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Wireless sensor network for monitoring soil water content on field scale

For the demand to monitor soil water dynamics at field scale, this study presents a solar-powered wireless cell that containes a water content sensor with a communication module and a data-logger. The electronical components and the operation mode were designed to reduce the energy demand and to attain a continuous operation even under the canopy of field crop. To evaluate its feasibility in the field, three cells were independently installed in a bare plot, a maize plot and a sugar beet plot for a period of two months.

Keywords

Mobile sensors, autarkic sensor system, sensor node, soil monitoring

Abstract

■ Soil water content plays an important role in governing crop growth and yield. To monitor soil water content dynamically in the root zone a sensor technique, which has high accuracy and reliability, rapid response, low energy consumption and cost, is desired [1; 2]. Earlier techniques for this purpose were a plaster sensor and tensiometer, but their response was unsatisfactory and there was hysteresis error between wetting and drying [3]. Since Topp et al. [4] presented a three-order polynomial to approximate the relationship between VSWC (volumetric soil water content) and relative dielectric constant (ε_r) of moist soil, various dielectric sensors, based on TDR (time domain reflectometry) and FD (frequency domain) principles, have been developed and have become commercially available [5]. TDR sensors only take a number of seconds to complete a water content measurement [6]. A more rapid response can be achieved with a FD sensor, which only needs a fraction of a second [7]. Thus, both sensors can meet the requirement of dynamic measurement. However, there are still some technical limitations for these dielectric sensors to be a node of wireless network. One of the main limitations is to supply a long-term power to the sensors that are remotely and stand-alone located. Another demand is to wirelessly transfer the data with other sensors, data-loggers or routers across a certain distance. In this study, a solar-powered wireless cell for the dynamic measurements of soil water content in the root zone was designed and then a field evaluation was conducted under three canopy conditions.

General description of the designed cell

The cell consisted of a solar panel (multi-crystalline silicon, diameter 170 mm), a supporting rod (stainless steel, diameter 10 mm, length 600 mm), a soil water content sensor and a wireless communication module (nRF905, Nordic, Norway) (**figure 1**). Besides, a micro-controller (MSP430F149) together with an extended memory chip (Flash, 1MB) acted as a data-logger. A major feature of this configuration was to allow for simple setting at a range of depth (100-500 mm) and replacement in the field. **Figure 2** shows the electric layout of entire system arranged in a circuit board. To provide electric power, four batteries (Ni-MH, AA 1.5 V, 2000 mAh), recharged by solar energy, were used in series.

Table 1 summarizes the power requirements of each component. Because the operating current of the micro-controller was considerably lower (0.1 mA), it was reasonably disregarded when compared to the power consumption of other components. To reduce the power consumption of the system as less as possible, the sensor could be switched from operating mode to stand-by mode at different intervals, as required. During this experiment, the measurement interval was every 15 minutes because of a weather station that provided rainfall information with the same interval in the experimental field. As presented in **figure 3**, the executing sequence of the cell in the operating mode took 12 seconds for a sampling process. According to the current consumption of each component in **table 1** and the executing sequence in **figure 3**, the average current consumption of the system was equal to 3.2 mA.

Water content sensor

Figure 1 shows two electrodes (a metallic ring and tip) of a capacitor that was embedded at the bottom of the supporting rod. The soil particles surrounding the electrodes created a dielectric material of the fringe-capacitance sensor. A segment

of coaxial line connected the electrodes to the high-frequency oscillator (100 MHz) through the center of the rod. Therefore the capacitance or dielectric constant of soil could be measured, and subsequently converted into VSWC via a specific calibration.

