A MULTI-CHIP-MODULE MICRO-SYSTEM FOR SOIL MOISTURE MEASUREMENTS

António Valente[1], avalente@utad.pt – Raul Morais[1] – José Boaventura Cunha[1] – José Higino Correia[2] – Carlos Couto[2]
[1]UTAD - Universidade de Trás-os-Montes e Alto Douro, Vila Real, Portugal
[1]CETAV – Centro de Estudos e de Tecnologias do Ambiente e Vida, Vila Real, Portugal
[2]UM – Universidade do Minho, Guimarães, Portugal

This study presents a Multi-Chip-Module-based (MCM) micro-system suited for irrigation control and management applications. The micro-system includes the soil moisture sensor and an analogue-to-digital converter with signal processing circuitry. The same basic fabrication concepts and materials which made microelectronics successful are now being adapted to making low-cost, small, and high-performance sensor systems with integrated electronics on the same micro-system. Since this sensor has low-cost fabrication for mass production, a network could be implemented in order to achieve an accurate measurement of the soil moisture at the plant root level. A dual-probe heat-pulse technique is used (measurement of the maximum temperature rise at some distance from the heater, after applying a heat-pulse) to determine the volumetric heat capacity and, hence, the water content of the soil. The sensor module is about 30 mm long, 6 mm wide, and 0.8 mm in height; the probe pitch is 3 mm allowing small-scale spatial measurements of soil moisture, which can be made near the soil surface where large root densities are found. The heater uses a nickel-chrome resistor for resistive heating (thermo resistive effect – Joule heat). The temperature sensors (probe and reference) are high-accuracy CMOS smart temperature sensors.

Keywords: Precision agriculture, soil moisture sensor, irrigation control.

1. Introduction

The developers of irrigation systems are under increasing pressure to manage water more prudently and more efficiently. This pressure is driven by product quality requirements, economic factors, demands on labor and the desire to minimize the resource degradation and yield loss that can result from inefficient irrigation. For Charlesworth (2000), the need for farmers to irrigate more efficiently has led to an explosion in the range of equipment available for measuring soil water status.

Today, a large number of sensors, based on different methods: nuclear, electromagnetic, tensiometric and capacitance, are available for measuring soil moisture.

Generally, these methods have several limitations that restrict their integration in irrigation systems. Among others, the main disadvantages are: soil dependency, inaccuracy and high cost.

Time domain reflectometer (TDR) sensors, which are based on the influence of soil water content over the propagation of electromagnetic waves, are independent of soil texture, temperature and salt content, but its high cost restricts the applicability to these systems (Topp et. al., 1980, Topp and Davis, 1985). Therefore, the development of a low-cost miniaturized system with electronics, network solution, and external communications that could be implemented next to the plant roots will be a breakthrough.

The same basic fabrication concepts and materials, which have made microelectronics successful, are now being adapted to making low-cost, small, high-performance sensor systems devices, e.g. a MCM soil moisture sensor. The dual-probe heat-pulse (DPHP) sensor is about 30 mm long × 6 mm wide × 0.8 mm in height; the probe pitch is 3 mm for allowing small-scale spatial measurements of θ_v, which can be made near the soil surface where large root densities are found.

2. Theory

The heat capacity of soil, ρc_p, is evaluated by adding the volumetric heat capacities of the soil constituents:

$$\rho c_p = 1.92 X_m + 2.51 X_o + 4.18 \theta_v \tag{1}$$

where X_m, X_o, and θ_v are the mineral, organic, and water fractions of the soil, respectively. The leading coefficients represent the volumetric heat capacity (MJm^{-3}°C^{-1}) of each soil constituent. When a pulse of heat is applied during a fixed interval of time to the heater probe, the maximum rise in temperature (ΔT_m) at some distance from the heater is measured. As mentioned by Campbell et al. (1991), the relationship between the ρc_p and ΔT_m is,

$$\rho c_p = \frac{q}{e \pi r^2 \Delta T_m} \tag{2}$$

where q (Jm^{-1}) is the heat applied per unit length of the heater, e is the base of natural logarithms, and r (m) is the distance between the heat and temperature probes. The use of this model requires the assumptions: (i) that the finite heater is closed to an infinitely long heater,

(ii) that the cylindrical heater approximated a line source of heat, and (iii) that the short-duration heating approximated an instantaneous release of heat. Providing that (i) the ratio of heater half-length to temperature probe spacing is greater than to 2.5, we could assume (0.14 % error) that the probe heater is infinite. In addition, (ii) the ratio of heater radius to temperature probe spacing is less than 0.06, and (iii) the heating duration is less than 8 s, Kluintenberg et al. (1993) shows that the errors are minimized and sustains the use of Campbell model, Eq. (2), as a model for determining heat capacity. Substituting Eq. (1) into Eq. (2) and rearranging yields an expression that shows the relationship between θ_v and ΔT_m,

$$\Delta T_m = \frac{q}{e\pi r^2\left(1.92X_m + 2.50X_o + 4.18\theta_v\right)} \tag{3}$$

or,

$$\theta_v = \frac{\dfrac{q}{e\pi r^2 \Delta T_m} - (1.92X_m + 2.50X_o)}{4.18} \tag{4}$$

