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Designing Sensor Node to Measure Soil Moisture Used in IoT Network

Hieu T. Nguyen**, Hung N. Kieu, Hieu B. Nguyen
Posts and Telecommunications Institute of Technology, Hanoi, Vietnam
**Corresponding author email: hieunt@ptit.edu.vn*

Abstract

Together with the Industry 4.0 revolution, the IoT networks have been continuously growing, accompanied by the invention and improvement of communication protocols and sensor terminals. New sensor nodes in the IoT systems need to adapt to the protocol and optimize the built-in data collection and measurement capabilities. In this paper, we present a new development direction for the IoT network sensor node, namely the use of a capacitive sensor principle to research and develop the sensor node to measure soil moisture. Simulation has been carried out to evaluate the advantages and disadvantages of the method and to propose the applicability of sensor nodes in IoT systems.

Keywords: Coplanar plate, IoT, soil moisture, MySensors, STM32F030F4P6.

1. Introduction

In recent years, along with the rapid development of sensor devices, soil moisture has become an important parameter, which should be controlled in many fields such as agriculture [1,2], geology, ecology, biology, and hydrology [3-5]. Manufacturers have been constantly developing and improving sensor devices to control this factor.

However, most of the products currently available in the market focus on controlling this factor only on specialized equipment [6,7]. With the increasing demand for soil moisture measuring, producing powerful, low-cost equipment with reliable measuring abilities remains a challenge.

Capacitive sensing technology has been applied to address this challenge [8]. From the basic physical phenomenon of a capacitor with two coplanar poles, many studies have investigated to achieve an optimal design. The factors forming the two plates such as the width of the plate, the thickness of the probe [9], the frequency of scanning the plate [10], the material of the plate [6] are all utilized thoroughly.

The general design for this type of sensor has two directions, namely, the scanning design using a fixed oscillator circuit [10] and a controlled scanning circuit [11].

The sensor types using fixed frequency oscillators require a lot of research and development efforts for surveying as well as high-cost materials. However, thanks to the elaborate investigation, these sensor types always have high accuracy and stability with environmental factors. In contrast, the sensor lines used with a controllable sweep frequency are greatly influenced by environmental noises. These controllable sensor types usually use a microprocessor to serve the control operations [11,12]. This makes the research process much more convenient than that of fixed frequency oscillators.

In general, the soil moisture sensors have achieved certain results, but it is still a separate development of each module. To use these sensors, users have to spend a lot of money to be able to ensemble all the modules into a single system.

Inheriting previous advancements of sensors using capacitive sensing technology, we decided to choose a sensor design with a controllable scan frequency. With this direction, the product will aim for high integration, short survey time, low cost, and high performance.

The content of this paper is divided into five parts. Part 2 presents the theoretical basis of the capacitive sensor principle and measurement method, some products of the same type. Part 3 presents the direction of design, manufacturing, and optimization. In Part 4, the experimental results are presented and discussed. Finally, Part 5 concludes the paper and suggests the development direction.

2. Theoretical Background

2.1. Capacitive Sensing Technology

Capacitive sensing technology is based on exploiting the voltage difference between the two plates of a capacitor (Fig. 1) [4]. In practice, the performance on capacitors of the two most common types is parallel capacitors and coplanar capacitors.

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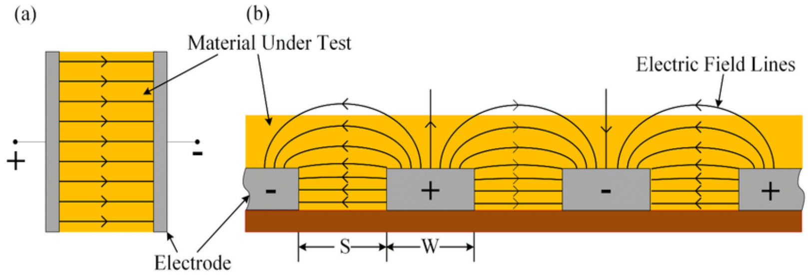

Fig. 1. Electromagnetic field of the capacitor: a) parallel plate capacitor b) coplanar plate capacitor

Based on the change in the environment between the two plates of the capacitor, many products have been invented such as touch screens, fingerprint sensors. Therefore, the use of this principle to develop sensor is possible to measure soil moisture.

