A MCM-based Micro-system for Soil Moisture Measurements

A. Valente[1], Raul Morais[1], Carlos Couto[2], J. H. Correia[2]
[1]UTAD University, Dept. of Engineering, Apartado 202,
5001 911, Vila Real, Portugal, avalente@utad.pt
[2]Minho University, Dept. of Industrial Electronics, Guimarães, Portugal

SUMMARY

This work presents a Multi-Chip-Module (MCM) based microsystem for irrigation control in agriculture. The proposed microsystem includes a soil moisture microsensor, an analog-to-digital converter, signal processing circuits (digital filtering and sensor interface) and a RF 433MHz transmitter. A heat--pulse technique is used to determine the volumetric heat capacity and hence the water content of a porous media, such as the soil. This method is based on the Joule effect (heater probe) and in Seebeck effect (temperature probe). By using CMOS standard processes (low-cost) a network could be implemented in order to achieve an accurate measurement of the soil moisture at the plant root level.

Keywords: Soil moisture sensor, integrated micro-sensor, heat capacity sensor, sigma-delta converter.

Subject category: Applications

INTRODUCTION

The economics factors and the desire to minimize resource over-consumption have increased the requirements for irrigation management systems to manage water more efficiently. This need 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, capacitance, are available for measuring soil moisture. Generally, these methods present several drawbacks in irrigation management systems: soil dependency, inaccuracy and high cost. 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.

THEORY

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

$$\rho c_p = 1.92 X_m + 2.51 X_o + 4.18 \theta_v \qquad (1)$$

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 ($MJm^{-3o}C^{-1}$) 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. The relationship between the ρc_p and ΔT_m is [1],

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

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. Substituting Eq. (1) into Eq. (2) and rearranging yields an expression that shows the relationship between θ_v and ΔT_m,

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

MACROSENSOR

A heat-pulse macro device [2], illustrated schematically in Figure 1, was used in this study to test the dual-probe heat-pulse method.

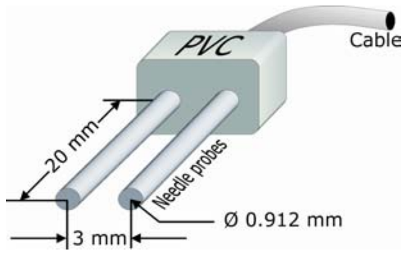

Fig. 1: *Sketch of the soil moisture macrosensor*

SYSTEM OVERVIEW

The multi-chip module is basically made of three blocks, schematically represented in Figure 2: a micromachined sensor, a mixed signal interface, and a wireless front-end.

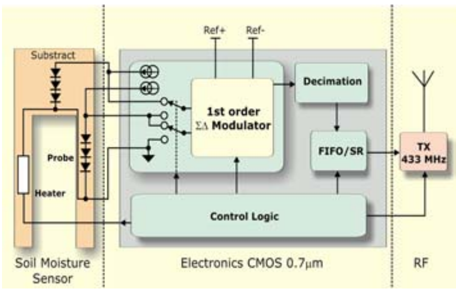

Fig. 2: *Schematic representation of the system*

Micromachined sensor module

Silicon has a large thermal conductivity and produces a thermal short-circuit between the heater-probe and the temperature-probe. To reduce heat transfer to the substrate, silicon dioxide growth (low thermal conductivity) and removal of bulk silicon, is used. Micromachined p-n junction arrays forms the temperature sensors.

The sensor 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 θ_v, which can be made near the soil surface where large root densities are found.

Mixed-signal interface

In order to measure the temperatures a 1-bit 1st order continuous-time Sigma-Delta (ΣΔ) modulator was chosen due to its simplicity, power constrains and size. The modulator's output bit stream is then converted to a 12-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 ΣΔ modulator, the FIFO and for keying transmitter (serial) with data fed through a shift register. For sensor performance experiments, data is transmitted using a commercially available transmitter operating at 433MHz.

The mixed-signal interface was designed using Alcatel-Mietec 0.7-micron process.

RESULTS AND DISCUSSION

Macrosensor results

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 macro 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).

Figure 3 a shows typical temperature response for heat-pulse measurements.

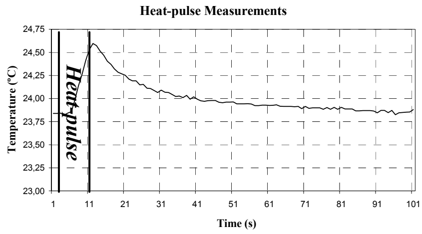

Fig. 3: *Typical temperature by time data.*

Microsensor simulations results

Thermal simulations were made to assure that there is no thermal short-circuit between the heater and the temperature probes. Figure 4 shows the simulation result of the heater cross section.

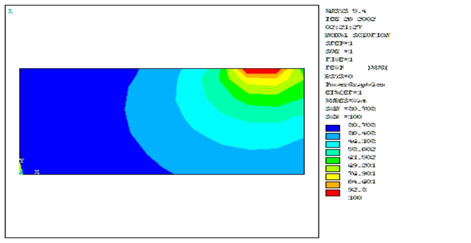

Fig. 4: *Heater probe thermal simulations*

Mixed-signal simulation results

Simulations have shown that it can be expected an effective resolution of 12-bit for the ΣΔ modulator (13-bit using off-chip digital filtering) with a conversion time of 40 ms (clock frequency 200 kHz).

CONCLUSIONS

The design and modeling of a MCM-based microsystem for soil moisture measurements using the Dual-Probe Heat-Pulse (DPHP) method were achieved. At this time the microsistem includes the soil moisture sensor, the first order ΣΔ converter and the signal processing circuits. The DPHP method proved to be the most appropriate to measure soil moisture at different soil depths, in a non-destructive and automated manner. This is the first time that the DPHP method is implemented in a MCM-based microsystem and the first integrated sensor for soil moisture.

REFERENCES

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

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