type T thermocouples, which do not require an external power source to operate, were used to collect temperature data. Wire with a ‘special limits of error’ (SLE) specification was used for higher accuracy. Other advantages of these sensors include their low cost, durability, and availability to the researchers.

**Representative of temperatures measured at relevant soil depths.** Constraints for the minimum and maximum temperature measurement depths were defined. Soil near the surface may exhibit greater heterogeneity than soil at greater depths due to high variability in surface fluxes of soil water, vapor, and heat transfer; this can cause noise in the expected temperature wave pattern at these depths. As a result, soil temperature dynamic patterns have less noise at depths of 5 cm or greater (Costello, 1986). Therefore, the minimum sensor depth was defined as 5 cm. While root depths can reach several feet into the soil, over half of the root biomass can typically be found in the upper 20 cm of soil for most crops (Fan, 2016). Therefore, the maximum sensor depth was arbitrarily chosen to be 20 cm to create a probe of practical length that would still reflect the majority of available soil water. At the
20 cm depth, the soil will exhibit measurable diurnal patterns of soil temperature. Four sensor depths were selected in this range, namely 5, 10, 15, and 20 cm depths for each probe (Figure 1).

**Consistent and precise in depth.** A standard method of construction was developed to create prototypes that demonstrated consistent and precise depths of temperature sensors. Jigs were constructed for key steps within this method to ensure consistent placement of sensors across probes.

**Minimally disturbing to the soil.** It was important to minimally disturb the soil while collecting temperatures at precise depths to minimize the effect of the device on the soil’s thermal properties and obtain accurate measurements. An ideal method would be to dig a hole adjacent to the location of interest, then insert sensors horizontally from the void and into the undisturbed soil at the appropriate depths (Costello and Horst, 1991). However, this is a labor-intensive method that would be impractical to perform at a large scale on a farm, so a more efficient method was needed. Therefore, to achieve temperature collection at multiple depths, the final design was a probe consisting of a short length pipe into which the lead wires of thermocouples could be inserted, with soldered junctions secured at precise depths; this probe would be inserted perpendicularly into the ground. The probe would ideally have a small diameter and no significant protrusions, thus minimizing soil disturbance. It was also important for the measurement junction of each thermocouple to make good contact with the soil at the targeted depth.

In selecting an appropriate pipe material, several goals were established. It was important for the material to have a low thermal conductivity to prevent temperature differences at different depths from propagating up and down the probe and altering thermocouple readings. Further, the inner diameter of the pipe needed to be large enough for four thermocouple wires to be fed through; simultaneously, the outer diameter needed to be minimized to decrease soil disturbance. The pipe also needed to be durable, with enough strength and rigidity to maintain its shape after being inserted to a depth of 20 cm.
Plastic pipe (¼” PEX) was ultimately chosen as the material for the thermocouple conduit. Common pipe materials like copper and brass have thermal conductivity values in the range of 200–400 W/(mK) (Georgia State University HyperPhysics, 2020). Contrastingly, plastic materials have very low thermal conductivity values, around 0.4 W/mK (Plastic Pipe Institute, 2014); therefore, several plastic conduit materials were considered. Plastic pipe can be sized in a range of nominal pipe sizes; alternatively, hollow plastic tubular stock is also available in standard sizes. For example, the polymer PVC is very commonly used in plumbing and electrical conduit applications; however, there was not a clear way to make the sensor junction reliably come in contact with the soil at the precise depth.

The inner diameter of 0.36 inches for ¼” PEX is large enough to feed four thermocouple wires through without too much difficulty, while the outer diameter remains relatively small at 0.5 inches. Though PEX is highly susceptible to damage from sunlight, it is being used exclusively underground and away from damaging solar radiation in this design; therefore, it is a relatively durable option.

PEX also has the unique feature of copper crimp-rings designed for use to attach PEX piping to its fittings. A system was devised to crimp each thermocouple measuring joint into place on the probe so that they would stay secured horizontally at the defined depth, with the crimp-ring protecting the thermocouple from being shifted or damaged during insertion.

Because of PEX’s sensitivity to sunlight, PVC was used as a transition piece from underground to above ground components (Figure 1). PVC was selected for use because it is inexpensive, has familiar and easy joining techniques, and is readily available at a low cost.

Relatively inexpensive cost per device. The total cost of materials to build one sensor with the majority of parts sourced locally was approximately $14, making this sensor a low-cost option in comparison to other soil moisture sensors. It should be noted that the cost does not include the signal processing electronics that will be needed.
Safe to operate without a license. None of the materials or methods included in this design require a license to operate, unlike other devices like neutron probes.

Figure 1. Diagram of multi-depth temperature sensor array. Note thermocouples positioned at four depths (left), and crimp-rings subsequently attached over thermocouples (right).
4. Sensor Fabrication Methodology

A method was developed to fabricate the sensor array device with a repeatable result. A detailed description of this methodology is detailed in Appendix A. Safety goggles were worn during several of the manufacturing steps of this process, including the soldering, PEX alteration (drilling, sanding, etc.), and crimping steps.

4.1 Thermocouple Construction

First, four type T thermocouples were constructed for each sensor. About 5 ft of thermocouple wire was cut for each thermocouple. The jacket was removed from the end of the wire, and then the wires were stripped, twisted together tightly, and soldered together. Emphasis was placed on creating a smooth, shiny solder joint to prevent noise in the thermocouple readings. It was important for the solder joint to come out smooth, shiny, and free of excess solder for a proper thermocouple.

4.2 Construction of Tubing Section

Next, the tubing section of the probe was constructed. The principal function of this device is to measure soil temperature at multiple, defined depths; inaccurate depth of the thermocouples could cause biases in the collected data that don’t properly fit the model. Therefore, an emphasis was placed on constructing the tubing section with highly accurate positioning of thermocouple locations.

First, because PEX is highly sensitive to sunlight, a bushing assembly to transition the underground PEX to above-ground PVC was constructed. Polyvinyl chloride (PVC) was selected for use as the above-ground material because of its inexpensive and simple joining techniques. The PVC sheet stock (¼” thick) was cut into a 1.5” x 2” section (Figure 2). In the center of this piece, a 13/16” hole was drilled using a drill press to accommodate a ½” to ¾” PVC reducing bushing. The bottom of the bushing
was coated with PVC solvent, then placed inside of the hole in the PVC plate (Figure 3). The plate was carefully positioned to be flush with the bottom of the bushing. This was allowed to fully cure.

Next, a 27” length of ⅜” PEX pipe, intended to be the conduit for the thermocouples, was cut with a miter saw to ensure a square cut. About an inch of the outside of one end of the pipe was sanded to increase the pipe’s roughness and enhance epoxy attachment.

Then, the holes for the locations of the four thermocouples were drilled into the PEX. A jig, referred to as the Drill Hole Jig, was constructed to drill the holes at precise, repeatable depths of 5, 10, 15, and 20 cm on the tubing (Appendix B). The Drill Hole Jig was guided onto the length of PEX with the 5 cm end of the jig appropriately located near the sanded end of the PEX (Figure 4). The bushing assembly was firmly placed, but not yet permanently attached, onto the sanded end of the PEX; the jig was firmly pressed against the bushing (Figure 5), then clamped and taped in place onto the PEX. A 9/64” drill bit was used to drill a hole through one side of the PEX at each location provided by the jig, at 5, 10, 15, and 20 cm (Figure 6).
Figure 4. Lining the cut PEX up in the Drill Hole Jig to ensure a proper fit. The bottom end should be flush with the bottom of the jig, while the top end should protrude from the jig by 1 cm.