Although ΔT_m varies with ρc_p and θ_v, q can be selected to produce an adequate temperature signal for the expected range of θ_v for a typical agricultural soil (0.05 to 0.35 m^3m^{-3}). Sensitivity of ΔT_m decreases as less energy is applied to the probe (q), so the use of less supply will imply the need to use an A/D converter with more resolution to maintain accuracy. Previous studies show that a minimum of 0.5°C for ΔT_m is a good choice (Bilskie, 1994).

3. Implementation

The micro-system consists of two needle probes mounted in parallel to provide a heater and a sensor probe, Figure 1, as reported by Tarara and Ham (1997) and Song *et. al.* (1998). The needles were made from stainless steel tubing, 0.912 mm in diameter, which protrude 20 mm beyond the edge of the acrylic mounting. Spacing is 3 mm between the heater and the sensor probe.

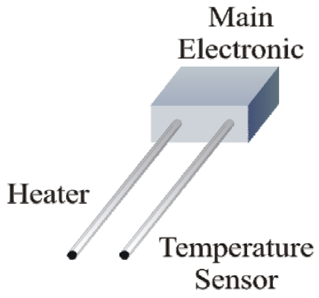

Figure 1. Sketch of the soil moisture micro-system

The heater was made from nickel-chrome deposited in a ceramic substrate and placed in the middle of ‘heater’ needle. The heater resistance is about 100 Ω. A high-accuracy CMOS temperature sensor with amplifier is placed in the center of the ‘temperature sensor’ needle. The needles were then filled with high-thermal-conductivity epoxy glue to provide water-resistant, electrically insulated probes. The Figure 2 shows the placement of the heater and temperature probes.

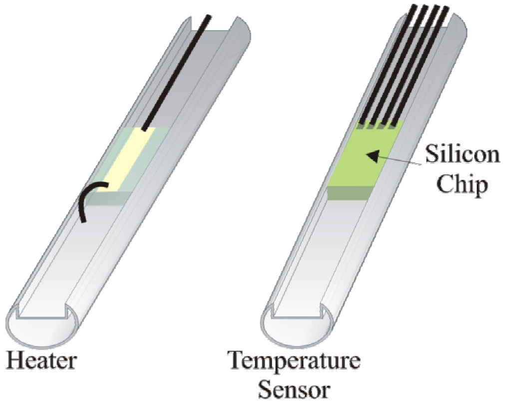

Figure 2. Heater and temperature sensor detail.

The heat pulse was generated by applying voltage (5V) from a direct current supply to the heater for a fixed period (8 s). This gave a nominal value for q of 600 Jm^{-1} [$(5\ V/100\ \Omega)^2 \cdot 30\times10^3\ \Omega m^{-1} \cdot 8\ s$]. A 14-bit Σ-Δ analogue-to-digital converter and radio-frequency transmitter form the main electronic circuitry.

In order to measure both temperatures, a 2nd order switched-capacitor Σ-Δ converter with an over-sampling ratio of 512 and sampling frequency of about 423 kHz was employed. The output bit stream is then converted to a 14-bit word by using a counter as a simple decimation filter. Data is then stored in a FIFO memory and later transmitted to a central collection system. The control logic is responsible for generating all clock signals for the Σ-Δ converter, FIFO and for keying transmitter with data fed through a shift register. Data is encoded and transmitted by the on-chip RF transmitter operating at 433.92 MHz.

4. Results and Discussion

Thermal simulations were made to assure that there is no thermal short-circuit between the heater and the temperature probes. Figure 3 shows the simulation result of the heater cross section.

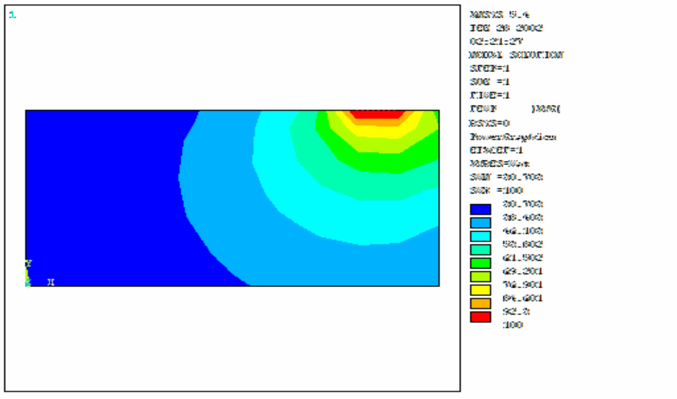

Figure 3. Heater probe thermal simulations

Soil samples of Almendra silt loam, which were wet to predetermined water content and mixed, were packed into a cylinder 77 mm in diameter by 70 mm long, with the soil moisture sensor at the center. Measurements were taken and then the soil was weighed and dried at 105 ºC for 24 h to determine bulk density and water content (thermo gravimetric method),

$$\theta = \frac{(wet\ weight) - (dry\ weight)}{dry\ weight} \tag{5}$$

Table 1 lists the thermo-gravimetric soil water content (θ_g) and the measured values; maximum temperature rise (ΔT_m) and the heat applied per unit length of the line source (q).

