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A Compact Hardware Design of a Sensor Module for Hydroponics

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***Abstract*— We developed a compact sensor module for hydroponics that measures the nutrient concentration and water level using simple oscillator circuits. Oscillation frequencies are measured and are found to change in response to the resistance and capacitance between metal wires on a printed circuit board submerged in liquid fertilizer. A microprocessor is mounted on the sensor board for measurement and communication. Expressions relating the oscillating frequencies, liquid fertilizer concentration, water level and temperature were derived through experiments using the sensor module.**

Keywords—smart agriculture, hydroponic culture, Arduino, sensor module

I. Introduction

The field of smart agriculture technology that monitors and controls a plant's environment using IoT (Internet of Things) is expanding rapidly [1]-[5]. In order to provide an oasis and a relaxing space for city life, we are introducing hydroponics systems on rooftops, balconies and verandas, as shown in Fig. 1. Sensor modules that are used to improve productivity in commercial agriculture are too expensive for personal use. Therefore, we developed a low-cost sensor module using a ribbon cable (Fig. 2) to measure the water level and liquid fertilizer concentration based on the capacitance and electrical conductivity (EC) of the cable [6]. The sensor circuit is able to perform highly accurate measurements, but the unstable shape and position of the cable in water affected the measurement. The sensor module was designed to be a daughter card of an Arduino equipped with an 8-bit ATmega328 processor which is used for measurement. Therefore, the module cannot be used with other processor boards.

Fig. 1 Hydroponic culture systems

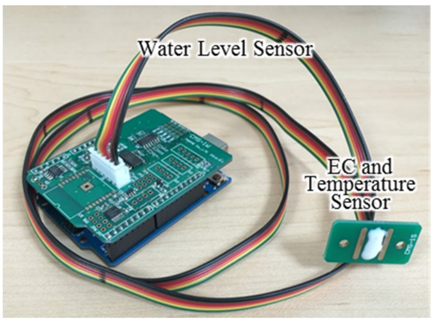

Fig. 2 Sensor module with a ribbon cable stacked on Arduino

In order to solve these issues, a new sensor module was developed, where a hard PCB (Printed Circuit Board) was used in place of a ribbon cable, and the ATmega328 processor was mounted on the board for the measurement and serial communication with various processor boards. In this paper, the structure and operating principles of the sensor circuit is described, and its performances are demonstrated thorough experiments.

II. New Sensor Module

Fig. 3 is the new sensor module whose dimensions are 280-mm long by 25-mm wide. The module has the processor, oscillator circuits, and a cable connector at the root of the board, and has electrodes for EC measurement and water temperature at the end of the board. The old sensor module uses the processor on Arduino for the EC and water level sensing, but the new module uses its own processor. The module performs serial communication for data transfer and thus wireless communication can also be supported easily, by connecting a wireless module that supports transparent mode to a serial communication port. The module also supports the I^{2}C communication protocol. The module accepts a power supply of 3.3 V or 5 V, and an internal voltage of 2.5V for the sensors is generated from the source. Therefore, characteristics of the sensors are not affected by the power supply voltage. The water temperature sensor output analog data is between 0-2.5V, and thus a 2.5V signal is fed to a reference voltage input of the processor voltage.

Fig. 4 shows a circuit diagram of the sensing block. The circuit has two oscillators whose oscillation frequencies are changed with the resistance r between the electrodes and the capacitance c of

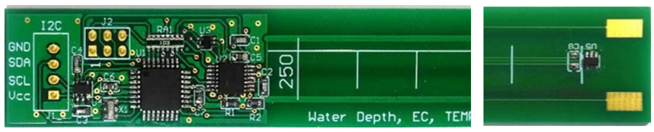

Fig. 3 New sensor module (left : top end, right : bottom end)

parallel metal wires on the PCB dipped into water. The frequencies are counted by a 16-bit timer of the processor as a number of 2.5V pulse signals per time unit (set to 1ms, 2ms, 4ms, or 8ms). The number of pulses is monitored by performing timer interruptions using an 8-bit timer of the processor.

The 2-input exclusive-OR gate X_5 is used as a voltage level shifter and as a selector for the two oscillators. In order to switch the oscillators, control signals PC0 and PC1 are used. When PC0=0 or PC1=0, the 3-inverter oscillator with XOR gates X_1 and X_3 or the oscillator with X_2 and X_4 is stopped. During an idling state, both signals are set to '0' to reduce power consumption.

