

On the Design, Construction and Calibration of Dual-Probe Heat-Pulse Soil Moisture Sensor: Towards an Industrial Solution

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Abstract—There is a need for a multi-functional probe for small-scale measurements of different soil properties measured within identical soil volumes. Dual Probe Heat Pulse (DPHP) sensors are an economical solution for this since they measure simultaneously temperature, volumetric water content, and soil thermal properties: diffusivity and volumetric heat capacity. However, all DPHP sensors to date have very complex manufacturing processes. This paper aims to design and build a DPHP sensor based only on a Printed Circuit Board (PCB) board, which comprises the probes and all supporting electronics leading to a low cost and simple manufacturing process. The proposed system includes signal-processing circuits, a microcontroller, and communicates by a Serial Digital Interface at 1200 baud protocol (SDI-12). The sensor needs a one-time two calibrations: distance from heater to temperature sensor calibration using agar solution; and sensor calibration in soil using Tottori Dune sand. Both calibration processes showed a reasonably good agreement between measured and fitted data. In conclusion, results also show that it is possible to build the multi-functional DPHP sensor in a low cost process, and this was the first time that a multi-functional probe was build using a Printed Circuit Board (PCB) as support.

Keywords—soil moisture sensor; soil thermal properties; dual-probe; heat-pulse sensor; thermal conductivity; thermal sensors.

I. INTRODUCTION

The heat pulse-based soil moisture sensors, of which stand out Dual Probe Heat Pulse (DPHP) sensors, are an economical solution for soil moisture measurements. This paper is an extension of [1] and focuses the construction and calibration of PCB based soil moisture sensor based on the DPHP method.

The DPHP-based sensor has two elements, the heater and the temperature sensor, separated by a short distance, r , as depicted on Figure 1. The heater and the temperature sensor are placed in a physical support, the heater probe and the temperature sensor probe, respectively. A voltage pulse, with finite duration t_0 , is applied to the heater element causing the heat to flow in all directions around the heater element. Heat

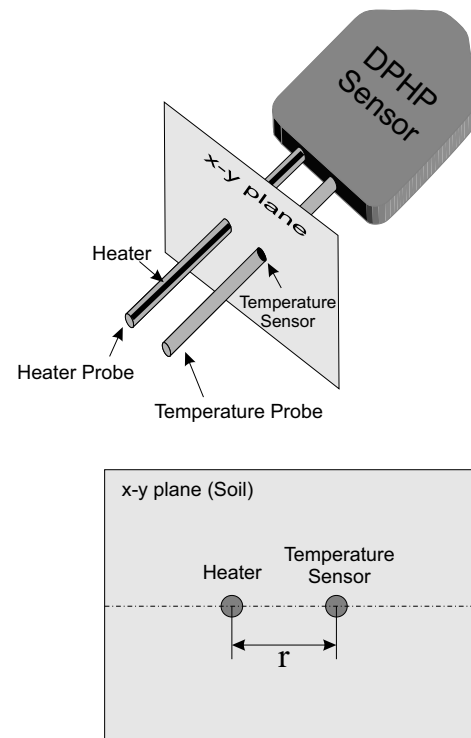


Figure 1. Dual Probe Heat Pulse method.

‘traverses’ the surrounding soil and the temperature rise will be measured by a sensor on the temperature probe.

Most sensors use needles as heating element and temperature sensing element. There are very few cases where the sensor is not directly connected to a data-logger, that is, all the inspection, control and processing is not done in

the sensor itself, but in an external element - the data-logger (which implies, almost always, a dedicated data-logger for each sensor).

The use of needles, and the control, acquisition and processing, external to the sensor, has made this method difficult to use in the field. Therefore, in this work we resolve these shortcomings.

In particular, we make the following contributions:

- Place all the electronics near the probes (heating and temperature probes). This contribution (Section IV), although already achieved by [2], uses only a temperature probe, making the construction of the sensor simpler at the expense of measuring the flow of water in the soil.
- We present a new form of sensor construction which uses the PCB, also used for the rest of electronics, as a support for the temperature and heating probes (Section IV). This is a great achievement as it will enable the industrial production of the sensor at a reduced cost.
- All calculations of the model used (Section III) are performed inside of the on-board microcontroller.
- Two calibration types: calibration of the distance between the heater element and the temperature sensor (for this calibration process it was used agar); and calibration of the sensor using Tottori Dune sand as soil type whose physical characteristics are widely reported [3]–[5]. The results of the calibrations (Section V) showed good results of the model used.

The rest of this paper is organized as follows. Section III describes the models implemented for the calculation of the soil thermal properties and volumetric water content. Section IV details all the fabrication process of the DPHP sensor, calibration method of the distance between heater and temperature sensor, and SDI-12 communication commands implemented. Section V addresses the sensor calibration results and shows sensor prototypes. The acknowledgement and conclusions close the article.

II. RELATED WORK

Since Campbell [6], much research has been done and reported that the heat pulse technique is an economical technique to measure soil thermal properties and soil moisture content [2], [4]–[21]. Although it is an economical method, for several reasons the sensors that use the DPHP method have not yet left the research laboratories.

Some works mention field use, such the work described in [11]. However, the sensors developed were prepared for use in the laboratory and were subsequently used in the field. This solution leads to some problems such as accidental and continuous heating of the dual-probe heat-pulse sensors during a field test, causing the heater element resistance to be damaged, as reported in [11].

