High-Accuracy and Low-Cost Sensor Module for Hydroponic Culture System

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***Abstract*— A high accuracy sensor module for hydroponic culture system was developed. The module measures water level, temperature, and nutrient concentration values by using a single device equipped with a low-cost ribbon cable and electrodes. The module has two oscillators and the water level and the concentration value are converted into frequencies of the oscillator signals. After the conversion mechanism and adjustment scheme are explained, the high accuracy of the sensor module is demonstrated.**

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

I. INTRODUCTION

IoT (Internet of Things) technology is expanding rapidly, and agriculture is one of promising applications where sensor and wireless communication devices are used to monitor and control cultivation environment [1][2]. However, the high cost of the devices and cultivation systems only allows this technology to be used in a large-scale plant factory managed by a big company or conducted as a government project [3][4][5]. However, a variety of microcomputer platforms, such as Arduino [6] and RaspberryPi [7], and sensor devices that can be applied to plant cultivation, are being introduced to a consumer market recently.

We have developed a hydroponic culture system powered by photovoltaic generation, and cultivate tomatoes as shown in Fig. 1 [8]. The system is equipped with a prototype wireless sensor module using Arduino, supporting remote monitoring of temperature, humidity, illuminance, and water level data. In order to put the system into production, we developed a new sensor device that supports monitoring of EC (Electro Conductivity) for nutrient solution concentration, water temperature, and water level using a single module. While the module is very simple and low cost, it achieved high accuracy measurement. In this paper, the structure and principle of the sensor module are described, and its characteristics are demonstrated.

Fig. 1. Hydroponic culture system with wireless sensor module

II. NEW SENSOR MODULE

Fig. 2 shows the sensor module stacked on Arduino, and Fig. 3 is its circuit diagram. A low-cost ribbon cable is used to measure the water level, and electrodes for EC and a temperature sensor TI TMP20 coated by resin are connected at the end of the cable. Capacitance of the cable changes according to the water level in a tank, and electrical resistance between the electrodes changes with the nutrient solution concentration. The changes of capacitance and resistance are detected as frequencies of oscillators connected to the ribbon cable. Then the frequencies are converted into the water level and the EC value. Details are described in following sections.

In the measurement of the frequency, a 16-bit timer/counter of the microprocessor ATMega328P built in Arduino is used. However, the processor has only one timer/counter, and thus its input is alternately used to measure the EC value and the water level. AC current is used to measure the EC value because electrodes are electrolyzed if DC current flows continuously in one direction.

III. EC SENSOR

Fig. 4 shows a three-inverter oscillator used for measurements of the EC, where r is a resistance between the electrodes, which changes according to the concentration of

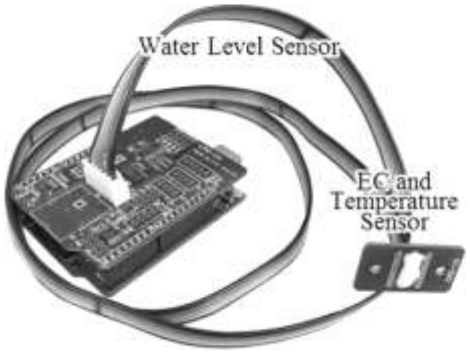

Fig. 2. Developed sensor module

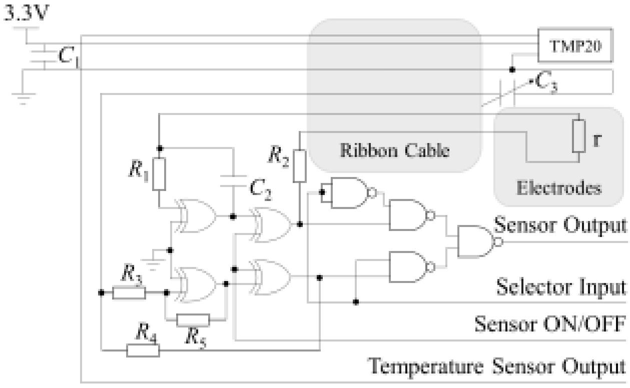

Fig. 3. Circuit diagram of sensor module

the nutrient solution. The oscillating frequency f_{EC} of the EC sensor is defined as Equation (1).

$$f_{EC} = \frac{1}{2.2C_2(r + R_2)} \text{ [Hz]} \tag{1}$$

Then EC value is obtained by Equation (2) as an inverse of the resistance.

