Sensors and Actuators A 233 (2015) 108–117

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

A low-power, low-cost soil-moisture sensor using dual-probe heat-pulse technique

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ARTICLE INFO

Article history:
Received 12 January 2015
Received in revised form 2 May 2015
Accepted 19 June 2015
Available online 25 June 2015

Keywords:
Low-power DPHP sensor
Soil density
System design
Wireless communication

ABSTRACT

This paper presents the development and testing of an integrated low-power and low-cost dual-probe heat-pulse (DPHP) soil-moisture sensor in view of the electrical power consumed and affordability in developing countries. A DPHP sensor has two probes: a heater and a temperature sensor probe spaced 3 mm apart from the heater probe. Supply voltage of 3.3 V is given to the heater-coil having resistance of 33 Ω power consumption of 330 mW, which is among the lowest in this category of sensors. The heater probe is 40 mm long with 2 mm diameter and hence is stiff enough to be inserted into the soil. The parametric finite element simulation study was performed to ensure that the maximum temperature rise is between 1 °C and 5 °C for wet and dry soils, respectively. The discrepancy between the simulation and experiment is less than 3.2%. The sensor was validated with white clay and tested with red soil samples to detect volumetric water-content ranging from 0% to 30%. The sensor element is integrated with low-power electronics for amplifying the output from thermocouple sensor and TelosB mote for wireless communication. A 3.7 V lithium ion battery with capacity of 1150 mAh is used to power the system. The battery is charged by a 6 V and 300 mA solar cell array. Readings were taken in 30 min intervals. The life-time of DPHP sensor node is around 3.6 days. The sensor, encased in 30 mm × 20 mm × 10 mm sized box, and integrated with electronics was tested independently in two separate laboratories for validating as well as investigating the dependence of the measurement of soil-moisture on the density of the soil. The difference in the readings while repeating the experiments was found out to be less than 0.01%. Furthermore, the effect of ambient temperature on the measurement of soil-moisture is studied experimentally and computationally.

1. Introduction

It is increasingly becoming apparent that technology can enhance the productivity of resource-challenged agricultural practices in developing countries. One of the most prominent technological advances is the use of soil-moisture sensors. In a country like India where dry-farming is prevalent, efficient technology-aided irrigation is beneficial. However, affordability and lack of adequate electrical power are practical challenges. With this in mind, we have developed a low-power and low-cost soil-moisture sensor, validated with white clay, and tested it in red soil that is germane to southern part of India.

There are many types of soil-moisture sensors as illustrated in Fig. 1. A good overview is reported in [1]. Gravimetric technique entails drying of moist soil for 24 h in an oven at a temperature of 105 °C and weighing it before and after drying [1,2]. It is one of the simplest and most accurate techniques. However, it is not suitable for regular monitoring of soil-moisture because it is slow and is not an in-situ technique. Capacitive, resistive, tensiometric, hygrometric, and other indirect measurement techniques have been developed [2]. Some of them have been miniaturized; e.g., polymer-based resistive method [3], micro-machined beam [4], micro-tensiometer [5] and heat-pulse [6] methods. Among these, the heat-pulse method is widely explored and well established with sound theory and extensive field-testing. The advantages and disadvantages of different methods, as indicated in Fig. 1, point to the

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http://dx.doi.org/10.1016/j.sna.2015.06.026

