IMPROVEMENTS OF AN SMART-AND-CONNECTED LOW-COST SENSOR SYSTEM FOR MEASURING CANOPY PROPERTIES IN THE CENTRAL U.S.

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Abstract

This article describes the most recent updates on a smart-and-connected low-cost sensor system called I-Canopy Sensor that measures near-surface air(temperature, humidity, and pressure) and soil properties(temperature and moisture) in order to provide necessary data for irrigation systems. Designed and manufactured in Iowa, I-Canopy Sensor is a real-time solar-powered IoT device that can be used in urban or rural areas under a variety of conditions. I-Canopy supports both Wi-Fi and LoRa-WAN for short-distance and long-distance transmission. The updates improve the sensor performance by adding voltage control functions, Internet connection logic optimization, rechargeable NiMH battery research, and temporary data storage function. These improvements enable the sensor with an ability to run under extreme circumstances including but not limited to below-zero freezing weather, interruption of Wi-Fi and LoRa Wan signal, and poor battery energy capacity. I-Canopy sensor has been tested in farms in Nebraska and Iowa and urban areas in Iowa, Illinois, and New York. With the latest update, the frequency of unexpected shutdowns is greatly diminished. In the firmware part, this article will expand on the cause of different kinds of shutdowns and practical solutions implemented to mitigate the problems.

Introduction

With the development of agriculture in the United States, more and more advanced digital technologies are required in the modern plantation. A new smart-and-connected low-cost sensor system called I-Canopy sensor system was developed under the support of the United States Department of Agriculture to support the planning of irrigation. This I-Canopy system measures air and soil properties, which is subsequently used together with a weather and crop forecast model to optimize the irrigation strategy in the field and maximize the overall crop yield. The I-Canopy sensor was developed for four years and has performed tests in a variety of locations in Nebraska, Iowa, Illinois, and New York with different environmental conditions. With a high demand for precision agriculture, this kind of remote digital sensor, such as I-Canopy, is more and more accepted by local farmers and business. A major advantage is that the operator can gather information without manually reading and recording the data. Integrated prediction models then allow us to perform calculations based on measured data and forecast future soil conditions. From the feedback from some farmers in Scottsbluff, Nebraska, they are starting to get used to these real-time soil sensors and check the soil properties regularly every time when they do the irrigation. Additionally, the collaborator of our research team computes a recommended soil moisture level for each kind of crop for the farmer as a reference to get a maximized potential crop yield. The I-Canopy sensor measures air temperature, air pressure, relative humidity, soil temperature, and soil moisture at different depths, especially in the crop field.

I-Canopy sensor supports two kinds of data transmission which are Lora-Wan and Wi-Fi. The Lora-Wan can transmit data up to 10 miles in flat terrains [1], while Wi-Fi has a lower transmit range but better accessibility in the residential neighborhood. Therefore, in a large-scale rural circumstance, a LoRa version is usually in the crop field that lacks direct access to Wi-Fi. In urban or rural residential areas, the Wi-Fi version is used as it is readily available. Furthermore, the air sensor can be used separately if only the air measurement is needed, so the volume of the sensor will be relatively small. It is mainly used in the backyard of a residential house to monitor air properties. Fig. 1 shows the appearance of the I-Canopy sensor.

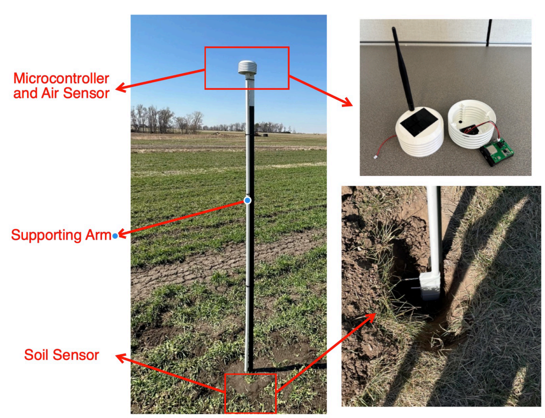

Fig. 1 I-Canopy sensor on a farm

The soil sensor in Fig. 1 is from a local farm in Iowa City. The air sensor is combined with a microcontroller and lifted to 2 meters. A soil sensor is inserted beneath the ground to measure the soil moisture at the root's depth, at 5 cm and 15 cm respectively. An antenna can be used to strengthen the receival of the Lora-Wan signal. Since the whole sensor is powered by solar energy and uses LoRa to transmit data, I-Canopy sensor is given the ability to operate far away from the residential area without any supply of power or Wi-Fi connection.