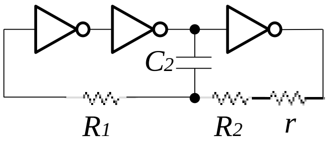

Fig. 4. Three-inverter oscillator

Fig. 5. EC meter MD-TDS-EC

TABLE I. FEATURE OF MD-TDS-EC

Measuring range	0 – 9.990 mS/cm
Accuracy	±2.0%
Operating temperature	0.1 – 80.0 °C

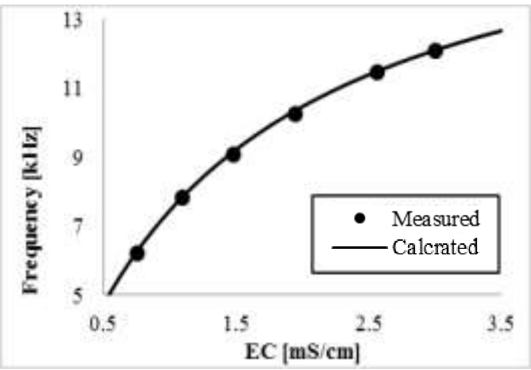

Fig. 6. EC vs. oscillating frequency

TABLE II. ERROR RATE OF EC VALUES

Measured (mS/cm)	Calculated (mS/cm)	Error rate (%)
0.75	0.75	0.082
1.096	1.10	0.381
1.482	1.46	1.355
1.942	1.91	1.885
2.564	2.57	0.044
3.002	3.00	0.006

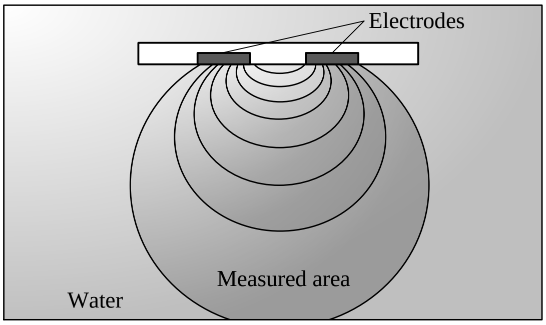

Fig. 7. The area which can measure EC

$$EC = \frac{1}{\frac{1}{2.2C_2 f_{EC}} - R_2} \ [S/cm] \tag{2}$$

It is said that typical EC value for hydroponic culture is between 1.0 – 2.5 mS/cm. In order to minimize variation of error between the EC values from Equation (2) and the sensor module around this range, the circuit parameters are determined as C_2=3.25μF and R_2=735Ω. Then, operating frequency of the sensor was measured by changing EC of water by mixing salt. The EC value of the salt water was measured by the EC meter shown in Fig. 5 and Table I. The measured values accord well with the calculated values as shown in Fig. 6 and Table II. However, the error rates around 1.5 – 2.0 mS/cm is slightly higher than the others in Table II. In the measurements, the electrodes are dangled in a water container about 3-cm above from the bottom. The gap between the electrodes is 10 mm and 2 – 3 cm area around the electrodes affects the EC values as shown in Fig. 7. Therefore, small displacement of the electrodes causes the increase of the error rate.