As mentioned, in almost all developed sensors [2], [4]–[16] uses needles as housings for the heat source and the temperature sensor. Normally, the heating probe is composed of a needle where a conductive wire (with a high resistivity, suitable for producing resistances for heating - 0.062 mm Evanohm enameled wire) is inserted inside. A single very fine

wire is threaded into the needle four times creating two turns. The heater wire was spliced onto copper leads to form the connections to the resistance forming the heater element.

The probe with the temperature sensor is elaborated in the same way, by inserting inside the needle and the longitudinally centering the temperature sensor (thermocouple or thermistor). Both needles are then filled with an epoxy glue of high thermal conductivity and low electrical conductivity. Therefore, the use of this process is laborious and difficult, if not impossible, for industrialization.

Other authors have attempted, without known success, to develop soil moisture sensors based on the heat pulse without the use of needles. In this group, there are the works of [17]–[19], [21] who developed microelectronics to try to improve the manufacturing process and in other works a button-shaped sensor was developed [16], [20]. The button-shaped sensor also use the same kind of wire (very thin) and in one of the works [16] a needle is used which is folded into a ring type shape. This needle, which is the heater element, uses the same assembly method described above.

Most of the work done with DPHP sensors uses data-loggers to acquire data from temperature probe, to control heat pulse duration and to perform calculations. A recent work [2] that presents a novel design of a multifunctional penta-needle thermo-dielectric sensor with advantage for in-situ and simultaneous determination of water content (θ_v), thermal conductivity (λ), and thermal diffusivity (κ) in porous media, overcomes this problem but still uses needle type probes.

In conclusion, of all the literature consulted, no sensor was found based on the heat pulse method that uses the supporting PCB for the reading, control and communication electronics, as well as support of the elements heater and temperature sensor. This fact allows us to think that this is the first time that this process is used, being a good basis for industrial production of this type of sensors.

III. THEORY

There are some models to describe the operation of sensors based on the DPHP method. The simpler model, described by Campbell [6], considers that the heat source is an infinite line and the heat pulse is released instantaneously. Other models [7] increase the constraints of the model of Campbell, considering that the heat pulse is finite, that the source line is finite and, finally, that it is not a source line, but a cylinder. Of these models the most common is the model which considers the finite heat pulse generated by an infinite source line [7]. In the present work, this will be the adopted model due to its precision and relative ease implementation in a microcontroller-based system. The solution for conducting radial heat from a short-duration, t_0 , heat pulse away from an infinite source line, for $t > t_0$ is

$$\Delta T(r, T) = \frac{q'}{4\pi\kappa\rho c} \left[E_i \left(\frac{-r^2}{4\kappa(t-t_0)} \right) - E_i \left(\frac{-r^2}{4\kappa t} \right) \right] \quad (1)$$

where, ΔT is change in temperature ($^{\circ}C$), r is radial distance from the line source (m), t is time (s), q' is the energy input

per unit length of heater per unit time (W m^{-1}), ρc is the volumetric heat capacity ($\text{J m}^{-3} \text{ }^\circ\text{C}^{-1}$), κ is the thermal diffusivity ($\text{m}^2 \text{ s}^{-1}$) of the medium surrounding the heater, and $-\text{Ei}(-x)$ is the exponential integral [22]. The thermal diffusivity (κ) and volumetric heat capacity (ρc) can be determined from heat-pulse measurements using the single-point method [8], or a nonlinear curve fitting where (1) is fitted to measured $\Delta T(r, t)$ data [10]. It was showed that accuracy in ρc will be limited by the accuracy of r , and accuracy in κ will be limited by the accuracy of both r and time of maximum temperature change, t_M [8]. The single-point method makes use of the fact that the temperature response at some distance r from the heater displays a maximum, so that we can take the derivative of (1) with respect to time, set the result equal to zero, and obtain the time, t_M , to the maximum temperature change (ΔT_M). This yields an expression for estimating κ where

$$\kappa = \frac{r^2}{4} \left[\frac{\frac{1}{(t_M - t_0)} - \frac{1}{t_M}}{\ln \left(\frac{t_M}{t_M - t_0} \right)} \right] \quad (2)$$

which is a function of r , t_M and t_0 . Rearrangement of (1) yields an expression for estimating ρc , for $t > t_0$,

$$\rho c = \frac{q'}{4\pi\kappa\Delta T_M} \left[\text{Ei} \left(\frac{-r^2}{4\kappa(t_M - t_0)} \right) - \text{Ei} \left(\frac{-r^2}{4\kappa t_M} \right) \right] \quad (3)$$

where κ is obtained from (2). To minimize errors, the single-point method requires an accurate measurement of r and times t_M and t_0 . For ρc estimation, in addition to κ from (2) and r , are needed accurate measurements of q' and ΔT_M . Volumetric heat capacity ρc of soil can be determined as the sum of the heat capacities of the individual constituents and considering that the air is ignored and solids defined to include the mineral and organic matter fractions then soil water content θ_v can be defined as a function of volumetric heat capacity [23],

$$\theta_v = \frac{\rho c - \rho_b c_s}{(\rho c)_w} \quad (4)$$

where ρ is density, c specific heat, θ_v volumetric water content, and the subscripts b, s and w indicates bulk, average properties of the solids (minerals+organic matter), and water, respectively. Since $(\rho c)_w$ is known, measurements of ρc obtained with the sensor can be used together with estimates (or preferably measurements) of soil bulk density (ρ_b) and specific heat (ρ_s) to obtain θ_v .