2.2. Measurement Method

Most of the current microcontrollers on the market have built-in analog-to-digital converters (ADCs) that can be used to measure voltage. Taking advantage of this, a change in the environment around the ADC readout will cause the ADC reading to change accordingly as is shown in Fig. 2.

In Fig. 2, C_x is the measuring environment corresponding to the voltage U_x and C_0 is the parasitic capacitor in the MCU corresponding to the voltage U_0.

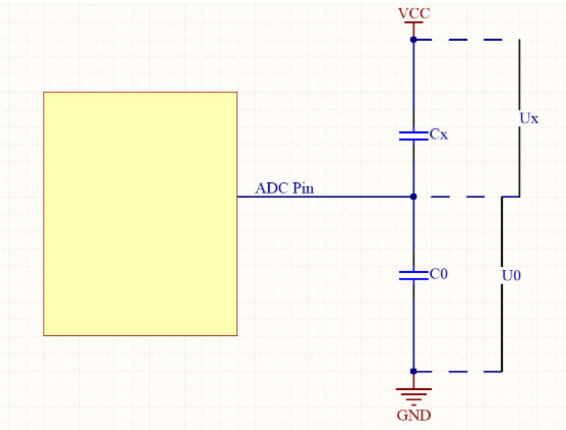

Fig. 2. Principle of voltage measurement of microprocessor

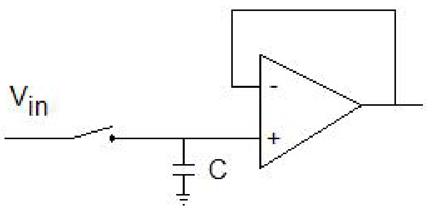

Fig. 3. Analog-to-digital converter (ADC)

In fact, when starting to read an ADC channel (Fig. 3), the obtained value is the voltage caused by the environment around the measuring channel. Compared to the GND of the processor, there is one more default parasitic capacitor.

Whether the voltage is read continuously or discretely, analog signal will be greatly affected by this parasitic capacitor. Furthermore, the specification of this component is not provided by the manufacturer. Therefore, if we simply read the analog values, the results will be skewed due to two following factors: noise from the environment and noise caused by parasitic capacitors. However, this is the premise for developing voltage measurement techniques in the next section.

2.3. Some Available Soil Moisture Sensor Products on the Market

If specialized equipment is not taken into account, soil moisture sensors have two main types, with control and without control of the sweep frequency.

2.3.1. Sensor type with sweep frequency control

This type typically uses an LC oscillator or an IC oscillator (e.g. NE555) to determine the time period of signal acquisition (Fig. 4). The result is returned in the form of an analog signal.

Advantages: integrated probe and control circuit in the same device with the compact size of 99mmx16mm.

Fig. 4. Sensor with sweep frequency control

Disadvantages: the control circuit has a fixed function that leads to a low adjustment and compatibility, and is difficult to install customizations according to different intents. Additionally, it needs to be connected to the radio and control unit to become an IoT node.

2.3.2. Sensor type without control the sweep frequency

The sensor measures according to the principle of exploiting the voltage difference between the two sensor branches (Fig. 5). The results obtained will be passed through an amplifier circuit to enhance the signal. Then, the result is returned as an analog signal.

Advantages: Energy-saving, sensitivity adjustable by using resistor.

Disadvantages: the device consists of many separate blocks, since the circuit uses a rheostat, the device's accuracy is affected by the weather and the environment. Moreover, the device needs to be connected to the radio and control unit to become an IoT node.