IV. WATER LEVEL SENSOR

The Schmitt-trigger relaxation oscillator shown in Fig. 8 is used for the water level sensor. C is the capacitance between two adjacent wires of the ribbon cable, and changes according to the substance around the cable such as air or water. The capacitance is grounded, and thus the GND line is shared with a temperature sensor attached to the electrodes to reduce resources. The ribbon cable was soaked into saline solutions, and oscillation frequency was measured by changing water level and EC value. As shown in Fig. 9, not only the water level, but the EC value also changes the frequency because it affects the capacitance C. The capacitance C of the cable is defined as Equation (3), where f_{WL} is the oscillating frequency of the water level sensor.

$$C \cong \frac{1}{f_{\mathrm{WL}} R_4} \ (F) \tag{3}$$

Fig. 10 shows the capacitance of the cable calculated by Equation (3). The capacitance is linear with respect to the water level for each EC value, and thus the water level can be easily calculated from the capacitance.

Fig. 11 shows an equivalent capacitance model of the cable. C_v is the capacitance inside of coating determined by

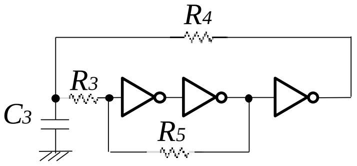

Fig. 8. Schmitt-trigger relaxation oscillator

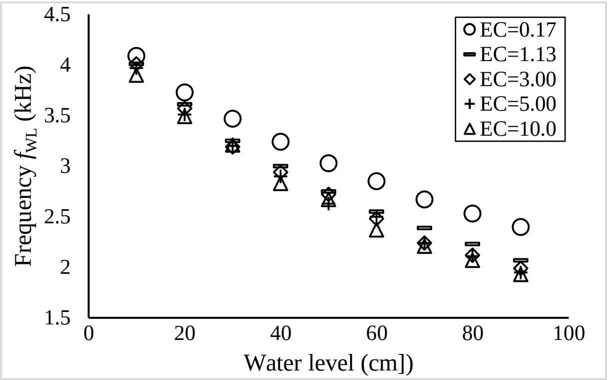

Fig. 9. Oscillation Frequency vs. water level

length L of the cable. The capacitance C_v which is outside of the coating changes according to the water level x. When C_v changes to C'_v, then the total capacitance of the cable $C(x)$ is defined as Equation (4).

$$\begin{aligned}C(x) &= \int_0^x \frac{C_cC'_v}{C_c+C'_v}dx + \int_x^L \frac{C_cC_v}{C_c+C_v}dx \\ &= \frac{C_cC'_v}{C_c+C'_v}x + \frac{C_cC_v}{C_c+C_v}(L-x) \\ &= \left(\frac{C_cC'_v}{C_c+C'_v} - \frac{C_cC_v}{C_c+C_v}\right)\mathrm{x} \\ &\quad + \frac{C_cC_v}{C_c+C_v}L\ (\mathrm{F}) \qquad (4)\end{aligned}$$

Here, $\frac{C_cC_v}{C_c+C_v}L$ is the capacitance of the cable when the water level is 0. Then, Equation (4) becomes as follows.

$$C(x) = \left(\frac{C_cC'_v}{C_c+C'_v} - \frac{C_cC_v}{C_c+C_v}\right)x + C(0) \qquad (5)$$