IV. MATERIALS AND METHODS

The developed sensor is a complete solution and this approach, together with the non-use of needles for the heating and temperature probes, is new. Next, all details of the sensor construction, as well as its firmware, the communication protocol and as referred to in the previous section the knowledge of the true value of r (r_{eff}) through calibration in agar, will be explained in detail.

A. Sensor System Description

In Figure 2 is depicted the electronic layout of the sensor system, the core unit is on-board 16 bit microcontroller (PIC24F32KA301) with very low power consumption, 12-channel 12 bit Analog-to-Digital Converter (ADC), serial communications modules (UART - Universal Asynchronous Receiver-Transmitter, SPI - Serial Peripheral Interface, and I²C - Inter-Integrated Circuit), and hardware Real-Time Clock (RTC) Calendar with alarms. The temperature sensor probe consists of a 10 k Ω (NCP15XH103F03RC) thermistor, a precision (0.1%) voltage reference of 2.048 V (LM4128) and a 24 bit ADC (MCP3421). The heating probe consists of a series of 15 resistors of 1 Ω , controlled by an electronic switch composed of transistors. The system power is from the SDI-12 power (6 V to 12 V) that feeds a dual DC regulator: 2 V to 5 V for powering the heat pulse (LM1117), and 3.3 V for the rest of the system (MIC5219). The voltage control of the first DC-DC converter is achieved with a pulse (Pulse With Modulation - PWM pulse) controlled by the microcontroller.

The microcontroller controls the heat pulse through the transistors switch to enable/disable the power to the heater. To determine accurately the value of q' (heat input per unit length per unit time), average current through the heater was determined by sampling the voltage across a 0.18 Ω resistor (1%) in series with the heater 15 Ω resistor ($15 \times 1 \Omega$), and the voltage across resistance series of the heater and current measure resistor. The value q' is determined by

$$q' = V_{\text{heater}} \times I_{\text{heater}} \times \frac{1}{l_{\text{heater}}} \quad (5)$$

where V_{heater} is the measured voltage across the heater, I_{heater} is the current through the heater given by $I_{\text{heater}} = V_{R=0.18}/0.18 \Omega$ ($V_{R=0.18}$ is the measured voltage across the 0.18 Ω resistor), and l_{heater} is the length of the heater (0.0353 m). All voltages measured for q' calculations, are performed by microcontroller internal ADC (12 bit). Temperature from the temperature probe was measured by sampling the voltage drop across the thermistor in series with a 10 k Ω (0.1%) resistor. This was done on the 24 bit ADC to ensure sufficient sampling accuracy for determining temperature.

B. Sensor Construction

The prototype of the developed sensor, as shown in Figure 3, is based on the printed circuit board (PCB) as substrate. In the PCB are welded all the components necessary for the operation of the sensor. The design of the PCB was made in the form of a fork with two 'rods' that form the

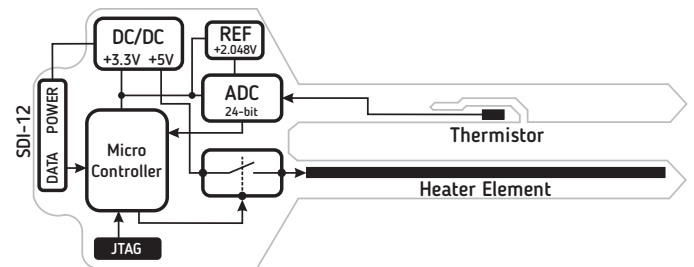


Figure 2. Sensor overview

heating probe and the temperature probe. The thermistor in the temperature probe is placed in a thermally insulated tab. The distance between these two elements were designed to be 6×10^{-3} m. However, this distance has to be calibrated because as previously described an error in this parameter contributed significantly to the error in the determination of κ and ρ_c [9].

The process of mounting the sensor is as follows:

- Manufacture of PCB board;
- Assembly of all electric components, except for the first resistance of the heating element due to the mold;
- Sealing, using a mold as depicted on Figure 4, with thermoplastic molding resin to achieve high quality sealing and protection of components of the main circuit. Overtec 820 15 Hotmelt Glue Gun, from Techsil Limited, UK, was used with the respective polyamide resin OverTec 5 FR;
- Missing resistor placement;
- Placement of an epoxy adhesive in the heating element (in all resistors forming it) and in the thermistor.

As can be seen from the description of the process used for the elaboration of the prototype, it can be turned into an industrial process.

C. Firmware

The developed firmware, after all the initialization, enters into sleep mode waiting for a SDI-12 command. After a aM! command the firmware will perform a complete measurement as presented on Figure 5.

For the implementation of the exponential integral in (3) in order to obtain the ρ_c value, the Chebyshev approximations for the Exponential Integral $E_i(x)$ were used [24]. The implementation was elaborated in C and can be executed in the microcontroller used (16 bit with 32 kB of program memory and 2 kB of SRAM).