In general, the products on the market have achieved promising results, but are mainly still stuck in the form of discrete modules. These sensors will only work well in certain environments due to low customizability. If integrated into a large system, it will be expensive as well as difficult to install. Therefore, it is essential to design and manufacture a versatile, highly customizable humidity sensor. This sensor should not only evaluate on single tests but also integrates ready-to-build features into an IoT node prototype and immediate use in the data collection system. The application will be meaningful both in terms of technique and practical application.

3. Design and Manufacture of Product Prototypes

In this section, we will demonstrate voltage measurement techniques, perform product design, and optimize prototype designs.

3.1. Voltage Measurement

From the above theoretical basis, it can be seen that only discretely measuring ADC values on a signal measurement pin will not be able to promote capacitive sensing technology. Capacitor Cx must be discharged after each measurement and charged before a new value is measured.

The continuous measurement model is shown in Fig. 6. With this measurement technique, the obtained ADC value will reflect the change in the environment continuously. Then the obtained results will be put into a statistical model to describe the variation of the environment around the signal measuring pin.

We calculate the average signal of *N* samples as:

$$E(X) = \frac{1}{N} \sum_{k=1}^{N} \mathrm{X(k)} \quad (1)$$

Fig. 5. Sensor without sweep frequency control

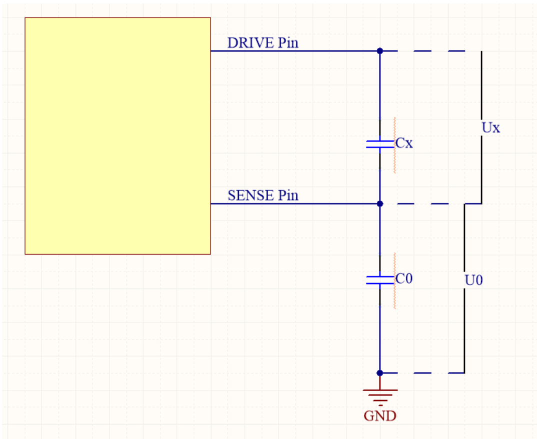

Fig. 6. Controllable scanning system principle

or $P_{Signal} = E(X)$

The variance of N samples is calculated:

$$Var(X) = E[(X - E[X])^2] \quad (2)$$

Noise is determined as:

$$P_{Noise} = \sqrt{Var(X)} \quad (3)$$

Then the signal-to-noise ratio (SNR) is

$$SNR = \frac{P_{Signal}}{P_{Noise}} \quad (4)$$

The above statistical equations show the following:

- The smaller the P_{Noise} magnitude, the more accurate the measurement
- The larger the SNR, the more precise the measurement
- The smaller the measurement time, the more effective the control of the measurement environment

3.2. Sensor Design

For the purpose of designing to integrate sensors and IoT nodes into a single product, we have chosen STM32F030F4P6 as the control MCU.

From the reviews of the previous section, the measurement of the signal cannot be completely dependent on CPU. This is mainly because using the CPU for measurement operations will generate a lot of delays, causing a lot of measurement errors since the CPU has to calculate and control at the same time.

To overcome the disadvantage of timing, the measurement will be run entirely according to an MCU timer. According to the diagram in Fig. 7, the DMA and Timer will automatically take control steps to measure the values. Peripheral connection diagram is implemented as shown in Fig. 8. By this control model, the CPU only needs to take the obtained value, calculate and return the statistical values. However, in order to measure the correct values according to the theory and control model, the timer must operate relatively accurately in terms of time. The capacitor must be discharged, and the ADC must be activated correctly because improper control operations will lead to wrong results.

Therefore, we construct the measurement timeline as follows.

Fig. 9 is the ideal timeline for a measurement cycle. During a measurement cycle, the timer counts down to 0. In the timeline 4 events occur:

1. CC4: Timer activates ADC.
2. CC3: Timer activates DMA to control capacitor charging.
3. CC2: Timer activates DMA to get ADC value obtained after ADC finishes operation.
4. Update: Timer enabled DMA controller IO discharge capacitor.

Since it is not possible to simultaneously activate the ADC measurement and charge the capacitor, and to charge the capacitor also requires a transient time, we decided to measure the two channels alternately.