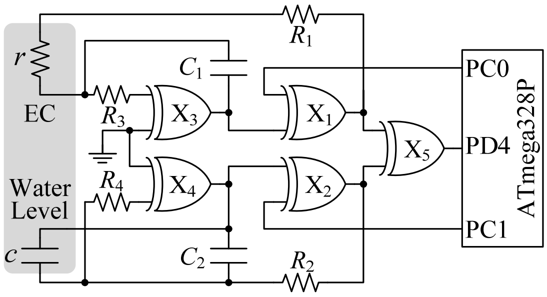

Fig. 4 Circuit diagram of sensing block

III. Experiments

A. EC sensor

Fig. 5 shows an experimental environment. Seven liquid fertilizers of different concentrations (0.2, 0.5, 1.0, 1.5, 2.0, 3.0, and 5.0 mS/cm) are heated from 5 to 30 ºC by 5 ºC step in a plastic bottle with the sensor module. Then, oscillation frequencies of the EC circuit f_{EC} are measured 50 times and are averaged for each temperature. Arduino is used as a serial to USB converter, and the sensor module is operable by itself.

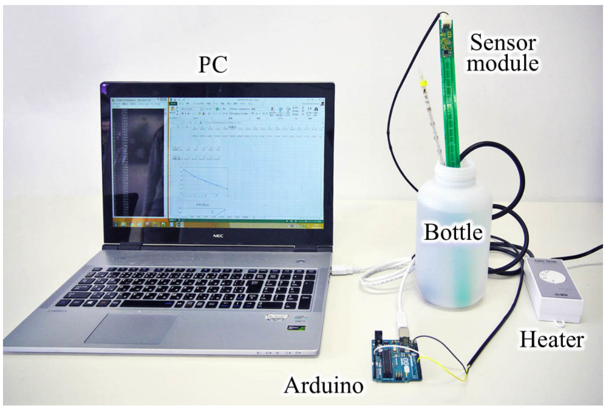

Fig. 5 Experimental environment

The liquid fertilizers have higher electro conductivity with higher temperatures, but the concentration of the liquid does not change. The concentration is important for plants, and thus EC meters for hydroponics show the EC value at 25 ºC after temperature correction. Fig. 6 shows relationship between the EC value and oscillation frequencies of the EC sensor at the reference temperature of 25 ºC. The solid line in the figure is a theoretical value with circuit parameters calculated as follows.

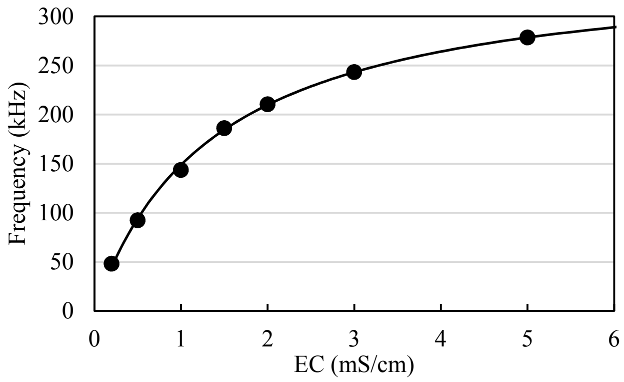

Fig. 6 Oscillation frequency vs. EC at 25 ºC

Fig. 7 is an equivalent circuit of Fig. 4 with PC0=1, and its oscillation frequency is given by Equation (1).

$$f_{EC} = \frac{1}{2.2C_1(r+R_1)} \tag{1}$$

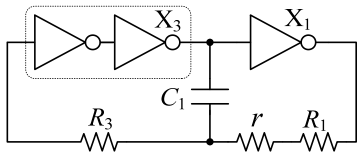

Fig. 7 Equivalent circuit of EC sensor

On the equation above, r represents the resistance of the liquid, and thus the electro conductivity EC (S/cm) is given as:

$$EC = \frac{1}{r} = \frac{1}{\frac{1}{2.2C_1 f_{EC}} - R_1} \ . \tag{2}$$

Where C_1=1.780 μF and R_1=717 Ω were obtained from the measured value using the least-squares method.

Now, the temperature characteristic of the EC value is considered. Fig. 8 shows relationship between the oscillating frequencies of the EC sensor and the water temperature, and Fig. 9 shows EC values calculated by Equation (2). In order to compensate the effect of temperature T in Fig. 9, f'_{EC} of Equation (3) is used in place of f_{EC}, where X is a quadratic polynomial of f_{EC} for Equation (2). The parameters of Equation (3) are calculated from experimental data by a least squares method.

$$f'_{EC} = f_{EC} + (25-T)(711 \cdot \log_e f_{EC} - 6639) \tag{3}$$

The compensated EC values in Fig. 10 are nearly flat over the temperature variation. It contains errors of ±8% at EC=0.2 and ±7% at EC=5.0, but they are acceptable for hydroponics.