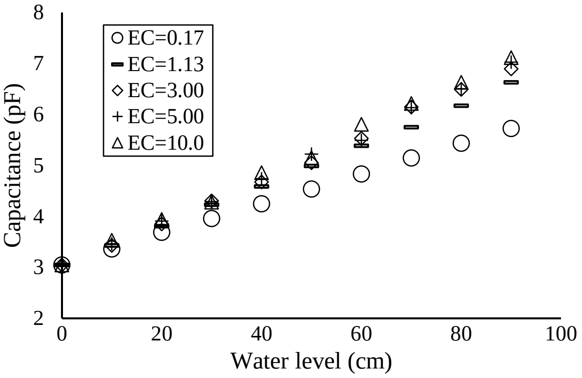

Fig. 10. Capacitance vs. water level

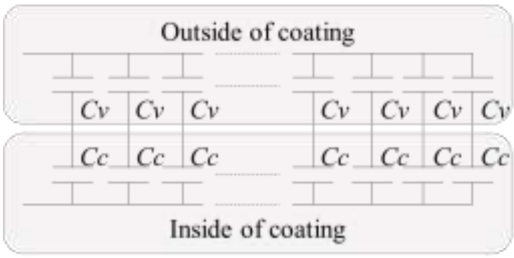

Fig. 11. Equivalent circuit of ribbon cable

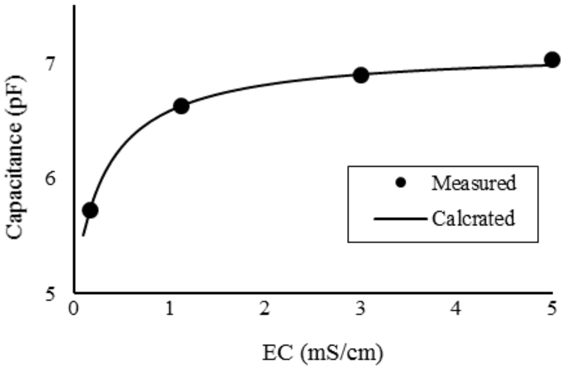

Fig. 12. Capacitance vs. EC

TABLE III. ERROR RATE OF WATER LEVE

EC (mS/cm)	Calculated value (pF)	Measured value (pF)	Error rate (%)
0.17	5.73	5.73	1.63×10^{-5}
1.13	6.63	6.63	7.73×10^{-5}
3.00	6.90	6.89	0.115
5.00	6.98	7.03	0.691
10.00	7.05	7.12	0.960

C'_vchanges with EC, but when EC is constant, $C(x)$ is linear to x. $C(0)$ is not affected by EC because it is the value of the cable in the air. Therefore, the water level can be calculated from the capacitance of the cable. When EC is increased, the cable capacitance is saturated as shown in Fig. 10. Therefore, the slope of $C(x)$ can be calculated from two points on $C(x)$, for example, $C(90)$ and $C(0)$. Here, we assumed relation between EC and the capacitance as $C(e)$, where e is the EC value, C_{sat} is the saturated capacitance and α, β, γ are parameters.

$$C(e) = \left(1 - \frac{\alpha}{\beta \cdot e + \gamma}\right) C_{sat}\ [F] \qquad (6)$$

We set the parameters $\alpha = 9.81, \beta = 0.0981, \gamma = 33.6$ to minimize errors between measured and calculated capacitances. As shown in Fig. 12 and Table III, the measured capacitances are in agreement with theoretical values, and small error rates less than 1 % were achieved.

V. CONCLUSION

We developed a sensor module for a hydroponic culture system, which can measure water level, EC, and water temperature values with a single device using a low-cost ribbon cable. The water level and EC values are converted from oscillation frequencies related to the capacitance and resistance of the device using the cable ribbon. The conversion method with approximation calculation were described and its high accuracy was demonstrated. However, it was found that there is a need to review the structure of the electrode for measuring EC.

The sensor module is being tested in the new hydroponic culture system of Fig. 13 that is 8-times larger than previous one of Fig. 1 for actual application and commercialization. In addition to tomato we cultivate various plants such as melon, zucchini, pumpkin, eggplant and herbs, all at the same time. We are also developing a raising seedling system as shown in Fig. 14, where the sensor module is used. Not only the three sensor values, but more parameters of cultivation environment and wireless communication will be supported by the module to introduce the systems into various locations in city area.

Our target is not to raise production efficiency of a single vegetable in a large plant factory, but to provide fun of cultivation with a variety of plants to users as a service business. In addition to the hardware development, we are going to develop remote management software on mobile terminal and communication tools for the user to expand new agriculture for fun.

Fig. 13. New hydroponic culture

Fig. 14. Raising seedling systems

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