Thus, the measurement results of the secondary channel will be discarded and only the results of the main channel will be taken. In the above timeline, the selected secondary channel is channel 14. According to the documentation from the manufacturer [16], the STM32F0x has all 19 ADC measurement channels, 16 external channels and 2 internal channels. With a limited number of IOs, the STM32F030F4P6 only supports 10 external measurement channels [16], so the remaining measurement channels are connected to GND by default. Taking advantage of hardware availability, reading the ADC from channel 14 has absolutely no effect on channel 0 or the control model.

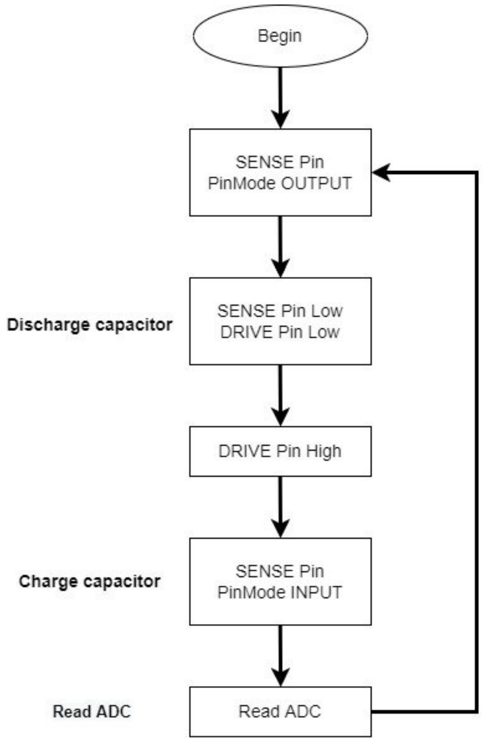

Fig. 7. Control model

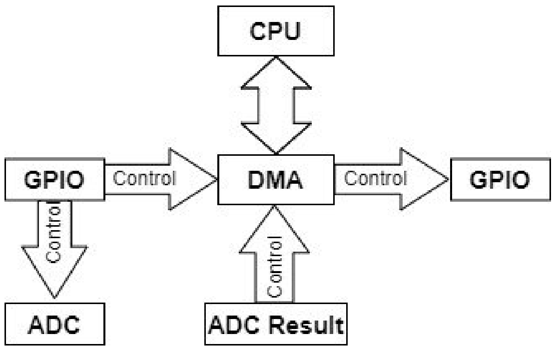

Fig. 8. Block diagram of peripheral operations

We conduct a survey of 4 timestones and conclude: CC3 is the most important milestone. CC3 must be after CC4 and before CC2. The best time will be the time for the highest signal-to-noise ratio. Conduct a CC3 survey running from CC4 to the end of the timeline for the following results. From the survey results, CC3 is selected so that the highest SNR is achieved.

These four timelines are completely interchangeable to accommodate different measurement environments and purposes. But the timestones are each very closely related to each other. If one timestone changes, the remaining parameters will have to change accordingly. In this survey, we performed experiments in an atmospheric environment.