Figure 5. Making sure the PEX fits properly in the Drill Hole Jig with the bushing on the top end.

Figure 6. With the Drill Hole Jig clamped in place and the PEX secured to the jig with tape, the holes are drilled at 5, 10, 15, and 20 cm positions.
4.3 Combining Thermocouples and Tubing

The completed thermocouples were then inserted into the PEX tubing. The thermocouples were fed through the drilled holes, solder end last, to the end of the piping, with the solder joint resting at the drilled hole, using a standard method (see Appendix A: Combining thermocouples and tubing). The solder joints were adjusted to ensure proper location within their respective holes (Figure 7).

![Figure 7. Thermocouple solder joints laying horizontally across the PEX tube after being threaded into the PEX.](image)

Next, a Dremel tool with a circular sander attachment was used to modify each hole to allow the solder joint to rest level with the tubing surface, carefully avoiding contact of the Dremel tool with the thermocouple joint or wire. A divot was carved into the PEX; it began at the drilled hole and extended to the end length of the sensing junction of each thermocouple (Figure 8).

![Figure 8. Modified hole in PEX tubing to allow an inserted thermocouple joint to sit flush with the surface (side view).](image)
4.4 Crimping exposed thermocouples

It was important to secure the thermocouples at the proper depth, so the exposed thermocouples were crimped in place. A PEX crimp tool designed for use with ¾” fittings was used to crimp ¾” PEX copper crimp-rings onto the PEX tubing to cover each drilled hole. A four-part jig, referred to as the Crimp Jig, was constructed in order to attach the crimp-rings at precise depths with a level of reproducibility across the different sensors (Appendix C). This jig consisted of one piece for each of the 5, 10, 15, and 20 cm depth crimps (Figure 9).

Figure 9. The PEX tube, with thermocouples wired through and holes properly modified, alongside the four-part Crimp Jig (copper pipe sections). The bushing assembly is placed to the right of the PEX tube. Crimp rings are located beside the Crimp Jigs in this image.

Due to the physical constraints of the jig and parts, it was important to attach the crimps in a specific order: 20 cm position, 15 cm position, 10 cm position, then 5 cm position. The bushing assembly
was guided over the wires extending from the PEX and firmly placed onto the sanded portion of the PEX. The first (20 cm) Crimp Jig was then guided onto the PEX, firmly pressed up against the bushing (Figure 10). A crimp ring was then guided up the PEX and butted up tightly against the jig over the horizontal thermocouple (Figure 11). It was carefully crimped into place (Figure 12). The jig and bushing were removed by guiding them back over the protruding wires (Figure 13).

Figure 10. The first Crimp Jig (20 cm) positioned on PEX pipe, flush with the bushing assembly on one end. The crimp-ring is guided onto the PEX, but not yet pushed into position (flush with the jig).

Figure 11. The first Crimp Jig (20 cm) positioned on PEX, flush with the bushing assembly on one end. A crimp-ring is in position, flush with the end of the jig.
Figure 12. Crimping the first crimp-ring onto the PEX after it has been successfully positioned by the jig.

Figure 13. PEX with the first crimp-ring (20 cm position) successfully crimped into place and Crimp Jig and bushing removed.

The remaining crimp-rings were attached in the same manner with their respective Crimp Jig piece, with each part guided over the thermocouple wires due to the location of the 20 cm crimp (Figure 14).
4.5 Attaching the bushing assembly to the PEX tube

After insertion of the thermocouples and crimping was completed, the bushing was threaded back over the wires, placed firmly onto the PEX and permanently attached to the PEX using a coating of epoxy. It was clamped in place so that gravity would hold the bushing level onto the PEX and allowed to fully cure. Any excess epoxy that dripped from the bushing onto the exposed PEX was carefully wiped or sanded off. It should be noted that PEX typically cannot be joined using adhesives or solvents. However, because this connection should not typically experience strong forces after insertion, it was thought that creating a rough surface by sanding could allow the PEX pipe to have enough grip to successfully use adhesive (epoxy) to the inside of the PVC bushing for the duration of data collection. In a commercial product, another manufacturing method should be considered.

4.6 Preparing the end of the tubing for ground insertion

The PEX pipe utilized has limited rigidity at the length used for this device, so it was suspected that driving it directly into hard soil could be a difficult process and could potentially deform or damage the tubing. Therefore, it was important to reinforce the end of the tubing that was going to be driven into the ground for easier installation.

The end of the PEX opposite of the bushing was drilled approximately 1 inch deep with a ⅜” drill bit. A roughly 1.5” long piece of ¾” cylindrical PVC stock was cut, then the top 1” was coated with a layer
of epoxy and hammered into the bottom of the PEX (Figure 15). This was allowed to cure; then the PVC stock and PEX were sanded into a point using a belt sander (Figure 16).

5. Inserting Sensors

At each location, a circle of ground with a diameter of roughly 6 feet was trimmed to bare soil with a weed eater to avoid potential variation in the heating of the soil surface caused by the presence of grass. A datalogger was placed near the middle of this trimmed area, and four devices were inserted radially around it, 24 inches apart from one another (Figure 17, 18). First, a pilot rod constructed of PEX was driven 27 cm into the ground using an insertion jig (Figure 19) that was constructed to help drive the pilot rod in perpendicularly. It was important to drive the devices into the ground perpendicular to the surface, as failing to do so would change the depth at which each thermocouple was positioned and create bias in the sensor array’s readings. Next, the jig and pilot rod were removed, and the sensor probe was inserted into the remaining hole. Care was taken to ensure that the sensor array was inserted until the flat PVC piece was level on the ground.
Figure 17. Radial positioning of four sensor array devices (white tubing with gray PVC pieces) around the data logger (contained inside of the white box). The devices are not yet driven into the ground.

Figure 18. Front view of the radial positioning of sensor array devices (gray PVC pieces) around the data logger (contained inside of the white box). The devices have been fully driven into the ground and are ready to collect data.
6. Selecting field testing locations

Two field testing locations, detailed in Appendix D, were chosen to collect data to view the repeatability of the sensor’s performance in two different soils. Criteria for the selection of each plot was defined: each sensor testing location needed to be in an area that was out of the way of daily operations, away from particularly low topography to avoid pooling water, and needed to have adequate drainage. For each location, the soil texture and bulk density were determined as part of the record due to the substantial effect these soil properties have on thermal diffusivity (Arkhangelskaya, 2015; Xie, 2018).

Thermal diffusivity is strongly influenced by soil texture, i.e. sand, silt, and clay content. Examining the presence of this phenomenon in the data would be useful in determining how the sensor
operates in a variety of environments, which is important due to the presence of spatial variation of texture in and across agricultural fields. Therefore, it was desired to collect data from two field testing locations of differing texture. Particularly, the percentage of sand contained in the soil was used for selection. Thermal diffusivity typically varies more with water content in soils that have greater sand content than in soils that contain more clay or silt (Arkhangelskaya, 2018).