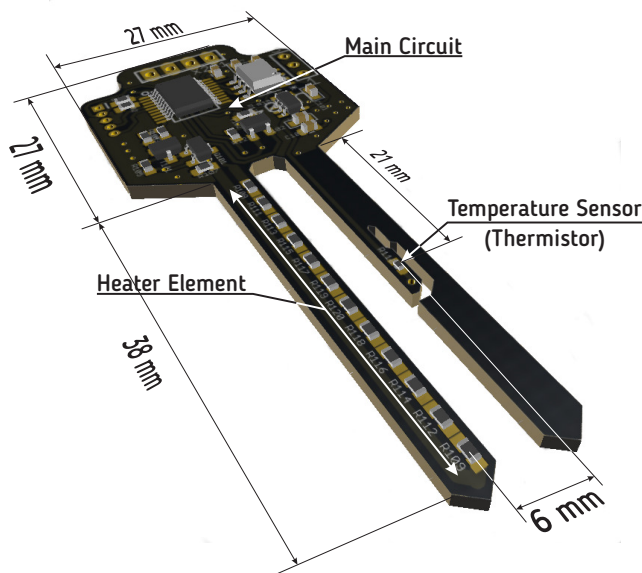


Figure 3. Sensor 3D view.

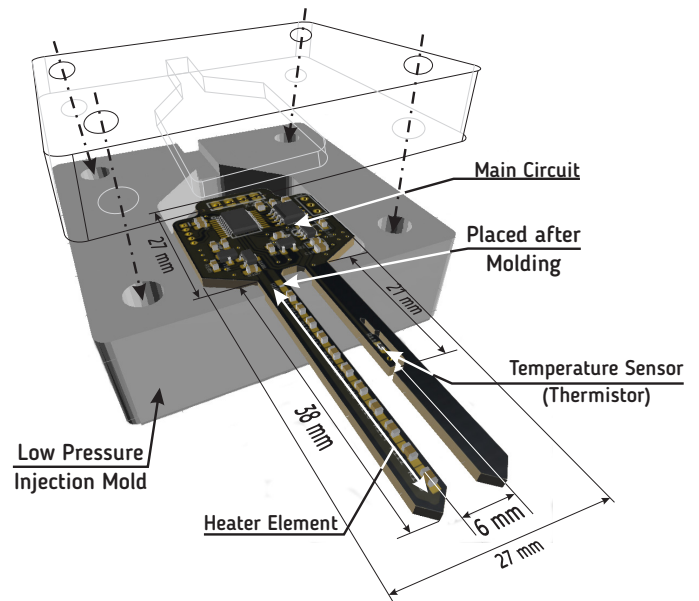


Figure 4. 3D view of the construction details.

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1: repeat      ▷ Read soil temperature before applying heat
2:   StartTemperature ← temperature
3: until time < 12 s
4: HeatPulse ON (5 V)
5: repeat      ▷ Read heat power
6:   HeatVoltage ← voltage
7:   HeatCurrent ← current
8: until time < 8 s
9: HeatPulse OFF
10: Calculate q' using (5)
11: repeat      ▷ Read Temperature Increase
12:           ▷ (3 samples/second)
13:    $\Delta T$  ← temperature – StartTemperature
14:   DetectMaxTemperature ( $\Delta T_M$ , t_M)
15: until time < 120 s
16: Calculate  $\kappa$  using (2)
17: Calculate  $\rho_c$  using (3)
18: Calculate  $\theta_v$  using (4)
19: Enter SLEEP mode (760 s)

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Figure 5. Firmware algorithm

The presented values for the heater voltage (5 V), the heating duration (8 s) and the time allowed for the next measurement are the defaults. These values can be change as described next.

D. Digital Communications

The sensor uses SDI-12 protocol for digital communication of sensor data and change sensor parameters. SDI-12 is a standard to interface battery powered data recorders with micro-processor based sensors designed for environmental data acquisition. All SDI-12 communications are transmitted using American Standard Code for Information Interchange (ASCII) at 1200 baud with 7 data bits and an even parity bit. The standard also specifies a communications protocol that allows sensors to remain in a low-power sleep state until awoken by

TABLE I. SDI-12 SENSOR COMMANDS

Command	Description	Command	Description
?!	Return address of the sensor	a!	Return sensor identification
aAb!	Change actual address to new 'b' address	aXGQ!	Return heating power, q' , value
aM!	Start all measurements	aXGV!	Return heater applied voltage
aM1!	Start soil temperature measurement	aXSVn.n!	Assign heater voltage (from 2.0 to 5.0 V)
aD0!	Read measurements data	aXGT!	Return maximum temperature rise, ΔT_M
aHB!	Raw data of temperature curve	aXGH!	Return heat duration, t_0
aXGP1!	Return soil volumetric water content, θ_v	aXGI!	Return heater current
aXGP2!	Return soil thermal diffusivity, κ	aXGR!	Return spacing, r , value
aXGP3!	Return soil volumetric heat capacity ρc	aXSRn.nnn!	Assign new spacing value (from 5.500 to 6.500 mm)
aXGB!	Return soil bulk density, ρ_b	aXSHn!	Change heat duration (from 6 to 30 s)
aXSBm.nn!	Set soil bulk density (from 0.90 to 2.00 10^3 kg m^{-3})		

a serial break signal sent by the master. The first character of each command is a unique sensor address, a , that specifies with which sensor the recorder wants to communicate.