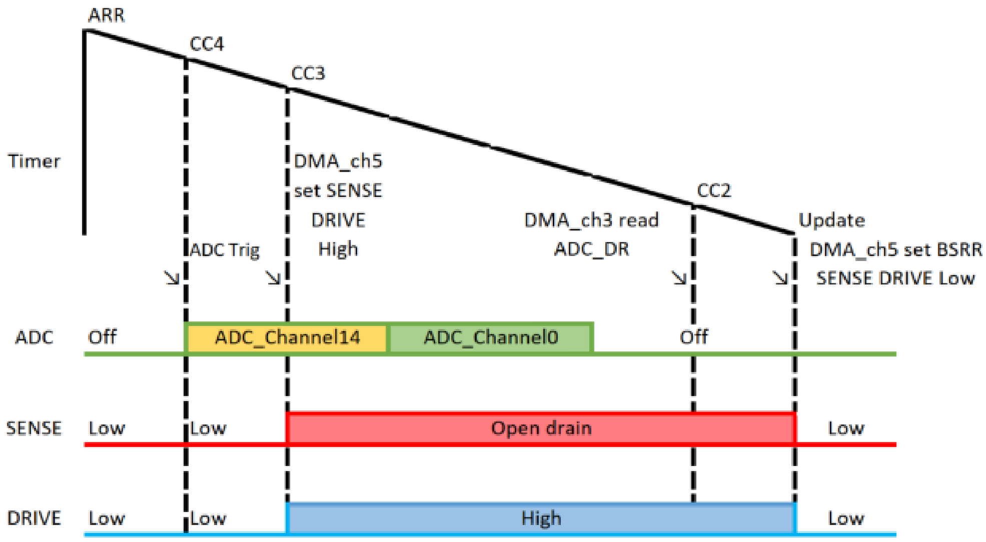

Fig. 9. Timeline of measurements

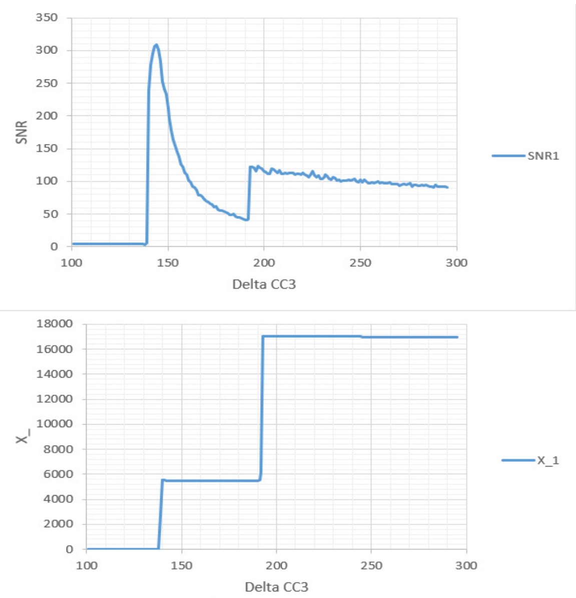

Fig. 10. Signal capability survey

3.3. Prototype Design

Applying the principle of operation of a coplanar capacitor, to design the transducer, it is necessary to pay attention to the parameters of the two plates (Fig. 11) [13].

The capacitance of the two plates will be changed depending on the environment around them:

$$C = \varepsilon_r \varepsilon_0 \frac{S}{D} \quad (5)$$

where the dielectric constant in a vacuum is

$$\varepsilon_0 = 8{,}854 \times 10^{-12}\, Fm^{-1}$$

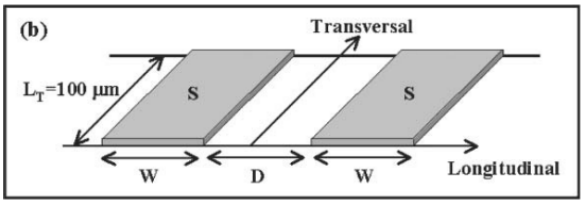

Fig. 11. Parameters of the pole plate

To increase accuracy and reduce survey time, we use a free, off-the-shelf platform to assist with probe design. Just enter specific parameters, this website [14] will give optimal results. Referring to the theoretical calculation parameters and experimental surveys of previous studies [8], the time used for hardware design has been significantly reduced.

Moreover, in designing a good probe that integrates the transceiver module is a difficulty in the research process. There are many good transmission modules today such as Lora, Zigbee, Bluetooth, infrared, RF. However, we have chosen the nRF24L01 transceiver module to integrate into the product [17]. With the advantage of cost, capacity as well as the ability to communicate with MCU simple, and being easy to use, nRF24L01 is the most suitable module. The circuit will act both as a sensor and a node in the IoT network.

Therefore, we focus on integrating the transceiver module while ensuring good transducer operability. The first prototype is designed as in Fig. 12, Fig. 13, Fig. 14.