The soil texture for each location was found using a particle-size analysis procedure. Within a sedimentation cylinder, 50 grams of soil from the location of interest was mixed with 50 mL of sodium hexametaphosphate (Calgon) and enough water to bring the mixture to 1 L. For the particle-size analysis, this mixture was thoroughly plunged to mix the particles. A hydrometer was then used to measure the density of the suspension at key points in time: 40 seconds, 6 hours, and 12 hours. These hydrometer readings were then input into an equation to find the sand, silt, and clay percentages of the soil. Three iterations for each location were performed to obtain an average sand, silt, and clay percentage for each plot.

Of the several locations that were tested, all had a texture of 20-37% sand; therefore, two soils of drastically different sand contents could not be identified for data collection. Due to time constraints, the researchers ultimately chose plots that satisfied the defined plot criteria and were conveniently located.

The bulk density of the 0-10 and 10-20 cm was measured as well. A soil core of known volume was collected and dried. The mass of the dry sample was then measured using a scale. The bulk density was calculated by dividing the mass of the dry soil by the volume of the initially collected sample.

The two selected locations were respectively referred to as the Farm Plot and the Workshop Plot (Appendix D). The Farm Plot had a soil texture of 36.3% sand, 59.6% silt, and 4.1% clay, and a bulk density of 1.24 g/cm³. The Workshop Plot had a soil texture of 28.3% sand, 59.6% silt, and 12.0% clay, and a bulk density of 1.32 g/cm³.
7. Manual Data Collection

Approximately twice a week for the duration of the experiment (from January 31st, 2020 to March 20th, 2020 - 7 weeks), soil samples were collected to determine soil moisture content in order to view the behavior of the sensors at different levels of soil moisture. This was not performed during weeks with heavy rains throughout.

Three moisture content samples per plot were taken. A soil push probe was inserted perpendicular to the surface of the soil to a depth of 8 inches (approximately 20 cm) and removed; the collected sample was placed in a labelled paper bag. Within 30 minutes of taking the sample, the combined weight of the bag and soil sample was recorded. Next, the sample was dried in an oven at 70°C for at least 48 hours, then the weight of the combined sample and bag were recorded again.

Three different empty paper bags from the same batch used to collect samples were weighed, and an average of this weight was taken. This average weight (assumed tare) was subtracted from the pre- and post-drying sample weights to determine the wet weight of the sample and dry weight of the sample, respectively. The dry basis moisture content for each collected sample was calculated as follows:

\[
\text{Moisture Content}_{\text{dry basis}} = \frac{\text{wet weight (g)} - \text{dry weight (g)}}{\text{dry weight (g)}} \times 100
\]
8. Sensor Probe Data Collection

Environmental data loggers (Model 23X, Campbell Scientific, Logan Utah) were used for data collection over the course of the experiment, one at each plot of interest. The data loggers were programmed to collect the temperature at each depth every 15 minutes. With a laptop computer, the program LoggerNet was used to collect the data from the data loggers. The full record of data was retrieved every 10 to 20 days.

9. Results

For each plot, the temperature data collected by each of the four sensor probes was graphed both by individual sensor-probe readings, as follows:

- Figures 20-23: Temperature data collected by each individual sensor array located at the Farm Plot (Sensor-probe 1, 2, 3, and 4, individually).
- Figures 24-27: Temperature data collected by all sensor arrays located at the Farm Plot, with graphs separated by depth (5, 10, 15, and 20 cm).
- Figures 28-31: Temperature data collected by each individual sensor array located at the Workshop Plot (Sensor-probe 1, 2, 3, and 4, individually)
- Figures 32-35: Temperature data collected by all sensor arrays located at the Workshop Plot, with graphs separated by depth (5, 10, 15, and 20 cm).
9.1 Farm Plot Sensor Temperature Data

**Figure 20.** Temperature data collected by Sensor 1 of the Farm Plot, with readings at 5, 10, 15, and 20 cm depths.

**Figure 21.** Temperature data collected by Sensor 2 of the Farm Plot, with readings at 5, 10, 15, and 20 cm depths.
Figure 22. Temperature data collected by Sensor 3 of the Farm Plot, with readings at 5, 10, 15, and 20 cm depths.

Figure 23. Temperature data collected by Sensor 4 of the Farm Plot, with readings at 5, 10, 15, and 20 cm depths.
Figure 24. Temperature data collected by each of the four sensors of the Farm Plot at the 5 cm depth.

Figure 25. Temperature data collected by each of the four sensors of the Farm Plot at the 10 cm depth.
**Figure 26.** Temperature data collected by each of the four sensors of the Farm Plot at the 15 cm depth.

**Figure 27.** Temperature data collected by each of the four sensors of the Farm Plot at the 20 cm depth.
9.2 Workshop Plot Sensor Temperature Data

**Figure 28.** Temperature data collected by Sensor 1 of the Workshop Plot, with readings at 5, 10, 15, and 20 cm depths.

**Figure 29.** Temperature data collected by Sensor 2 of the Workshop Plot, with readings at 5, 10, 15, and 20 cm depths.
Figure 30. Temperature data collected by Sensor 3 of the Workshop Plot, with readings at 5, 10, 15, and 20 cm depths.

Figure 31. Temperature data collected by Sensor 4 of the Workshop Plot, with readings at 5, 10, 15, and 20 cm depths.
Figure 32. Temperature data collected by each of the four sensors of the Workshop Plot at the 5 cm depth.

Figure 33. Temperature data collected by each of the four sensors of the Workshop Plot at the 10 cm depth.
Figure 34. Temperature data collected by each of the four sensors of the Workshop Plot at the 15 cm depth.

Figure 35. Temperature data collected by each of the four sensors of the Workshop Plot at the 20 cm depth.
9.3 Manually collected data

Manually determined moisture content values for each date and time were averaged for each plot (Table 1).

Table 1. Average moisture content values (mean and standard deviation, n = 3) manually determined for the Farm Plot and Workshop Plot at various dates and times.

<table>
<thead>
<tr>
<th>Date and Time</th>
<th>Farm Plot Average Moisture Content (dry basis)</th>
<th>Standard Deviation (%)</th>
<th>Date and Time</th>
<th>Workshop Plot Average Moisture Content (dry basis)</th>
<th>Standard deviation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2/6/20, 5:15 PM</td>
<td>24.0%</td>
<td>-</td>
<td>2/6/20, 4:45 PM</td>
<td>23.9%</td>
<td>-</td>
</tr>
<tr>
<td>2/13/20, 4:15 PM</td>
<td>23.6%</td>
<td>1.1</td>
<td>2/13/20, 3:30 PM</td>
<td>24.5</td>
<td>0.4</td>
</tr>
<tr>
<td>2/16/20, 4:30 PM</td>
<td>24.8%</td>
<td>0.9</td>
<td>2/16/20, 5:00 PM</td>
<td>23.1</td>
<td>1.8</td>
</tr>
<tr>
<td>2/20/20, 4:30 PM</td>
<td>24.9%</td>
<td>1.4</td>
<td>2/20/20, 5:30 PM</td>
<td>22.4</td>
<td>1.0</td>
</tr>
<tr>
<td>2/22/20, 9:30 PM</td>
<td>21.5%</td>
<td>-</td>
<td>2/23/20, 12:40 AM</td>
<td>20.6</td>
<td>-</td>
</tr>
<tr>
<td>3/1/20, 10:00 AM</td>
<td>23.0%</td>
<td>0.4</td>
<td>3/1/20, 10:30 AM</td>
<td>21.3</td>
<td>0.4</td>
</tr>
<tr>
<td>3/3/20, 4:30 PM</td>
<td>22.9%</td>
<td>1.2</td>
<td>3/3/20, 8:00 PM</td>
<td>20.1</td>
<td>0.4</td>
</tr>
<tr>
<td>3/8/20, 4:45 PM</td>
<td>21.7%</td>
<td>2.4</td>
<td>3/8/20, 4:00 PM</td>
<td>17.8</td>
<td>1.3</td>
</tr>
</tbody>
</table>
10 Analysis

For each plot, the residual temperature data (that is, differences between individual probe readings at a chosen depth compared to the mean of the 4 adjacent probes at the same depth) for each probe was graphed, as follows:

- Figures 36-39: Residual temperature data for each sensor located at the Farm Plot at a particular depth, with graphs separated by depth (5, 10, 15, and 20 cm).
- Figures 40-43: Residual temperature data for each sensor located at the Workshop Plot at a particular depth, with graphs separated by depth (5, 10, 15, and 20 cm).