B. Water level sensor

The water level sensor measures capacitance C between long metal lines on the PCB stick changing with a length of the stick in the water as a frequency of an oscillator circuit. Fig. 11 shows an equivalent water level sensor circuit in Fig. 4 for PC1=1, and oscillation frequency of this three inverter oscillator is given as

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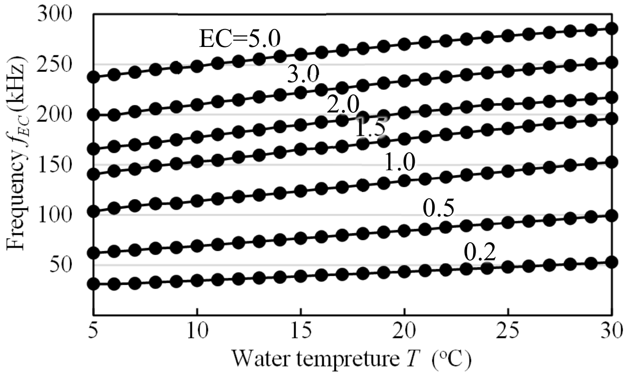

Fig. 8 Oscillating frequency of EC sensor vs. temperature

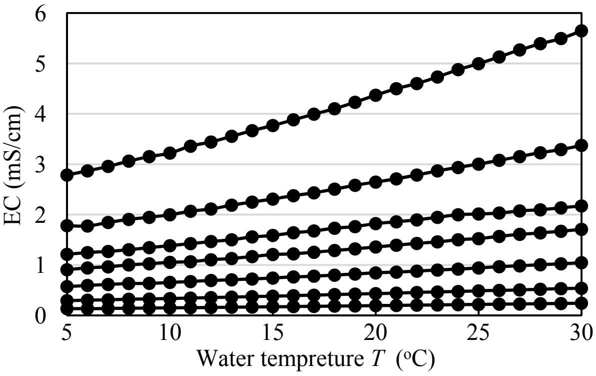

Fig. 9 EC vs. temperature

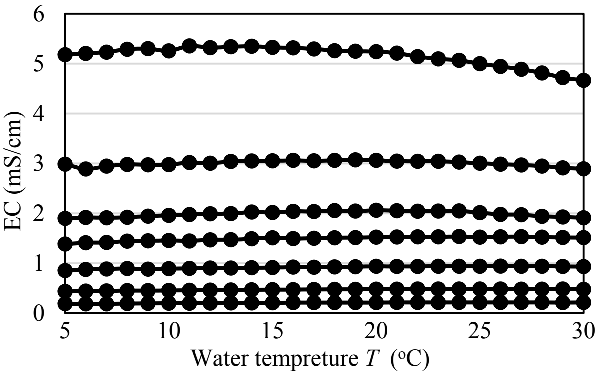

Fig. 10 EC with temperature compensation

$$f_{WL} = \frac{1}{2.2(c + C_2)R_2} \quad . \tag{4}$$

Therefore, the capacitance C_{WL} including the PCB stick in the water and the condenser device on the board is