Table I lists all the commands that the sensor will respond to. In addition to the standard commands it was necessary to implement a set of extended commands (with an X after the address) in order to configure the sensor and obtain individual readings of some parameters. These extended commands use letter G after the X to get extra data from the sensor (heater voltage, heating power, heater current, spacing between heater and temperature sensor, maximum temperature rise, time of the maximum temperature rise, soil bulk density, and individual sensor parameters readings: soil volumetric water content, soil thermal diffusivity, and volumetric heat capacity), and a letter S to set new values for heater applied voltage and heat duration, to new spacing value, and to set new bulk density.

Access to metadata is also available as presented in version 1.4 of the SDI-12 specification [25]. For calibration and whenever necessary, the raw values (16 bit unsigned floating point format) of the temperature curve can be requested using the High Volume Binary Command (aHB!).

E. Probe Distance Calibration

The measurement of κ and ρc are highly sensitive to effective separation distances, r , between the heater element on heater probe and the thermistor on temperature sensor probe [9]. Thus, calibration of this distance was crucial for accurate measurements. The calibration was performed by inserting the sensor in a gel that was made from a $4 \times 10^{-3} \text{ kg L}^{-1}$ agar solution, Figure 6. The agar has equal thermal properties as water, yet does not create heat convection as would occur by heating liquid water [6].

The measured temperature response in agar solution was used to calibrate the sensor separation distance for each thermistor by fitting the measured temperature change to (1) using known values of volumetric heat capacity ($4174 \text{ kJ m}^{-3} \text{ K}$) and thermal diffusivity ($1.436 \times 10^7 \text{ m}^2 \text{ s}^{-1}$) of water, as showed on Table II.

TABLE II. THERMAL PROPERTIES OF WATER AT 20 °C.

Physical Parameter	Value
ρ_w (kg m^3)	998.2
c_w ($\text{J kg}^{-1} \text{ K}^{-1}$)	4181.6
C_w ($\text{kJ m}^3 \text{ K}^{-1}$)	4174
κ_w ($\text{m}^2 \text{ s}^{-1}$)	1.4×10^{-7}

F. Sensor Calibration

In this study, the developed soil moisture sensor has calibrated in laboratory conditions with a constant temperature of 20 °C using Tottori Dune sand because it allows for rapid saturation and drainage across a wide water content range. Physical properties are listed in Table III. In this study the method used for water content determination was the gravimetric method. The mass of water present in the sample is given



Figure 6. Probe distance calibration in agar solution



Figure 7. Sensor calibration with Tottori sand.

by the difference in mass between the wet and dry sample.

Water content by mass is defined as the mass of water divided by the mass of dry soil. The conversion into volumetric equivalent can be done by multiplying the gravimetric water content by the dry bulk density of the sample (ρ_s), with a knowledge of water density (ρ_w). The volumetric water content was calculated using

$$\theta = \frac{m_w - m_d}{m_d} \rho_b \quad (6)$$

where ρ_b (kg L^{-3}) is the dry bulk density to which the material is packed, and m_w (kg) and m_d (kg) are the wet and dry soil.

TABLE III. PHYSICAL PROPERTIES OF TOTTORI DUNE SAND. AFTER [4]

Physical Parameter	Value
ρ_b (kg m^{-3})	1630
c_s ($\text{J kg}^{-1} \text{K}^{-1}$)	795.0

The soil, Tottori Dune sand, is oven dried (105°C) for 24 hours in order to get the *dry soil*. Then, soil was packed uniformly into a plastic container and was weighted ($m_d=0.600$ kg) and a measure was taken (dry soil measurement, $\theta_v=0.00 \text{ m}^3 \text{ m}^{-3}$), as shown in Figure 7. After that, water is applied until saturation was achieved (weight of the wet soil was 0.732 kg). For this type of soil, saturation was achieved with $\theta_v = 0.36 \text{ m}^3 \text{ m}^{-3}$ using (6) and data from Table III. With the soil sample at saturation a measurement was made, followed by three more measurements as the soil sample was drying in the air.

The values of sample weight, soil gravimetric water content (θ_G), and soil volumetric water content (θ_v) are summarized on Table IV.

TABLE IV. SOIL WEIGHT VALUES AND CALCULATED VOLUMETRIC WATER CONTENT

Soil Weight (kg)	θ_G (kg kg^{-1})	θ_v ($\text{m}^3 \text{ m}^{-3}$)
0.600	0.000	0.000
0.630	0.050	0.082
0.650	0.083	0.136
0.700	0.167	0.273
0.732	0.220	0.359

V. RESULTS AND DISCUSSION

Since this work is only about a description of the design and the construction of the sensor, only the results about the sensor assembly and the calibration of the distance between the probes will be discussed.

A. Printed Circuit Board

The developed Printed Circuit Board (PCB) is shown in Figure 8. In order to optimize the space provided by the supplier (Seeed Studio, China) that is $100 \text{ mm} \times 100 \text{ mm}$, it was possible to place three sensors with mechanical joints that after welding all components will be cut. This process also reduces costs by 1/3 of PCB production, with the production of 30 PCB for about 15 €.