The magnitude of the residuals appears to decrease with increasing depth. To explore this further, the coefficient of variation (CV) was determined for the temperature data for each plot at each depth (Table 2). It was observed that the CV decreased with increasing depth, with a maximum of 3.0% at 5 cm and minimum of 1.5% at 20 cm for the Farm Plot and a maximum of 2.1% at 5 cm and minimum of 1.0% at 20 cm for the Workshop Plot.

**Table 2.** Coefficient of variation (CV) values for temperature data for each plot (°C) (n=5379).

<table>
<thead>
<tr>
<th>Depth</th>
<th>Farm Plot CV</th>
<th>Workshop Plot CV</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 cm</td>
<td>3.0%</td>
<td>2.1%</td>
</tr>
<tr>
<td>10 cm</td>
<td>1.8%</td>
<td>1.9%</td>
</tr>
<tr>
<td>15 cm</td>
<td>1.6%</td>
<td>1.4%</td>
</tr>
<tr>
<td>20 cm</td>
<td>1.5%</td>
<td>1.0%</td>
</tr>
</tbody>
</table>
10.1 Farm Plot Residual Temperature Data

**Figure 36.** Residual temperature data of the 5 cm depth data collected by the four sensors located at the Farm Plot.

**Figure 37.** Residual temperature data of the 10 cm depth data collected by the four sensors located at the Farm Plot.
Figure 38. Residual temperature data of the 15 cm depth data collected by the four sensors located at the Farm Plot.

Figure 39. Residual temperature data of the 20 cm depth data collected by the four sensors located at the Farm Plot.
Figure 40. Residual temperature data of the 5 cm depth data collected by the four sensors located at the Workshop Plot.

Figure 41. Residual temperature data of the 10 cm depth data collected by the four sensors located at the Workshop Plot.
Figure 42. Residual temperature data of the 15 cm depth data collected by the four sensors located at the Workshop Plot.

Figure 43. Residual temperature data of the 20 cm depth data collected by the four sensors located at the Workshop Plot.
11. Discussion

The goal of this thesis was to create a prototype of these sensor arrays, and to determine if they were capable of measuring accurate, repeatable temperature readings at each different depth.

Comparison to above ground weather data. Weather data was collected from the University of Arkansas weather station, located approximately 1,000 feet from the Workshop Plot, to observe the relationship between weather activity and soil temperature (Figure 46). Good correspondence between the temperatures collected by the sensor arrays and the soil temperature data provided from the weather station can be observed (Figure 44, 45). It can be observed that air temperature had a significant effect on soil temperature, as the behavior of soil temperature mimics the behavior of air temperature. Peaks in both air and soil temperatures further appear to correlate with prolonged periods of increased solar radiation. Temperature decreases are apparent after periods of precipitation.

![Comparison of Weather Station Data and Workshop Plot Sensor Data at the 5 cm Depth](image1)

**Figure 44.** Comparison of Weather Station temperature data at the 5 cm depth to data collected by each of the four Workshop Plot sensor arrays at the 5 cm depth.

![Comparison of Weather Station Data and Workshop Plot Sensor Data at the 10 cm Depth](image2)

**Figure 45.** Comparison of Weather Station temperature data at the 10 cm depth to data collected by each of the four Workshop Plot sensor arrays at the 10 cm depth.
Figure 46. Weather data, including, solar radiation, precipitation, air temperature, and soil temperature at depths of 5 cm (Depth 1) and 10 cm (Depth 2). Obtained from the University of Arkansas weather station. Notice the trends in soil temperature in relation to weather activity.

**Expected Wave Patterns.** The expected qualitative wave behaviors in the measured soil temperatures can be observed when looking at the plots for each individual sensor probe. The amplitude of the temperature waves decreases as depth increases, and a lag is apparent at greater depths throughout time. A few periods of replicated periodicity are visible on some dates for each plot, such as March 5th through 7th (Figure 47, 48). Increasing lag with soil depth can be observed on these
dates by examining the minima and maxima of the waves. It can also be noted that these waves exhibit a daily trend that is not strictly sinusoidal. For this period of replicated periodicity, it can be viewed that solar radiation was consistent on a daily basis, likely indicating consistent levels of cloud cover, and there was a lack of precipitation beforehand and during.

**Figure 47.** Temperature data collected by Sensor 3 of the Farm Plot, with readings at 5, 10, 15, and 20 cm depths, for selected dates of March 5th through 7th. Notice the periodicity of the waves. Also notice that the shape of the daily trend is not strictly sinusoidal.

**Figure 48.** Temperature data collected by Sensor 3 of the Workshop Plot, with readings at 5, 10, 15, and 20 cm depths, for selected dates of March 5th through 7th. Notice the repetitive periodicity of the waves.
Repeatability. By examining the residual graphs (Figures 36-43), it appears that the overall majority of residual soil temperature remained at less than around 0.3 or 0.4°C for each sensor. However, on some occasions, the residual temperature reached values of around 1 °C, likely due to systematic error. The CV for soil temperature data decreased with increasing depth for each plot, indicating greater repeatability across sensors as depth increases (Table 2). This is likely due to the decreased dynamic changes and decreasing vertical temperature gradients at the deeper depths and the increased heterogeneity of soil properties near the surface attributable to greater variability in surface cover, micro-topography, and the movement of soil water, vapor, and heat transfer. The max CV for either plot was 3.0%, less than the hypothesized 10% CV value, indicating an acceptable level of repeatability in the frame of the hypothesis.

Figure 49. Residual temperature data collected for Sensor 3 of the Farm Plot, with readings at 5, 10, 15, and 20 cm depths, for selected dates of March 5th through 7th. Notice the periodicity of the waves.
Figure 50. Residual temperature data collected for Sensor 3 of the Workshop Plot, with readings at 5, 10, 15, and 20 cm depths, for selected dates of March 5th through 7th. Notice the periodicity of the waves.