Fig. 12. The top of our product

Fig. 13. The bottom of our product

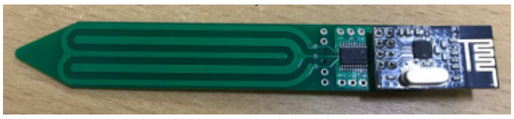

Fig. 14. Actual image of our product

Some characteristics of the designed sensor node are follows:

- Compact design with a size of 116 cm x16 cm.
- Integrated radio module nRF2401 to be able to transmit and receive data in an IoT network.
- Low power consumption.
- Suitable for large area smart irrigation systems.

All components have been integrated with the same circuit, so the device will be convenient and easy to use for people who are not knowledgeable about electronics.

4. Results and Discussion

This section presents an overview of the achieved results, discusses the comparison with other products on the market.

4.1. Experimental Model

The system model for evaluation of the humidity sensor and the IoT node operation is shown in Fig. 15

The model includes 1) IoT nodes designed by the team (Fig. 15); 2) IoT gateway; 3) Internet communication gateway; 4) Internet Cloud; 5) Computer. The functions of these components are:

- IoT Node: collecting information about soil moisture, then transferring it to the IoT gateway.
- IoT Gate: collecting and encapsulating information from IoT nodes to transfer to the internet communication gateway.
- Internet communication gateway: connecting IoT gateway via wireless or wired method, it is a bridge to bring information collected from IoT gateway to cloud and transfer control information from operating system to IoT gateway (if available).
- Internet cloud: storing information and data (here we use Things Board)
- Computer: used to collect, analyze, evaluate information, or give control commands.

4.2. Experimental Results

We evaluate the system with a random soil sample as shown in Fig. 16.

The average statistics of the results obtained in 1 hour are presented in Fig. 17.

We can have following comments:

- When the sensor is plugged into the ground, the sudden change in the environment results in a sudden change in sensor signal.

- During the first 10 minutes, the measured value from the sensor increases gradually due to the change in humidity.

- Since the sensor is designed to be very sensitive when the hand is close, it will cause interference.

- The capillary of the soil will determine whether the moisture change quickly or slowly.