In the development, I-Canopy sensor production fully collaborates with Iowa Protostudio. The overall cost for the (soil and air) sensor and assembly is around $500. It is relatively cheaper than most of Lora-Wan sensors. After the massive manufacturing, the cost would be significantly reduced and comes below $250 since previously most enclosure component is 3D printed.
I-Canopy sensor is also potentially able to become a commercial product as we have developed a manufacturing process, installation tutorials, online database, sensor location mark on the map, graphical data lookup on the website, daily report routine, and so on.

Hardware Design

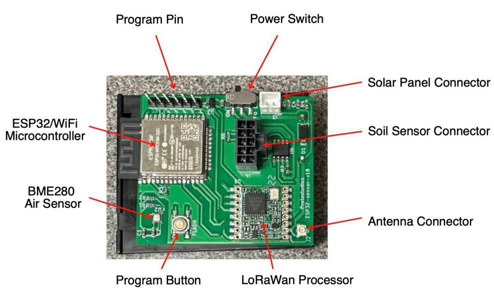

Fig. 2 PCB overlook of I-Canopy

I-Canopy sensor is built based on the ESP32 with Arduino as an IDE. The air properties are measured by BME 280 component, and the soil properties are measured by VH400 and DS18B20. Fig. 2 below shows a general component of the sensor. I-Canopy gathers all the air sensor components on this PCB, which means it is easy to program and install. At the back of the sensor, it contains three double A NiMH batteries for power supply. In the middle, it has a connection port to the soil sensor. It can be modified to connect to other meters such as oxygen sensors, and carbon dioxide sensors. The air sensor and the soil sensor have been tested in different areas in the U.S. to have high accuracy[2].

Firmware Design

In the past generation of the firmware, some battery voltage shortage problems can occur frequently, which leads to a brownout problem when measuring the data. The brownout problem means that components in the device cannot get a minimum power supply so that the device will automatically restart or hibernate to prevent the leak of memory[3], which is a built-in circuit protection function. The brownout voltage limit is usually higher than the memory-leak critical voltage. Even in the cases when the brownout function is disabled, a slightly lower voltage will eventually cause the restart problem. This unwanted restart clears out all the temporarily stored variables (such as boot count) in the memory. In some cases, the restart does not solve the voltage supply problem, so the device will keep restarting and eventually drain out all the power in the battery. To solve this, a failure voltage point is first analyzed based on the previous year's sensor operation data. Figure 3 is a histogram showing the frequency of voltage shortage occurring at different points.