Potential Systematic Error. A few potential sources of error for temperature readings could have been present. Potentially, one or more of the thermocouple sensors might not have been positioned at precise depths, which would result in systematic error in the measurements. This could arise from several causes. During the insertion of the devices, it was at times very difficult to drive the pipe into the ground, even after creating a pilot hole as detailed in the insertion process. This resistance to insertion and the resulting force required to push the probe into the ground could have potentially bent or warped the pipe in a way that caused one or multiple of the thermocouples to be positioned at an incorrect depth, impairing the placement precision. Further, during insertion it is suspected that the epoxy may have failed on one or more of the sensors, as a few of them felt as though they may have shifted while being pushed into the ground. Shifting of the device components could change the depths of the thermocouples, reducing their precision and introducing error. Finally, in order to construct the Crimp Jig, a standard crimp-ring size was assumed; however, due to manufacturing practices, crimp-ring widths likely vary by small measures, causing small changes to the depths being monitored.
For dates with high periodicity such as the one specified above, the residual soil temperature remained within approximately 0.6 °C of the average for the Farm Plot (Figure 49) and within 0.2 °C for the Workshop Plot (Figure 50). It can be observed that the residuals for these dates would regularly reach a value of relative maximum near 9 AM and a relative minimum near 2 PM. This repeating pattern may indicate the presence of systematic error in temperature data as opposed to random variations. The residual behavior for these dates, where residuals for all 4 sensors on one probe seem to rise and fall together, may suggest a depth-offset error, where the whole probe depth may have deviated in the installed depth from the other probes in that plot.

It is expected that error due to improper depth would result in a larger (if the depth were smaller than expected) or smaller (if the depth were greater than expected) amplitude of the incorrect sensor in comparison to other sensor readings, which would be observable in the residual data as a sinusoidal wave (Costello, 1986). This sinusoidal residual trend would likely be present through all readings, not just on certain days. The residuals demonstrated a consistent sinusoidal nature which was at time repetitive, so it is likely that improper depth placement occurred.

Error due to non-homogeneity of soil may have been present, which would have also been reflected in the residual temperature data as a sinusoidal wave with a 24 hour period (Costello, 1986). This was observed, even on days that demonstrated periodicity (Figure 50, 51), indicating that some level of non-homogeneity was likely present.

**Conclusion.** A maximum CV across the testing period of 3.0% occurred at the 5 cm depth of the Farm Plot, indicating a level of repeatability that falls within the limits of the defined CV of 10% hypothesized in the introduction of this thesis for all of the depths explored in this thesis. This performance indicates that these sensor arrays should be further explored for use as an irrigation scheduling tool. Some recommendations for proceeding have been formulated.
12. Recommendations

**Final Check.** The Design Objectives are listed in Table 3 with a summary comment about the success of the sensor array design in meeting those goals.

**Table 3.** Final Design Check.

<table>
<thead>
<tr>
<th>Design Objectives</th>
<th>Summary of Observed Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Low-powered</td>
<td>The thermocouples utilized for the sensor design are low-powered; the largest draw of power during experimentation was likely the data logger.</td>
</tr>
<tr>
<td>b) Representative of temperatures measured at relevant soil depths</td>
<td>The sensor successfully and consistently measured temperatures from 5 cm to 20 cm.</td>
</tr>
<tr>
<td>c) Consistent and precise in depth</td>
<td>The depth placement of some sensors may have been mildly imprecise, leading to small inconsistencies in temperature data and regular, sinusoidal trends in residual data.</td>
</tr>
<tr>
<td>d) Minimally disturbing to the surrounding soil</td>
<td>Each device created only a small diameter, 27” deep hole in the soil where it was located with no large protrusions, thus minimally disturbing soil.</td>
</tr>
<tr>
<td>e) Relatively inexpensive cost per device</td>
<td>Each device was approximately $14 to build for experimentation.</td>
</tr>
<tr>
<td>f) Safe to operate without a special license</td>
<td>Sensor operated with no safety concerns or hazards to the user after being inserted appropriately. If located in an area where vehicles operate, marking the location of the sensors with flags or tape can reduce the risk of accidents caused by driving into the sensor and datalogger area.</td>
</tr>
</tbody>
</table>

The designed sensor array met each design objective to some extent. The device used a low-powered temperature measurement method, so the largest consumer of power during experimentation was likely the data logger utilized for data collection. In practical field applications, a large, energy cumbersome datalogger could be replaced with a smaller, more efficient microcontroller designed for data collection, such as an Arduino. Each sensor array successfully measured dynamic temperatures at depths of 5, 10, 15, and 20 cm, with a relatively good level of repeatability across each depth,
demonstrating their capability of measuring temperatures at the representative, relevant depths defined in the sensor design section. Their relatively strong repeatability across sensors indicates relatively consistent depths; however, small inconsistencies in temperature measurements and regular, sinusoidal trends in residual data may indicate that there are some small depth placement inconsistencies. Each device was minimally disturbing to the soil due to the sensor design and insertion process design, indicating that designing the structure of the sensor array to be probe-like is successful in this regard. Each device was also very inexpensive to build, approximately $14 for materials for the base sensor array (not including signal processing electronics); several of these sensors could be created and utilized in a network for a single field for a relatively small investment, which was highly important for device design. Finally, this device was safe to operate. Potential areas of danger include the building process because of the tools used (which is not of huge relevance to farmers as they would obtain these devices fully assembled) and the insertion process, if the devices are not inserted in a safe manner or power tools are used for the process (for example, creating a pilot hole with a power drill). Another potential safety concern is if these sensors are located in an area with vehicle traffic; to assuage potential danger to both the sensors and people, it is important to mark the area the sensors are located in, perhaps with a flag or flagging tape.

**Device Design Recommendations.** Overall, it is thought that error in the temperature readings may have arisen from issues with the construction or installation process. Some suggestions to improve the device’s operation are formulated from this experience.

- It is suggested to use a more reliable method to join the PEX to the PVC bushing assembly, as the epoxy was not very appropriate and may have introduced depth error during the insertion process. Though no adhesives formulated for PEX were found during research, perhaps experimenting with a variety of adhesives would be useful. Alternatively, different joining
methods may be of interest, such as cutting threads on the PEX tubing and PVC adapter and screwing them together.

- Concerns with the rigidity of the pipe during insertion may be addressed by utilizing a different pipe material that is harder or more durable that PEX or developing a different insertion method that prevents more stress as the pipe is driven into the ground.
- Developing a more precise method accounting for manufacturing variations for attaching crimp-rings is needed to assure finer precision of depth placement, or a selection process for crimps of specific sizes should be developed.
- Though thermocouples are relatively precise and accurate, it may be of interest to explore the use of thermistors for their higher accuracy and precision while testing the power requirements for excitation.

**Follow-Up Research Recommendations.** Alterations to the testing methodology for these devices is recommended to test prototypes in a broader range of conditions.

- As mentioned previously, this model works under the condition that no significant movement of water is occurring. Precipitation occurred on several days during data collection (Figure 44), so the temperature behaviors of the soil on these days differ from the model expectations and are likely not suitable for determining thermal diffusivity. Further, as a result of these wet conditions, the lowest moisture content measured during testing was about 15% moisture content. The Management Allowable Depletion for plants to grow without stress can be as low as 5% in sandy soils, so data collection during a time of year with drier conditions that allow the soil to reach low moisture contents would be more representative of the situations these devices would be useful for and could, therefore, give more insight into the device’s viability at relevant moisture contents (Observant, 2016).
• Two testing areas of different texture could not be used for data collection. Future testing of these sensors in a range of soil textures would provide an understanding of how well these sensors operate in different conditions, providing more insight into their suitability for use in agricultural operations.