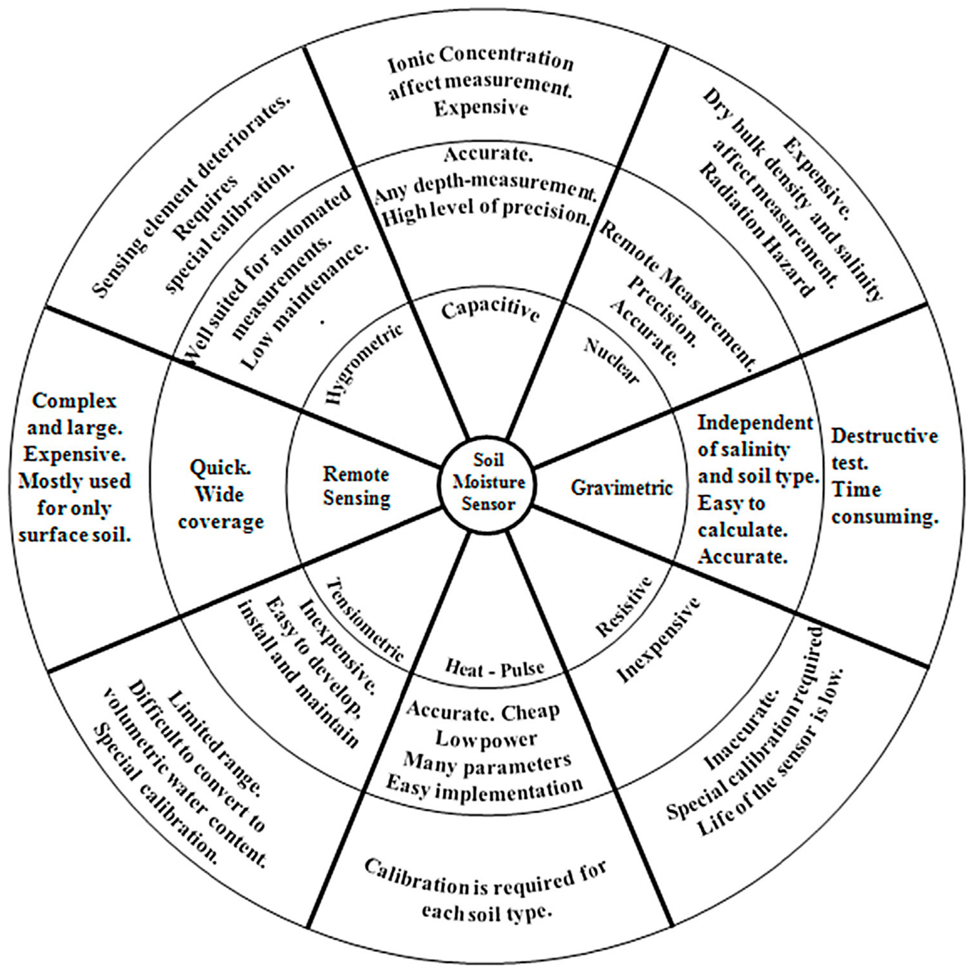

Fig. 1. Merits and de-merits of different soil-moisture sensor techniques.

suitability of the heat-pulse technique over the others for resource-challenged dry-farming practices. Consumed power is the main challenge in the heat-pulse technique and reducing it is the focus of this work besides keeping the cost low. Since the sensor network is implemented in an open field, we have used solar power for recharging the primary power source of the system, which is a Li-ion battery.

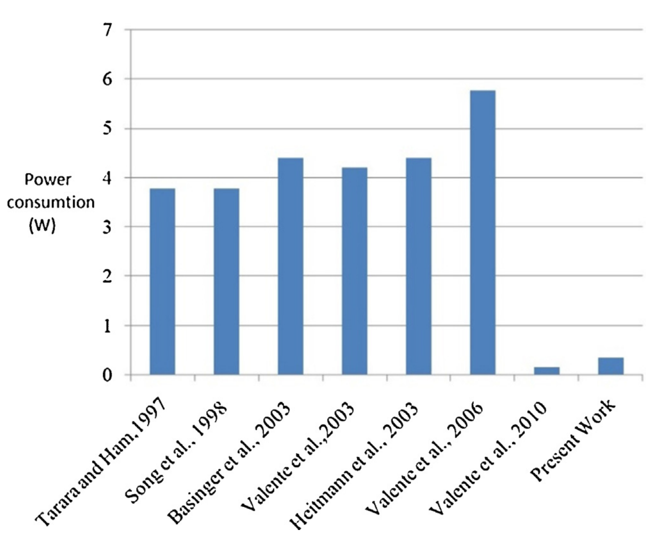

Fig. 2. Consumed power by the sensor element in watts by different attempts that use the DPHP technique.

Fig. 2 depicts the power consumption by different DPHP implementations reported in the literature [6–12]. As shown in the figure, power consumption by the device built in this work is the second lowest. Reported low-power sensor in [12] uses a disk-shaped heater with 16 mm diameter, which disturbs the soil matrix and hence soil-moisture measurement might not be accurate. To overcome this problem, we have designed a thin heater probe with the diameter of just 2 mm to achieve low power and negligible disturbance of the soil matrix. In order to reduce the consumed power, we first simulated and examined the temperature profiles under varied parameters of the system to choose the duration of the heat pulse for power optimization.

2. Heat-pulse technique: theory

The premise of the heat-pulse method, introduced by Campbell et al. [13] to measure soil-moisture, is that the maximum temperature rise at a predetermined distance from a line heat-source resulting from an instantaneous heat-pulse has inverse relationship to the volumetric specific heat of the soil. Thus,

$$(\Delta T_{\max})_{r=r_{\mathrm{m}}} = \frac{q}{e\pi r_{\mathrm{m}}^2 C} \qquad (1)$$

where $\Delta T_{\max}$ is the maximum rise in temperature, r_{m} the radial distance from the line-source at which the temperature rise is measured, q the heat input to the line-source, and C the volumetric specific heat of the soil. Campbell et al. [13] also note that if the time lapse between the injection of the heat-pulse and the measurement of temperature is $\frac{r_{\mathrm{m}}^2}{4k}$($k$ is the thermal diffusivity of the