$$C_{WL} = c + C_2 = \frac{1}{2.2 f_{WL} R_2} \, . \tag{5}$$

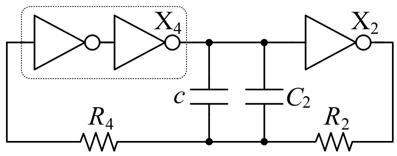

Fig. 11 Equivalent circuit of the water level sensor

Fig.12 shows the oscillating frequency f_{WL} by changing the

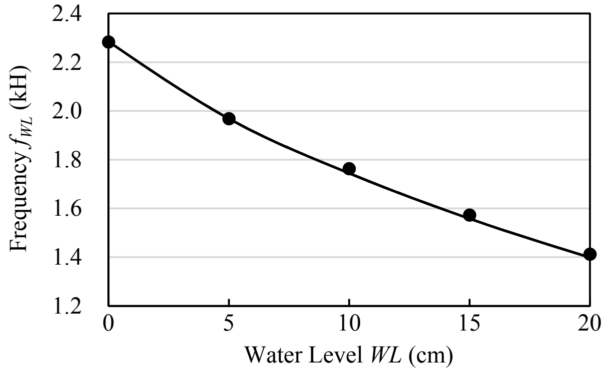

Fig. 12 Oscillating frequency vs. water level

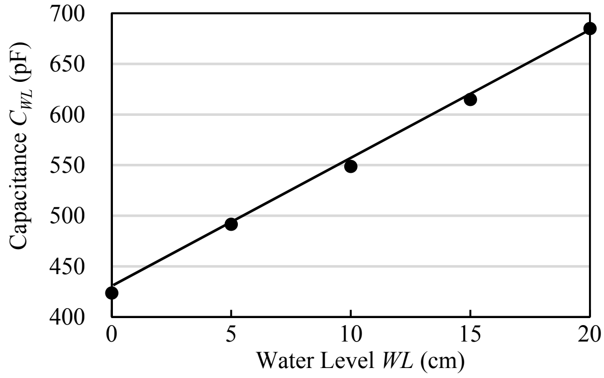

Fig. 13 Capacitance vs. water level

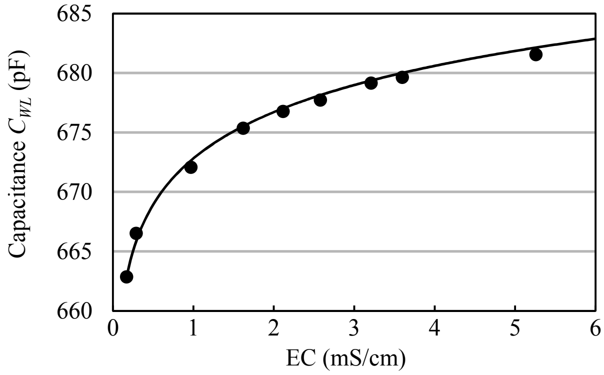

Fig. 14 EC vs. Capacitance at water level of 20 cm

length of the stick in the water as 0, 5, 10, 15, and 20 cm. The frequency is measured 50 times and averaged for each dot. Fig. 13 shows the capacitance C_{WL} converted from f_{WL} of Fig. 12 by applying Equation (5). C_{WL} in Fig. 13 is linear to the water level WL, thus the slope of C_{WL} can be calculated from two points such as C_{WL0} and C_{WL20} for the water level 0 and 20 cm. Note that C_{WL0} is a constant value not affected by EC because the stick is not in the water. At the 20-cm water level, the frequency f_{WL} was measured by changing EC, then the dots in Fig. 13 are obtained by calculating C_{WL20} using Equation (5). Here, EC is temperature correction value. Various formulas were applied to approximate C_{WL}, and Equation (76 using the natural logarithm, showed as a solid line in Fig. 13, fits perfectly.

$$C_{WL20} \cong (5.375 \times \ln(EC) + 672.7) \times 10^{-12} \tag{6}$$

The water level WL is linear to the capacitance C_{WL}, and two points (C_{WL0}, 0), (C_{WL20}, 20) are on the linear line. Therefore, WL is calculated by Equation (7).

$$WL = 20 \times \frac{C_{WL} - C_{WL0}}{C_{WL20} - C_{WL0}} \tag{7}$$

Finally, we obtained Equation (8) that converts the frequency f_{WL} into the water level WL by applying Equation (5) into Equation (7).

$$WL = 20 \times \frac{\frac{1}{2.2 f_{WL} R_2} - C_{WL0}}{C_{WL20} - C_{WL0}} \tag{8}$$

IV. CONCLUSION

We developed a sensor module for a hydroponic culture system to enable advanced agriculture techniques to become widely accessible in urban areas as a service industry. The module measures an electro conductivity (EC) to determine the concentration of the liquid fertilizer, and water level by using a PCB stick dipped in the liquid. The module has two oscillator circuits whose operating frequencies vary with the EC between electrodes and an electrostatic capacitance of two metal lines on the stick. Then the frequencies are converted into EC and the water level. The module includes integrated sensor circuits, an ATMega328 processor, serial and I^2C communication interfaces on a single PCB stick, which was a significant improvement from the prototype module, which required an Arduino ATmega328 processor card for sensing and communication.

Through experiments with various water parameters, formulas to convert oscillation frequencies of the sensor module to EC and water level with temperature correction were obtained. The experiments were performed in a stable indoor environment with temperatures of 5 – 30°C. However, the hydroponic system with the sensor module is intended to be used not only in a room, but also on rooftop and balcony, where temperature varies widely and a water pump often changes the water level. Therefore, long-run performance test and durability tests in the open air are required. Variations in electric characteristics such as capacitances and resistances of IC chips on the module may affect precision of sensing data, and thus the development of a self-compensation mechanism is being considered for a future work.

Currently, we are developing the compact hydroponic system shown in Fig. 15 as a commercial product, and an improved version of the sensor module will be installed on the system.

Fig. 15 Compact hydroponic culture system

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