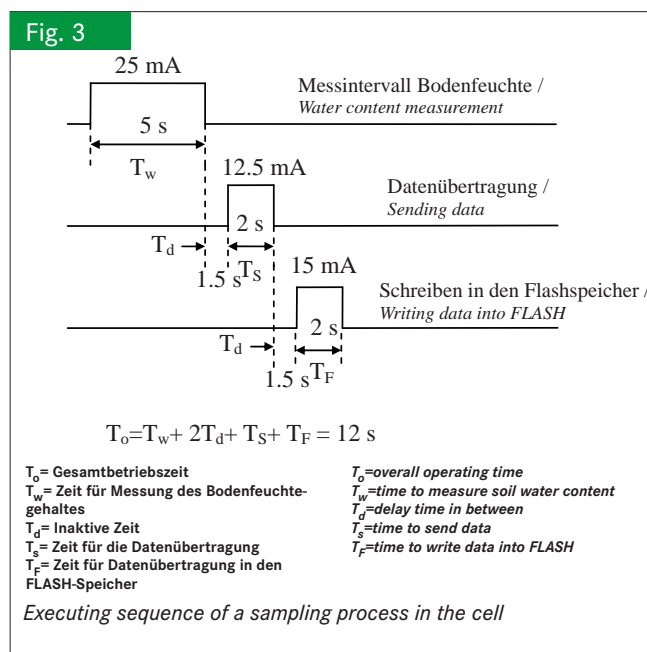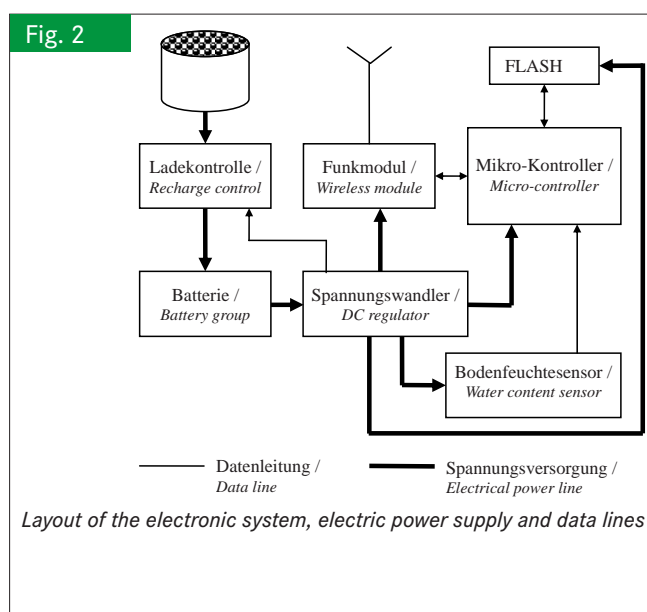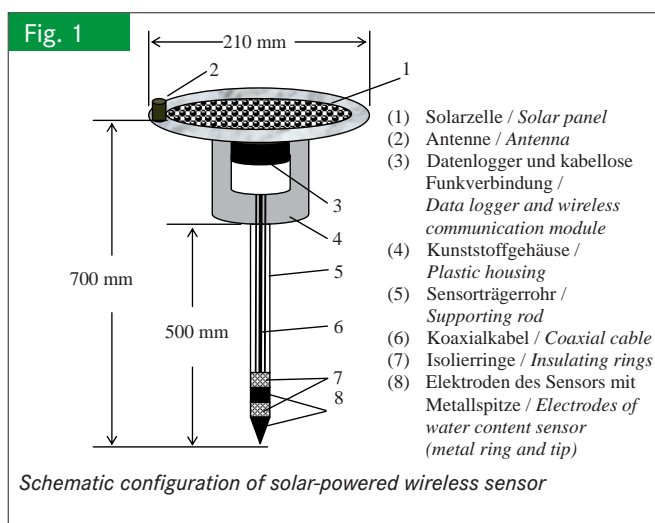## Experimental conditions in the field