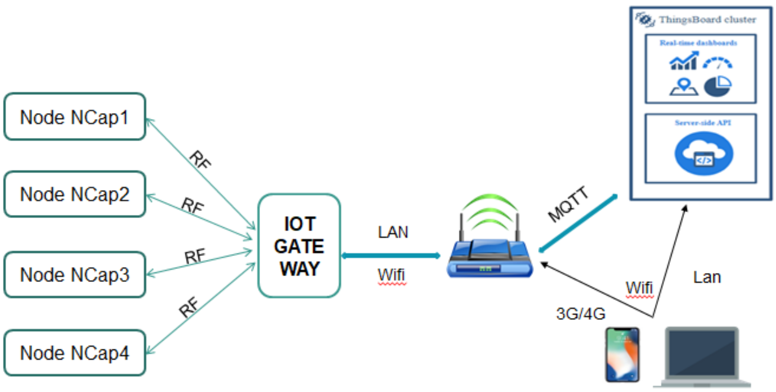

Fig. 15. Experimental IoT system model

Fig. 16. Experimental survey setup

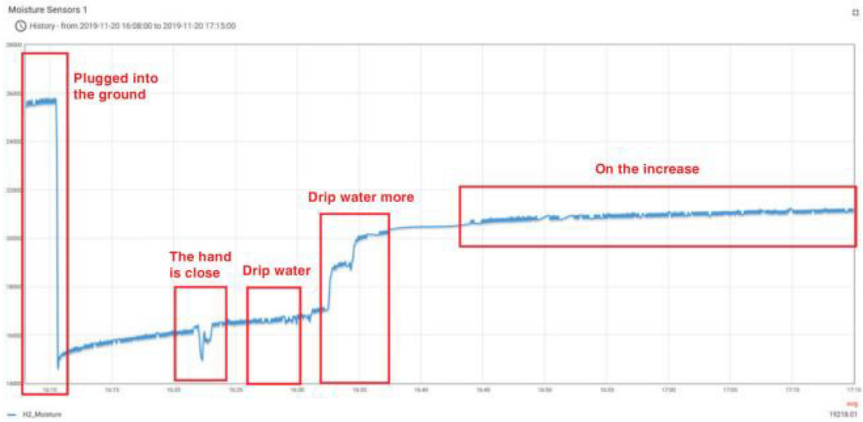

Fig. 17. Results of 1 hour survey

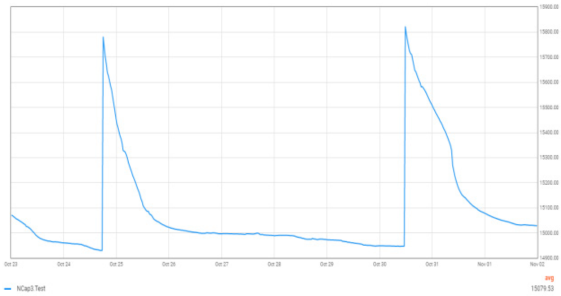

Fig. 18. Survey of soil mixed with sand

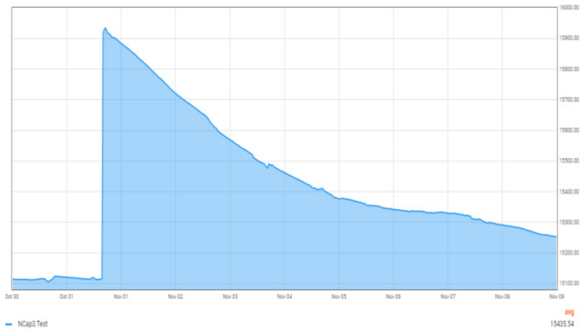

Fig. 19. Survey of soils that are not mixed with sand

Investigate the sensor's operation with different soil types such as soil mixed with sand (Fig. 18), and soil not mixed with sand (Fig. 19).

Comment: With sand-mixed soil, moisture decreases faster than in normal soil since the capillary will determine how the moisture change. This fact has proven that the sensor node is showing the correct moisture content in the soil.

4.3. Evaluate Advantages and Disadvantages

Advantages:

Compared with other moisture meter products on the market, our products have some outstanding features such as:

1. The ability to integrate transmission and reception communication: the node has a built-in radio communication module nRF24L01 that allows compatibility with many network protocols.
2. The ability to customize with the environment: due to the concrete flowchart, it is easy to obtain time samples corresponding to different soil samples. Sensors with the same principle are not currently able to do this;
3. Reduce production costs: due to integration of the communication module with the sensor, the IoT network, if used, will reduce the cost of buying separate sensor modules;
4. Low power consumption: the product does not require additional power for discrete modules and the CPU usage is optimized;
5. Using the MCU to preprocess input data to improve the quality of data sent to the monitoring and control center.

Disadvantages:

1. The sensor is extremely sensitive to the environment, so it is easily affected by unwanted factors directly affecting the sensor node.
2. The survey for each soil environment still has to be done manually.

5. Conclusion

Based on a developed technology, we have redesigned and improved a soil moisture sensor to integrate into the IoT node, thereby enriching the current sensor network components. With low cost, high performance, the product has given a promising direction for sensor design as well as IoT node design. This paper has focused on researching and finding a measurement method that is more effective than available products on the market, and the highlight is the ability to measure with control to help take initiative in methods and solutions to apply in practice. The product can completely replace similar products on the market.

In an IoT system in smart agriculture that needs to use a relatively large number of sensor nodes, it is important to consider the cost reduction and mastering the core technology when applying it to life. With a compact design, highly customizable, easily compatible with technical parameters according to the purposes of use, the ability to develop and apply sensors into practice is possible.

Based on the controlled measurement technique, the product can be improved to become other types of sensors that can be widely used in both production and life such as water, fog, obstacle or movement sensor.

To survey and evaluate products, we apply the sensor network system [15]. Thanks to the versatility of the nRF24L01, it may be suitable to operate under the more common IoT network that is Mesh network.

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