B. Assembled Sensor

Figure 9 shows the assembled sensor without the thermo-plastic molding resin and the final version of the sensor. The sensor is small in size, compact, robust and easy to use. The final product is comparable to commercial versions of other soil moisture sensors using other measuring methods, such as the EC-5, 5TE and 5TM probes from Decagon Devices Inc., USA.

This type of sensor (DHP sensor) compares with capacitive type of sensor in terms of accuracy ($\pm 3\%$ [26]), and is very different from very low-cost resistive sensor. Resistive sensors give only qualitative estimation of the moisture content [26].

C. Probe Distance Calibration

The probe distance calibration was determined by obtaining five sensor readings in agar solution with an interval of 1 h between readings and with heating power of $q' = 51.65 \text{ W m}^{-1}$. Figure 10 presents the measured temperature response as a function of measurement time of one of these readings. The measured temperature data was fitted using the non-linear least-squares Marquardt-Levenberg algorithm. There is a good agreement between measured and fitted data. The fitted values of effective separation distance, r_{eff} , for all 5 readings are presented in Table V. The average value of r_{eff} is $5.534 \times 10^{-3} \text{ m}$. The differences between the designed PCB layout value ($6 \times 10^{-3} \text{ m}$) and effective distances are likely caused by unprecise placement of the components (heater and/or thermistor) because they are hand welded. In an industrial process this error could be minimized and lead to two kinds of sensors: agar calibrated and uncalibrated lowering the costs.

It can also be observed in Figure 10 that, compared to other works [4], [8], [27], just to mention a few, which uses

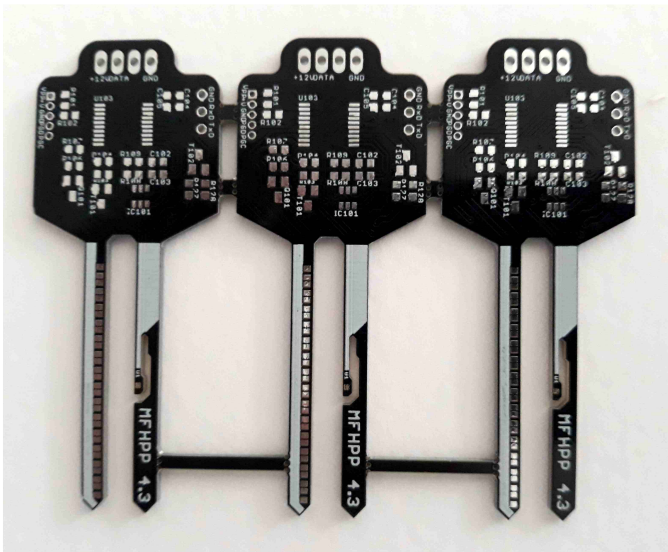


Figure 8. Developed Printed Circuit Board

data-logger for reading and control of the DPHP sensor, this prototype presents a better resolution (18 bit against 13 bit of most data-loggers) and a better sampling rate (1 sample/s against 3 samples/s). This will give a better precision on calculating ΔT_M and t_M . We can also observe a good signal to noise ratio ($\Delta T_M = 0.3728^\circ\text{C}$ for a value of 100% of θ_v , agar \Rightarrow water) even for a lower heat power (51.65 W m^{-1} against 60 W m^{-1} - minimum found in literature [8]). This low power (could be less and adjusted depending on θ_v values - lower values less power) is very important in order to use the sensor in wireless systems (Internet of Things - IoT).

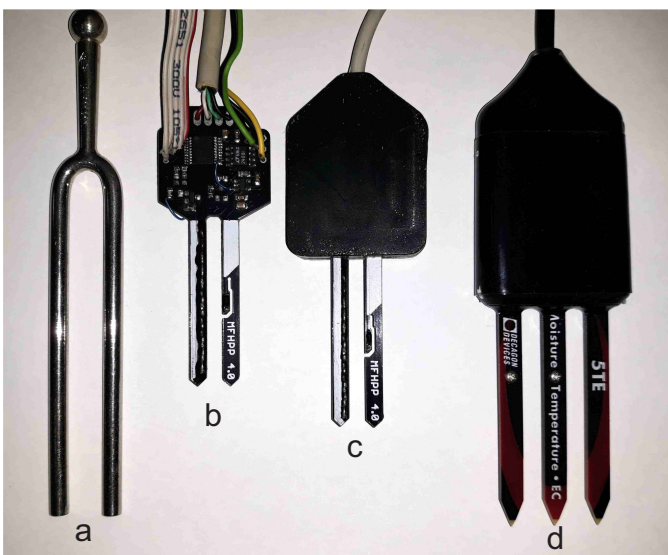


Figure 9. Developed prototypes of the DPHP sensor. a) Diapason; b) Prototype for debug without protective resin; c) Final prototype with protective resin; d) Decagon STE.

TABLE V. CALIBRATION OF THE EFFECTIVE SPACING, τ_{eff}

Sensor Readings	r (m)	τ_{eff} (m)
#1	0.006	0.005566
#2		0.005522
#3		0.005521
#4		0.005512
#5		0.005551
Average		0.005534

D. Sensor Calibration

For sensor calibration the sensor was connected to an Arduino development board according to the wiring diagram of Figure 11. The SDI-12 listed commands from Table I can be sent through the serial port (USB) and the Arduino software (using the Arduino library for SDI-12 communications [28]) is responsible for converting to the SDI-12 protocol for the sensor.