Three cells were separately installed in three adjacent plots (denoted with plot A, B, C) at the Poppelsdorf experimental field (6°43'33'' E, 50°43'9'' N) of Bonn University from DOY (day of year) 221 to 270 (from the early of August to the end of September), 2008. The distance between each pair of cells was less 100 m so that the atmosphere conditions above the field were nearly identical. Plot A was a piece of bare field after winter wheat harvests, whereas plot B and plot C were planted with maize and sugar beet, respectively. The plant canopy either in plot B or plot C primarily filled the field of view. In the vicinity of the weather station, these cells were uniformly installed at a depth of 25 cm, and thus the height of the part above the ground was 45 cm.
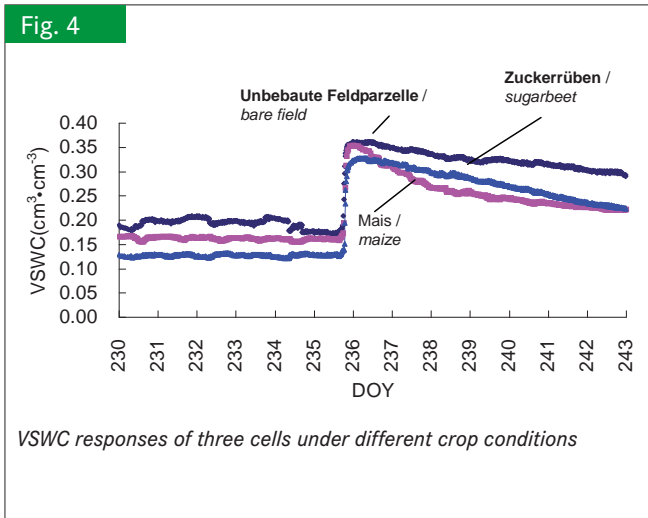
Solar panel

The solar radiation at the experimental field in July to September 2008 was in average $5.5\,kWh \bullet m^{-2} \bullet d^{-1}$ with a minimum of $0.8\,kWh \bullet m^{-2} \bullet d^{-1}$ and maximum of $10.7\,kWh \bullet m^{-2} \bullet d^{-1}$. The energy demand for the cell as specified in **table 1** and **figure 3** with components in non permanent operation was 0.03 Wh and for permanent operation components 0.29 Wh in a day. The capacity of the batteries was chosen to cover the energy supply for the operation of the cell for 40 days under field conditions with elevated corn stamps causing low solar radiation. In order to discern an appropriate size of solar panel for the cell, two rings were tested to quantify an optimal area. When the solar panel was covered with either the large or the small ring, the exposed area was 93 cm², or 124 cm², respectively. When both rings were employed, the exposed area was 62 cm².

Results and discussion

To allow for the equilibration of the water content sensors, the data collected from the first 10 days after installation in the field were excluded. The results, presented in **figure 4**, show the data collected by each sensor from DOY 230 to 243 for plots A, B and C, respectively. For the bare field (plot A), the curve reduced linearly over the period of the experiment but was higher overall compared with other plots that had plant canopies. For plot B (maize canopy), the soil water content dropped rapidly from $0.37\,cm^3 \bullet cm^{-3}$ to $0.26\,cm^3 \bullet cm^{-3}$ over a period of three days (DOY236-238), and then the rate of loss became steady after DOY 238. The rapid decline of soil water content for plot B (comparing to plot C) presumably resulted from the higher water uptake by the maize. Indeed, the linear decline of soil water content in plot C after a rainfall also indicates that sugar beet was relatively insensitive to drought stress.

Fig. 1

Schematic configuration of solar-powered wireless sensor

(1) Solarzelle / *Solar panel*
(2) Antenne / *Antenna*
(3) Datenlogger und kabellose Funkverbindung / *Data logger and wireless communication module*
(4) Kunststoffgehäuse / *Plastic housing*
(5) Sensorträgerrohr / *Supporting rod*
(6) Koaxialkabel / *Coaxial cable*
(7) Isolierringe / *Insulating rings*
(8) Elektroden des Sensors mit Metallspitze / *Electrodes of water content sensor (metal ring and tip)*

Fig. 2

Layout of the electronic system, electric power supply and data lines

Fig. 3

$$T_o = T_w + 2T_d + T_S + T_F = 12\ s$$

T_o= Gesamtbetriebszeit
T_w= Zeit für Messung des Bodenfeuchtegehaltes
T_d= Inaktive Zeit
T_S= Zeit für die Datenübertragung
T_F= Zeit für Datenübertragung in den FLASH-Speicher

T_o=overall operating time
T_w=time to measure soil water content
T_d=delay time in between
T_S=time to send data
T_F=time to write data into FLASH