• Because this thesis focused on determining if the sensor arrays could produce repeatable results, thermal diffusivity values were not calculated. Upon improvement of the device build, future research should utilize the obtained temperature values to determine the thermal diffusivity of the monitored soil, using one of the models outlined in the literature review, then estimate the soil moisture content and compare to manually obtained values.
13. Acknowledgements

Dr. Tom Costello, for the formation of the concept of this thesis, foundational groundwork for which this thesis built upon, guidance throughout the process of this thesis, and general mentorship throughout my college career as a whole.

Dr. Kristofor Brye, for being a member of my thesis committee, providing tremendous soil expertise and advice, and lab space, tools, instructions, and assistance for conducting procedures.

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Dr. Vaughn Skinner, for taking time to help us find prototype testing plots and allowing us to use them, as well as providing weather station data.

Mr. Randy Andress, for providing the tools to collect the experimental data and assisting with the data collection software.
References


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Appendix A - Sensor Construction

A method was developed to build the sensor array device. Safety goggles were worn during several of the manufacturing steps of this process, including the soldering, PEX alteration, and crimping steps.

A1. Thermocouple Construction

Four thermocouples were constructed for each sensor. The thermocouple wire utilized was Type T stranded thermocouple wire from Omega Engineering, with Copper and Constantan wires, part number PP-T-24S-SLE. It can be noted that this wire is SLE, Special Limits of Error, and therefore has increased accuracy. About 5 feet of wire was cut for each thermocouple. The jacket was removed from the end of the wire with a box knife, then the wires were stripped and twisted together tightly. Tin/lead rosin core solder wire from Austor (Sn/Pb: 60/40 Flux: 1.8%) was used to solder the two wires together with a soldering gun set at 375°C. Emphasis was placed on creating a smooth, shiny solder joint to prevent noise in the thermocouple readings (Figure A1). Each thermocouple joint was inspected to ensure that the quality was acceptable.

Figure A1. Example of a thermocouple solder joint.
A2. Construction of Tubing Section

Next, the tubing section was constructed. The principal function of this device is to measure soil temperature at a defined depth; inaccurate depth positioning of the thermocouple can cause biases in the collected data that don’t properly fit the utilized model, which is highly sensitive to depth. Therefore, it was extremely important to construct the tubing section with highly accurate positioning.

First, because PEX is highly sensitive to sunlight, a bushing assembly to transition the underground PEX to above-ground PVC was constructed. PVC sheet stock $\frac{3}{8}$” thick and 2” wide (McMaster part no. 8740K33) was cut into a 1.5” x 2” rectangle (Figure A2). A hole to accommodate a $\frac{1}{2}$” to $\frac{3}{4}$” PVC male to female reducing bushing (McMaster part no. 4881K612) needed to be drilled into the center of this piece. First, a $\frac{3}{8}$” pilot hole was drilled in the center using a drill press (Figure A3). Then, a 13/16” hole was drilled through this pilot hole with a drill press; the drill bit was passed through the piece a few times to enlarge the hole (Figure A4). The bottom part of the bushing was coated with low VOC gray PVC solvent cement, then placed into the drilled hole of the PVC plate (Figure A5). The plate was carefully positioned to be flush with the bottom of the bushing, and this was allowed to cure completely, approximately 1 hour.
Figure A2. Cutting the ¼” PVC stock into 1.5”x2” sections.

Figure A3. Drilling the pilot hole into the PVC stock section with a ⅜” drill bit on a drill press.

Figure A4. Drilling the 13/16” hole into the previously cut PVC stock section on a drill press.

Figure A5. Attaching the bushing to the drilled PVC stock section with PVC cement.

Next, a 27” length of ⅜” PEX pipe, intended to be the conduit for the thermocouples, was cut with a miter saw to ensure a square cut (Figure A6). About an inch of the outside of one end of the pipe was sanded to increase the pipe’s roughness and enhance epoxy attachment.
Figure A6. Cutting the ⅜” PEX into 27” sections with a miter saw. The PEX is clamped tightly into place to avoid bends and assure a perpendicular cut.

Next, the holes for the locations of the four thermocouples were drilled into the PEX. A jig, referred to as the Drill Hole Jig, was constructed in order to drill the holes at precise depths of 5, 10, 15, and 20 cm on the tubing (Appendix B). The Drill Hole Jig was guided onto the length of PEX with the 5cm end of the jig appropriately located near the sanded end of the PEX (Figure A7). The bushing assembly was firmly placed, but not permanently attached, onto the sanded end of the PEX; the jig was firmly pressed against the bushing (Figure A8, A9), then clamped and taped in place with the PEX (Figure A10). A 9/64” drill bit was used to drill a hole through one side of the PEX at each location provided by the jig - at 5, 10, 15, and 20 cm (Figure A11).
**Figure A7.** Lining the cut PEX up in the Drill Hole Jig to ensure a proper fit. The bottom end should be flush with the bottom of the jig, while the top end should protrude from the jig by 1 cm.

**Figure A8.** Making sure the PEX fits properly in the Drill Hole Jig with the bushing on the top end.

**Figure A9.** View of PEX correctly lined up in Drill Hole Jig, bushing firmly placed on top (not yet permanently attached). End of PEX is flush with the end of the jig.

**Figure A10.** Clamping the Drill Hole clamped in place, with the PEX attached to the jig with tape.
A3. Combining Thermocouples and Tubing

The completed thermocouples were guided through the drilled holes, solder end last, to the end of the piping, with the solder joint resting at the drilled hole (Figure A12).

Figure A11. With the Drill Hole Jig clamped in place and the PEX secured to the jig with tape, the holes are drilled at 5, 10, 15, and 20 cm positions.

Figure A12. View of the inserted thermocouple solder joints laying on the PEX tube.
First, a thermocouple wire was inserted into the hole farthest from the outlet point for the wires (the 20 cm hole). This wire was pushed up through the PEX, until it arrived at the next hole (the 15 cm hole). At this point, another thermocouple was guided through the 15 cm hole, and the two were pushed together through the tubing until reaching the third (10 cm) hole. This was repeated for the third and fourth hole, until all of the wires were guided through the end of the tubing. The wires were then pulled through the tubing until the thermocouple solder joints were close to their respective holes. The solder joints were adjusted to ensure proper location within their respective holes.

Next, a Dremel tool with a circular sander attachment was used to modify this hole to allow the solder joint to rest level with the tubing surface, carefully avoiding contact of the Dremel tool with the thermocouple joint or wire. A trench was carved into the PEX, beginning at the side of the drilled hole and extending to the end of the solder joint when properly positioned (Figure A13, A14). It is important to note that the solder joint should remain horizontal with this modification to ensure accurate depths of temperature readings. A crimp ring was slid on top of this joint to ensure proper fit, and the tube was sanded further if necessary, to allow a smooth fit (Figure A15).

**Figure A13.** Modified hole in PEX tubing to allow the thermocouple joint to sit flush with the PEX surface (side view).

**Figure A14.** Modified hole in PEX tubing to allow the thermocouple joint to sit flush with the PEX surface (top view).
A4. Crimping exposed thermocouples

Next, the exposed thermocouples were crimped in place. A PEX crimp tool with $\frac{3}{8}$” fittings was used to crimp $\frac{3}{8}$” PEX copper crimp rings onto the PEX tubing above each drilled hole. A four-part jig, referred to as the Crimp Jig, was constructed in order to apply the crimps at precise depths (Appendix C). This jig consisted of one piece each for the 5, 10, 15, and 20 cm depth crimps (Figure A16).
Due to physical constraints of the jig and parts, it was important to attach the crimps in a specific order: 20 cm position, 15 cm position, 10 cm position, then 5 cm position. The bushing assembly was guided over the wires extending from the PEX and firmly placed onto the sanded portion of the PEX. The first (20 cm) Crimp Jig was then guided onto the PEX, pressed firmly against the bushing (Figure A17). A crimp ring was then guided up the PEX and pressed tightly against the jig, over the horizontal thermocouple (Figure A18). It was carefully crimped into place (Figure A19). The jig and bushing were removed by threading them back over the extruding wires (Figure A20).