The calibration of the sensor was done according to the method described in Section IV-F. When the values indicated on the scale were in accordance with the desired values, three sensor readings were taken with half an hour interval between

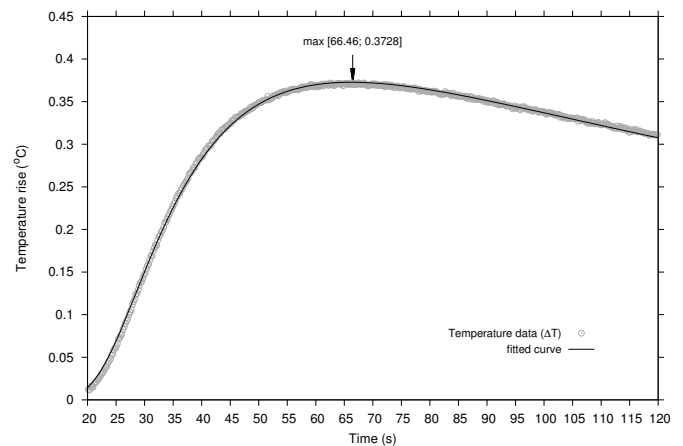


Figure 10. Measured temperature rise after the heat pulse in agar solution compared to the analytic modeled data (solid line).

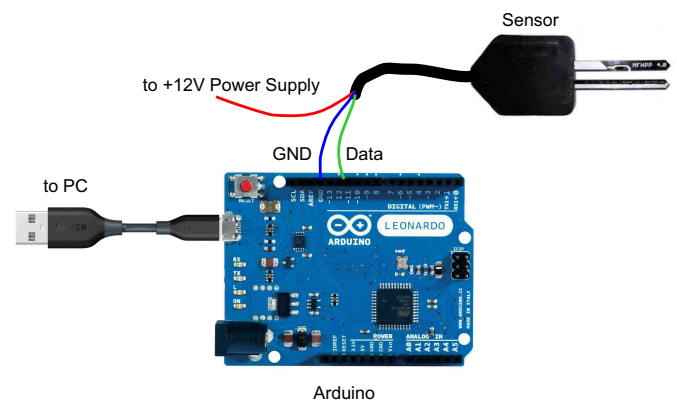


Figure 11. Sensor to Arduino connections for SDI-12 protocol conversion.

TABLE VI. OBTAINED AND CALCULATED VALUES FROM FIRMWARE IN THE SENSOR

θ_v from calibration ($\text{m}^3 \text{m}^{-3}$)	Obtained Values		Calculated Values		
	ΔT_M ($^{\circ}\text{C}$)	t_M (s)	κ ($\text{m}^2 \text{s}^{-1}$)	ρc ($\text{J m}^{-3} ^{\circ}\text{C}^{-1}$)	θ_v from sensor ($\text{m}^3 \text{m}^{-3}$)
0.000	1.130410			1.3150	0.0042
0.082	0.908076			1.6370	0.0816
0.136	0.788853	17.8317	6.8981	1.8844	0.1396
0.265	0.613252			2.4239	0.2684
0.359	0.525757			2.8273	0.3668

each one. Readings are made by sending the command 0M! followed by the command 0XGP2!, sent after the time indicated in the response to the command 0M1 (130 s).

The results obtained for the five calibration points presented in Table IV, are represented in Figure 12.

As can be seen, for the Tottori Dune sand measurement range ($0 \text{ m}^3 \text{m}^{-3}$ to $36 \text{ m}^3 \text{m}^{-3}$), the temperature rise value is only $0.65 ^{\circ}\text{C}$. In order to obtain, in comparative terms, a precision close to commercial capacity-based sensors (3%), the accuracy of the temperature reading should be better than $0.05 ^{\circ}\text{C}$ which is the accuracy achieved by the developed sensor.

During the acquisition of temperature, and according to the algorithm presented in Figure 5, the maximum value of the temperature rise, ΔT_M , and the time at which this maximum happens, t_M , were obtained from temperature reads and microcontroller timer. With these values and using the equations (2), (3) and (4), the values presented in Table VI

were calculated o microcontroller firmware.

It is important to note that the values of t_M , and consequently the value of κ (by (2)), can be verified that κ is only dependent on t_M since t_0 , the time of the heat pulse, and r , the distance between the heater element and sensor are constant and this last was subjected to a calibration process to minimize errors) are constant for the same type of soil. In this way, the firmware obtains the t_M value through a sliding average.

To verify the accuracy of the water content measurements, Figure 13 compares the results of water content from the sensor and calibration samples obtained with the method explained on Section IV-F. It is possible verify that the values for the sensor tted a linear relationship with $R^2 = 0.9995$ and $RMSE = 0.003 \text{ m}^3 \text{m}^{-3}$ over the entire range of θ_v from dry to saturation. With the mention two-step calibration the developed sensor achieved high-accuracy water content measurements.