Executing sequence of a sampling process in the cell

Fig. 4

VSWC responses of three cells under different crop conditions

Table 1

Power consumption from each component of designed electronic system

	Spannung (V)/ *Voltage*	Strom (mA)/ *Current*
Mikrokontroller/ *Micro-controller*	3,3	0,1
Bodenfeuchtesensor/ *Water content sensor*	6	25
FLASH-Speicher	3,3	15 (schreiben)/ *(writing)* 4 lesen/*(reading)*
Spannungswandler/ *Linear DC-regulator*	6	1 (Eigenverbrauch)/ *(self-consumption)*
Funkmodul/ *Wireless module*	3,3	12,5 (senden)/ *(emitting)* 11 (empfangen)/ *(receiving)* 0,002 (Ruhe)/ *(sleeping)*
Ladekontroll-Einheit/ *Recharge control unit*	6	2 (Eigenverbrauch)/ *(self-consumption)*

Energy supply by solar panel

Figure 5 presents two pairs of curves, which referred to plot B and plot C, respectively. Because the shoot of maize crop in plot B (approximate 2 m in height) was considerably taller than the cell height (45 cm) above the ground, a part of sunlight was shielded. Alternatively, there was no shadow problem in plot C. As a negative consequence, the solar panel in plot B collected rather less solar energy than that obtained in plot C. Indeed, from **figure 5** it can be seen that the running times of the cell in plot B were apparently shorter than those in plot C with respect to each size of solar panel, although they were recharged within identical daytime. The pair of discharge curves from plot B appeared a linear tendency with rather higher values of $R^2 > 0.948$ for all of the tested situations. Nevertheless, the cell with the exposed area of 124 cm² in plot B could continuously run up to 32 hours at a sampling interval of 15 minutes. That is, the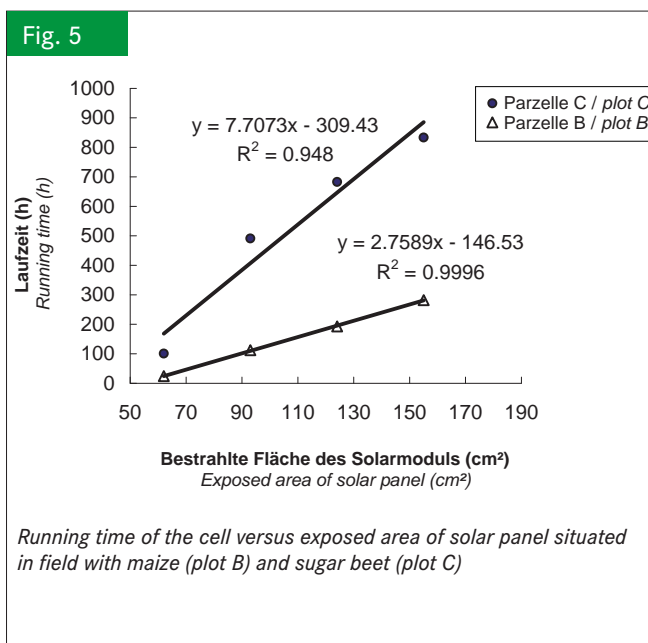 cell was capable of working overnight by using such smaller solar panel. Because the attenuation of solar radiation in plot B resembled in the situation that sky is partly or completely clouded, it is certain that the exposed area of the solar panel made from multi-crystalline silicon can be shrunk from 155 cm² to 124 cm² in size.

Conclusions

During overall experimental period, three cells worked satisfactory under the different canopy conditions. Owing to the strong impact of a heavy rain event, the response of each cell for water dynamics in each plot was observed. By interpreting the acquired data it is beneficial to better understand soil physical properties in the field and to manage the crop's growing process for resource conservation. On the other hand, from the experiment related to the solar panel size and energy consumption, it is possible for the cell to be miniaturized in physical dimension. Thus, this cell can be further developed as a node of wireless network at a field scale or be utilized individually in greenhouses.

Fig. 5

Running time of the cell versus exposed area of solar panel situated in field with maize (plot B) and sugar beet (plot C)

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