Figure A17. The first Crimp Jig (20 cm) positioned on the PEX pipe, flush with bushing on one end. The crimp-ring is guided onto PEX, but not yet pushed into position (flush with the jig).
Figure A18. The first Crimp Jig (20 cm) positioned on PEX, flush with bushing on one end. A crimp-ring is in position, flush with the end of the jig.

Figure A19. Crimping the first crimp-ring onto the PEX after it has been successfully positioned by the jig.
Because of the 20cm crimp, each part of the process now needed to be guided over the extruding wires. Therefore, the next step was to thread a crimp over the wires, then the 15cm jig, then the bushing to rest on the top of the PEX. The bushing assembly was pushed firmly against the PEX, then the Crimp Jig was pressed firmly against the bushing, and finally the crimp was pressed firmly against the Crimp Jig over the horizontal solder joint in to properly align all parts of the system (Figure A21). The crimp was carefully crimped into place, then the bushing assembly and Crimp Jig were removed (Figure A22). This process was repeated for the remaining two holes with their respective 10cm and 5cm Crimp Jigs (Figures A23, A24). The result of this process was the PEX piece with four thermocouples crimped into place at consistent depths (Figure A25).
Figure A21. PEX with second crimp-ring, second Crimp Jig (15 cm), and bushing guided on. Each of these pieces had to be guided up the thermocouple wire: first, the crimp; next, the Crimp Jig; finally, the bushing, which was firmly pushed onto the PEX. The Crimp Jig was then pushed firmly against the bushing, and the crimp-ring was pushed to be plush with the end of the jig, over the thermocouple.

Figure A22. PEX with the first (20 cm position) and second (15 cm position) crimp-rings successfully crimped into place and Crimp Jig and bushing subsequently removed.
Figure A23. PEX with third crimp-ring, third Crimp Jig (10 cm), and bushing guided on. Each of these pieces had to be guided up the thermocouple wire: first, the crimp; next, the Crimp Jig; finally, the bushing, which was firmly pushed onto the PEX. The Crimp Jig was then pushed firmly against the bushing, and the crimp-ring was pushed to be plush with the end of the jig, over the thermocouple.

Figure A24. PEX with fourth crimp-ring, fourth Crimp Jig (5 cm), and bushing threaded on. Each of these pieces had to be guided up the thermocouple wire: first, the crimp; next, the Crimp Jig; finally, the bushing, which was firmly pushed onto the PEX. The Crimp Jig was then pushed firmly against the bushing, and the crimp-ring was pushed to be flush with the end of the jig, over the thermocouple.

Figure A25. PEX with all crimp-rings successfully crimped in place and the bushing and final Crimp Jig removed.
A5. Attaching the bushing assembly to the PEX tube

After insertion of the thermocouples and crimping was completed, the bushing was threaded back over the wires, placed firmly onto the PEX and permanently attached to the PEX using a coating of epoxy. It was clamped in place so that gravity would hold the bushing level onto the PEX and allowed to fully cure, about 48 hours. Any excess epoxy that dripped past the bushing onto the exposed PEX was carefully wiped or sanded off.

A6. Preparing the end of the tubing for ground insertion

The PEX pipe utilized has limited rigidity at the length used for this device, so it was suspected that driving it directly into hard soil could be a difficult process and could potentially deform or damage the tubing. Therefore, it was important to reinforce the end of the tubing that was going to be driven into the ground for easier installation.

The end of the PEX opposite of the bushing was drilled approximately 1 inch deep with a ⅜” drill bit carefully to avoid creating a hole in the side of the PEX or making contact with the 20cm thermocouple (Figure A26). A roughly 1.5” long piece of ⅜” solid cylindrical PVC stock was cut, then the top 1” was coated with a layer of epoxy and hammered into this hole (Figure A27, A28). This was allowed to fully cure, approximately 1 hour. Then, the PVC stock and PEX were sanded into a point using a belt sander (Figure A29, A30).
Figure A26. Drilling a hole in the bottom of the PEX (the end closest to the 20 cm hole) with a ⅜” drill bit.

Figure A27. Hammering the ¾” solid cylindrical PVC stock into the previously drilled hole in the bottom of the PEX tube.

Figure A28. PEX tube with ⅜” solid cylindrical PVC stock inserted in bottom.
Figure A29. Sanding the ¾” solid cylindrical PVC stock inserted in PEX to a point with a belt sander.

Figure A30. PEX with ¾” solid cylindrical PVC stock sanded to a point.
Appendix B - Drill Jig Construction

A jig, referred to as the Drill Hole Jig, was constructed to ensure the proper placement of holes in the sensor and reproducibility of placement from sensor to sensor. In order to use this jig for multiple iterations while avoiding damage to it during the sensor construction process, it was created out of metal pipe. Copper pipe with a diameter of ½” was used for the jig because the ¾” PEX pipe fit snugly into it. A drill press was used to drill precise and accurate holes and to keep the holes straight.

First, a length of copper pipe was cut to 26 cm long with a miter saw to ensure a perpendicular end. On this pipe, the position for each thermocouple hole was carefully measured from one end of the pipe with a set of calipers. The positions 5 cm, 10 cm, 15 cm, and 20 cm from the end of the pipe were marked carefully with sharpie, then the calipers were used to create a small scratch in the sharpie to indicate the precise location for the hole to be located (Figure B1).

**Figure B1.** Marked tube for drill hole jig. Marks were created using a caliper with precision up to 3 decimal places. The caliper was used to scrape a small mark onto the sharpie for high precision placement of the hole.
The pipe was then clamped into place on the drill press and lined up appropriately (Figure B2). A pilot hole was drilled into one of the marked locations using a pilot hole drill bit (Figure B3). Then, a 9/64” drill bit was used to drill through the pilot hole (Figure B4). This was repeated for each of the four marked holes to create the final jig (Figure B5).
Figure B4. Drill Hole Jig clamped into drill press, with the 5 cm position hole drilled out using a 9/64” drill bit.

Figure B5. Completed Drill Hole Jig (copper piece), with a piece of PEX inside. Note the holes drilled at 5, 10, 15, and 20 cm from the left-hand side of the jig.
Appendix C - Crimp Jig Construction

A jig to apply the crimps, referred to as the Crimp Jig, was constructed for consistent and precise depths that could be reproduced from sensor to sensor. It was desired that each crimp would lay centered on top of the drilled hole.

The jig was designed as four different lengths of copper pipe (Figure C1). Each jig piece would be used one at a time, in succession. Each piece was designed to be positioned between the bushing positioned at the top of the drilled PEX and the crimp being attached to the pipe (Figure C2). Due to physical constraints of the jig and parts, it was important to attach the crimps in a specific order: 20 cm position, 15 cm position, 10 cm position, then 5 cm position. For instructions for using the Crimp Jig, see Appendix A.