Table 1. Soil water contents calculated using Eq.(4).

θ_g (m^3m^{-3})	ΔT_m (°C)	q (Jm^{-1})	θ_v (m^3m^{-3})
0	1.9	602	0
0.1	1.35	605	0.106
0.2	1.04	598	0.190
0.3	0.85	601	0.308
0.4	0.72	603	0.401

In soils with low organic matter, such as Almendra, X_o is neglected. The value of X_m is determined by dividing the soil bulk density by the particle density. An average value of 2.65 Mgm^{-3} is often used for particle density of soils. Therefore, using Eq. (4) the calculated values (θ_v) of soil water content are in good agreement with thermo-gravimetric values. Figure 4 shows a typical temperature response for heat-pulse measurements.

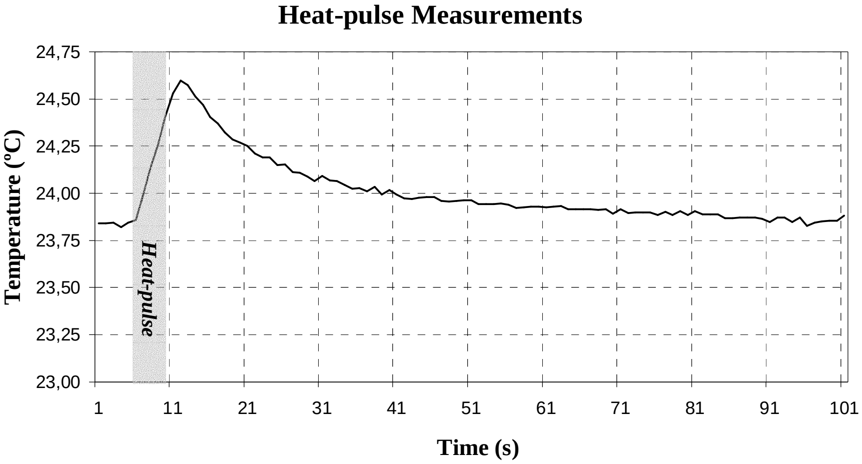

Figure 4. Typical temperature by time data.

All electronics is being implemented in Alcatel-Mietec 0.7μ Process. Simulations has showed that it can be expected for the Σ-Δ modulator an effective accuracy of 14-bit, although may be possible to extend it to 16-bit by improved digital filtering.

5. Conclusions

The design and modeling of a MCM-based micro-system for soil moisture measurements using the Dual-Probe Heat-Pulse (DPHP) method were achieved. The micro-system includes the soil moisture sensor, Σ-Δ converter, signal processing circuits (digital filtering and sensor interface) and a RF 433MHz transmitter. The DPHP method showed to be the most appropriate to measure humidity at different soil depths, and therefore, close to the surface of the soil in a non-destructive and automated manner. This is the first time that the DPHP method is implemented in a MCM-based micro-system and the first integrated sensor for soil moisture.

LITERATURE

Bilskie, J.R. 1994. (1994). Dual probe methods for determining soil thermal properties: Numerical and laboratory study. Ph.D. thesis. Iowa State Univ. Ames (Diss. Abstr. 9503532).

Campbell, G.S., C. Calissendorff, and J.H. Williams (1991). Probe for measuring soil specific heat using a heat-pulse method, Soil Sci. Soc. Am. J., 55, 291-293.

Charlesworth, P., (2000). Soil Water Monitoring, Irrigation Insights.

Kluitenberg, G.J., J.M. Ham, and K.L. Bristow (1993). Error analysis of the heat pulse method for measuring soil volumetric heat capacity, Soil Sci. Soc. Am. J., 57, 1444-1451.

Song, Y., J.M. Ham, M.B. Kirkham, and G.J. Kluitenberg (1998). Measuring soil water content under turfgrass using the dual-probe heat-pulse technique, J. Amer. Soc. Hort. Sci., 123(5), 937-941.

Tarara, Julie M., and Jay M. Ham (1997). Measuring soil water content in the laboratory and field with dual-probe heat-capacity sensors, Agronomy Journal, 89, 535-542.

Topp, C. G., J. L. Davis and A. P. Annan (1980). Electromagnetic determination of soil water content using TDR: Measurements in coaxial transmission lines, Water Resour. Res., 16, 574-582.

Topp,C. G., J. L. Davis. (1985). Measurement of soil water content using time-domain reflectometry (TDR): A field evaluation, Soil Sci. Soc. Am. J., 49, 19-24.