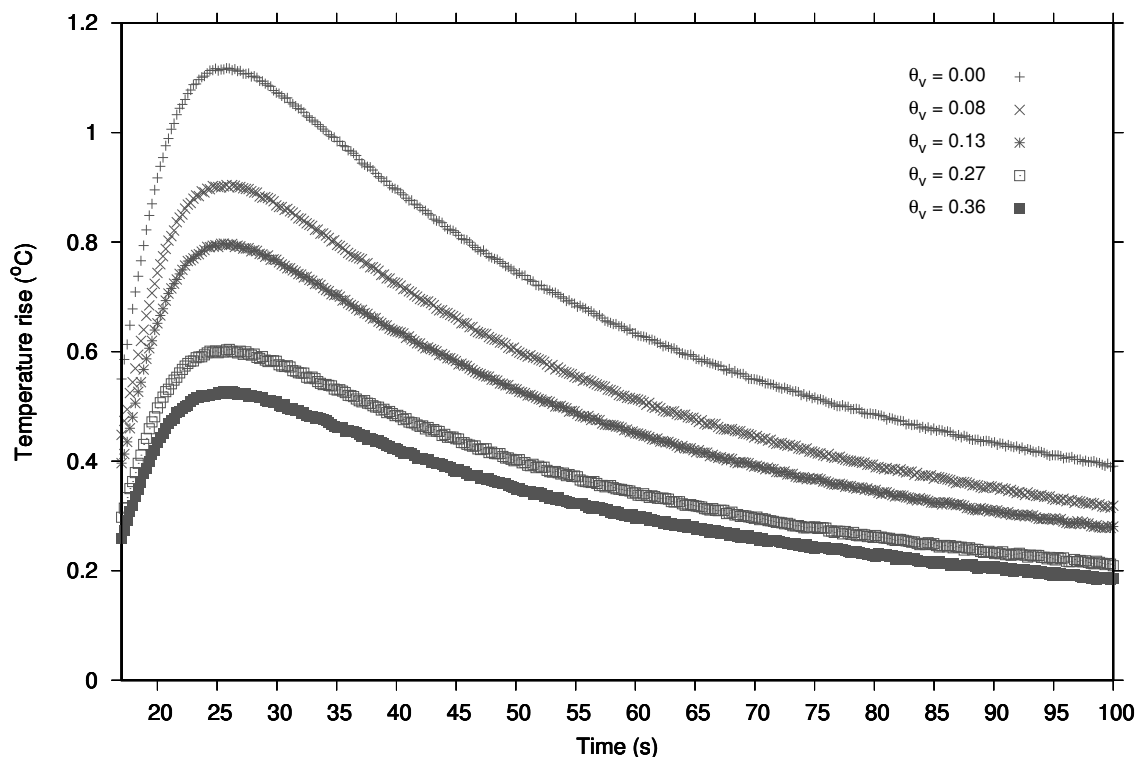


Figure 12. Measured temperature rise after the heat pulse in Tottori sand for five moisture contents.

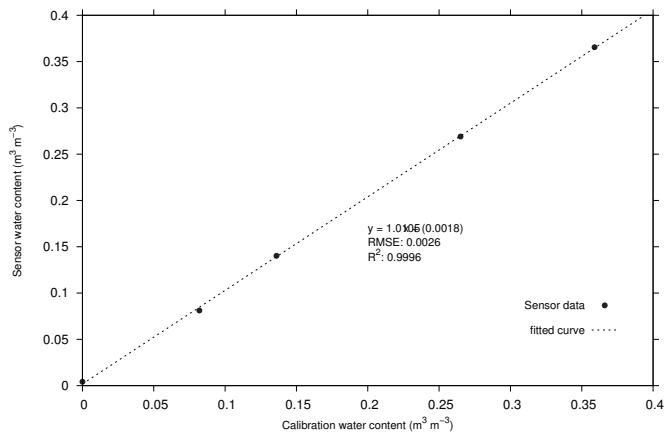


Figure 13. Comparison of volumetric water content measured by the sensor and the calibration water content.

VI. CONCLUSION AND FUTURE WORK

This paper presents a novel design and an industrial process to build a DPHP sensor based on PCB board as substrate. The process is based on four steps and two-step calibration process: in agar for probe distance determination, and using Tottori Dune sand for sensor validation. The prediction accuracy of soil volumetric water content, θ_v , by the developed sensor was validated as $0.003 \text{ m}^3 \text{ m}^{-3}$ for Tottoti Dune sand with θ_v varying from dry to saturation.

Results also show that it is possible to build the multi-functional DPHP sensor in a low cost industrial process (PCB and assembly). This was the first time that a soil moisture sensor, based on heat-pulse method, was build using a PCB as support. Further work must be done to find out the sensor accuracy, test sensor readings variations with soil type, and perform in-field and long-term stability tests.

Future work must needed to study the thermal properties determined under various thermal conditions to find any impact of the ambient temperature on the performance of the sensor. Also, the use of several sensors connected on the same datalogger must be evaluated on power consumption and communications stability.

The authors are producing about 48 sensors for use in the field and connected through SDI-12 to two data loggers with battery and solar support. The results of this study will be published in future work.

In addition, as the sensor has a PCB as substrate, pads can be placed to measure soil moisture using the capacitive method and to measure soil Electrical Conductivity (EC). This process may lead to a system with sensory fusion. The capacitive method, with lower energy consumption, would be the main method to be used and once or twice a day an acquisition by the heat pulse method would be made. By using, for example, a complementary filter, sensory fusion would be performed. In this way, it could have a precise sensor, of low cost and with less energy consumption.

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