Figure C1. Four-piece Crimp Jig constructed out of ____" copper pipe, with crimps positioned to the right. From top to bottom: 5 cm jig piece, 10 cm jig piece, 15 cm jig piece, 20 cm jig piece.
Figure C2. 20 cm Crimp Jig piece correctly positioned on drilled PEX piece. Notice the bushing assembly firmly pressed onto the PEX, the Crimp Jig firmly butted against the bushing assembly, and the crimp firmly pressed against the Crimp Jig.

The length of each jig piece needed to be determined. The crimps did not have a standard width listed online, so they were measured to be an average of 8.79 mm (.338 in) wide. Therefore, when making the jig pieces, each piece required that half of this measured width be removed from the jig length. Using this information and the desired depths of 5, 10, 15, and 20 cm, the lengths for each jig piece were determined (Table C1). A lathe was used to precisely cut copper pipe to each of these lengths.

Table C1. Required lengths for each Crimp Jig piece.

<table>
<thead>
<tr>
<th>Crimp location</th>
<th>Required length of jig</th>
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<tbody>
<tr>
<td>5 cm</td>
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<tr>
<td>10 cm</td>
<td>9.561 cm</td>
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<tr>
<td>15 cm</td>
<td>14.561 cm</td>
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<tr>
<td>20 cm</td>
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Appendix D - Testing Location Details

Two locations were selected for testing the probes in order to view the repeatability of the sensors’ performance in two different soils.

Criteria for the selection of each plot was defined: each location needed to be in an area that was out of the way of daily operations, away from particularly low topography to avoid pooling water, and needed to have decent drainage. It was also desired to select two areas of differing sand content because of the effect of soil texture on thermal diffusivity. However, due to the selection of available land to install the sensors on, this was not possible. Both testing locations were located in Fayetteville, Arkansas near the University of Arkansas on UARK Agricultural Extension property.

First plot: Farm Plot

The first plot, referred to as the Farm Plot, was located in an open area devoid of trees and tall structures which might block sunlight and alter temperature behavior in the soil (Figure D1). A stream and riparian area with trees and brush was located about 700 feet to the north of the testing location. The fields surrounding this location were used for agricultural purposes, particularly raising stock, during the course of data collection. The surrounding ground was covered with a short layer of grass. A telephone pole was located about 50 feet to the north of the plot and was assumed to have negligible effects on readings due to its northern location. No other obstacles of note were located nearby. It was observed that there was not excess standing water or lack of drainage for a significant time at this location after rain events.

According to the USDA’s Web Soil Survey, the soil in the plot location was likely to be Pickwick silt loam (PsB) (Figure D1) (USDA Web Soil Survey, 2020). This soil was expected to have a composition of approximately 13.7% sand, 69.3% silt, and 17.0% clay, according to the Web Soil Survey’s data. It should be noted that the area of interest was zoomed in beyond the scale that the soil map generated
by the Web Soil Survey was intended to be used. The surrounding soils were mainly silt loams, though some fine sandy loams were located to the north.

Figure D1. Soil map of the area containing the Farm Plot, marked as a red dot, from the USDA’s Web Soil Survey. The plot was expected to have a soil type of Pickwick silt loam, denoted by PsB. (USDA Web Soil Survey, 2020)

A particle size analysis procedure was performed to determine the texture of the soil (see “Selecting field testing locations” section for further information on this procedure), the results of which are shown in Table D1. The experimentally determined texture of the soil differed from the expected texture; the soil texture ended up having a greater quantity of sand and smaller quantity of clay and silt than expected, with a composition of 36.3% sand, 59.6% silt, and 4.1% clay.
Table D1. Expected and experimental sand, silt, and clay percentages for the soil of the Farm Plot, with standard deviation values from the experimental procedure provided for each particle size. The expected percentages were obtained from the Web Soil Survey, and the experimental percentages were obtained with a particle size analysis procedure. Note that the experimental values did not match the expected values: the quantity of sand was much greater than expected, while the quantity of clay was much less than expected.

<table>
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<th></th>
<th>Sand</th>
<th>Silt</th>
<th>Clay</th>
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<td>Expected percentage</td>
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<td>69.3%</td>
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<tr>
<td>Experimentally determined percentage</td>
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<td>Experimental Standard Deviation</td>
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The average bulk density of this plot to a depth of 8 inches (roughly 20 cm) was experimentally determined to be 1.24 g/cm$^3$, with a standard deviation of 0.05 g/cm$^3$ over three iterations. Further, the average bulk density of the plot at a depth of 0-10 cm was determined to be 1.12 g/cm$^3$, while the average bulk density at a depth of 10-20 cm was determined to be 1.36 g/cm$^3$.

Second plot: Workshop Plot

Many locations were considered for the second plot. The first selected plot was initially believed to have a particularly low sand content due to data from the Web Soil Survey; however, after particle size analysis, it was found to have a sand content of approximately 37%. Several plots throughout the available land were tested for sand content and were all found to have approximately 20-33% sand content.

Because of the difficulty in locating available plots with highly differing sand contents that fulfilled our basic plot criteria, and due to time constraints, the second plot was selected as a location
that was easy to access and fit the main criteria of the plots: away from daily operations that may interfere with the plot, not in an area of low topography, and well-draining.

The second plot, referred to as the Workshop Plot, was located in an unused, grassy field (Figure D2). A building was located about 50 feet to the south of the insertion location, and a group of trees was located about 75 feet to the east. It was determined that these structures would not cast shadow onto the plot, and no other obstacles of note were located nearby. This location had adequate drainage which prevented standing water or improper drainage after rain events.

According to the USDA’s Web Soil Survey, the insertion location was likely to be Nixa very gravelly silt loam (NaC), though it was close to the border of two other soils: Pembroke silt loam (PeC2) and Captina silt loam (CaB) (Figure D2) (USDA Web Soil Survey, 2020). This Nixa soil was expected to have a composition of approximately 19% sand, 69.3% silt, and 11.4% clay, according to the Web Soil Survey’s data. It is noted that the area of interest was zoomed in beyond the scale that the soil map generated by the Web Soil Survey was intended to be used. The surrounding soils were all silt loams.
Figure D4. Soil map of the area containing the Workshop Plot, marked as a red dot, from the USDA’s Web Soil Survey. The plot was expected to have a soil type of Nixa very gravelly silt loam, denoted by NaC. (USDA Web Soil Survey, 2020)

A particle size analysis procedure was performed to determine the texture of the soil (see “Selecting field testing locations” section for further information on this procedure), the results of which are shown in Table D2. The experimentally determined texture of the soil differed from the expected texture. The soil texture ended up having a greater quantity of sand and smaller quantity of silt than expected, with a composition of 28.3% sand, 59.6% silt, and 12.0% clay.

The average bulk density of this plot to a depth 20 cm was experimentally determined to be 1.32 g/cm³, with a standard deviation of 0.03 g/cm³ over three iterations. Further, the average bulk density of the plot at a depth of 0-10 cm was determined to be 1.29 g/cm³, while the average bulk density at a depth of 10-20 cm was determined to be 1.35 g/cm³.
Table D2. Expected and experimental sand, silt, and clay percentages for the soil of the Farm Plot, with standard deviation values from the experimental procedure provided for each particle size. The expected percentages were obtained from the Web Soil Survey, and the experimental percentages were obtained with a particle size analysis procedure. Note that the experimental values did not match the expected values: the quantity of sand was much greater than expected.

<table>
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<th></th>
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