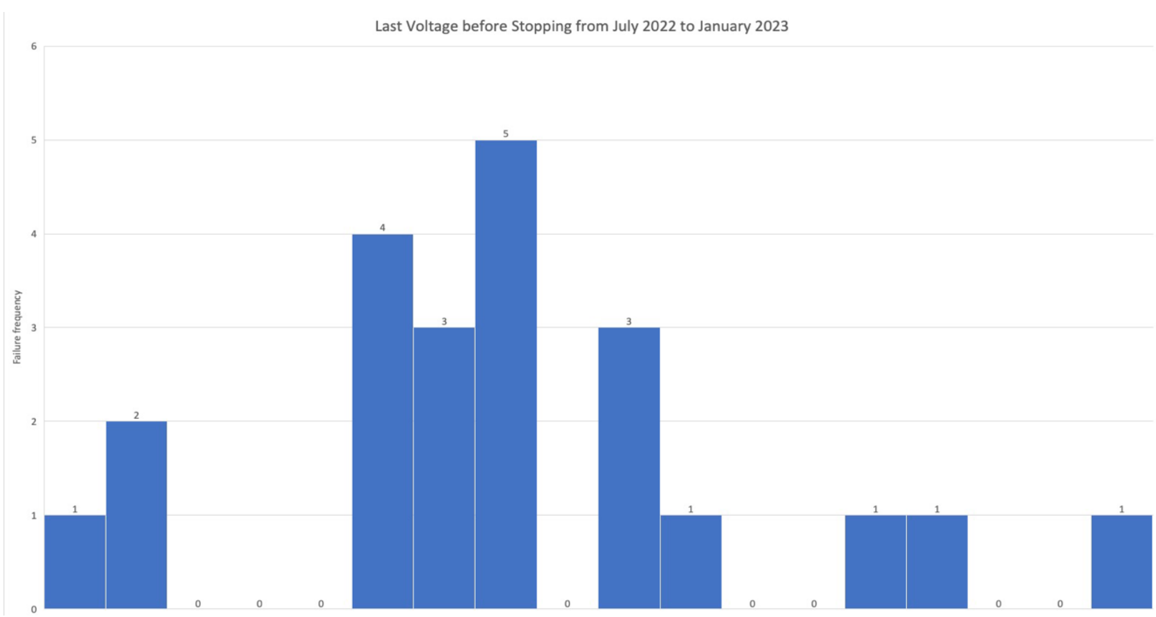

Fig. 3 Histogram of failure voltages

It is important to notice here that the battery age is a vital factor for battery performance. An aged battery has a lower capacity which means that the voltage can be more easily dropped from a high point to a low point. Fig. 3 shows that most failures (around 68%) happened under 3.433V. Therefore, the critical point is set to be 3.4V. Any voltage below it may have a higher chance to have a brownout problem. Thus, it is important to avoid this voltage range in daily operations. Consequently, the firmware is modified as shown in Fig. 4.

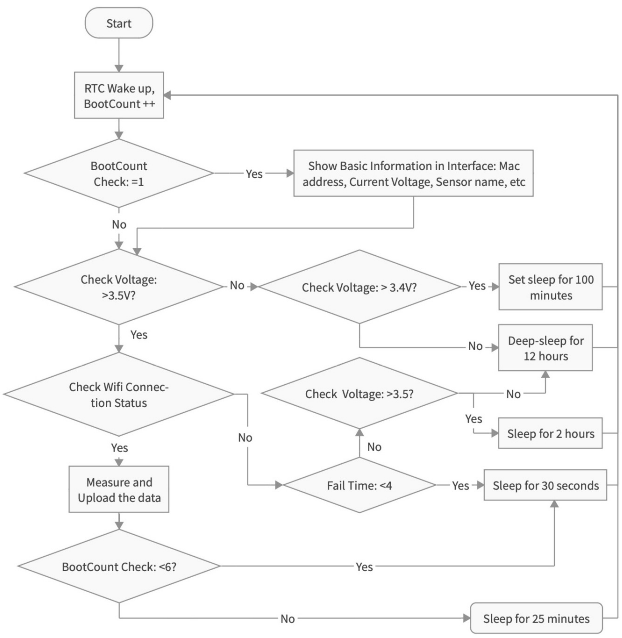

Fig. 4 Flow chart of the firmware design

Figure 4 shows a flowchart of a Wi-Fi sensor operation. When the sensor is started or turned on, it first wakes up and checks the boot count. If the boot count is equal to one, it means that it is the first time of operation. In the Arduino interface, some basic information such as device Mac address, current voltage, sensor ID, boot counts, and comments will be shown for programmers to identify sensor status. For every weak up, the voltage check function will check if the sensor is under a good voltage level before doing any environmental monitoring or any Internet connection. If the voltage is above 3.5V, which is considered a good condition, the sensor will measure the data every 25 minutes. If the voltage is between 3.4V and 3.5V, the status will be marked as a dangerous level, and the measured frequency will adjust to once per 100 minutes (instead of 25 minutes). This is to allow the sensor to perform normal measurements under certain weather conditions such as windy and rainy days when solar inputs are insufficient for a full charge of the battery. When the measured voltage is below 3.4 V, the wake-up interval is set to 12 hours. Because in common, the voltage starts to drop at night when there is no sunlight, most brownout problems also occur at night. The 12-hour gap skips the night and on the other hand, it ensures that the daylight period can be covered after the next wake-up. After checking and verifying the voltage level, the sensor will start to connect to the desired Wi-Fi network.

Once set up, the sensor automatically saves Wi-Fi access credentials and connects to the Wi-Fi each time when it wakes up. When the sensor is installed in the actual field, some users do not have a good awareness of the limitation of the Wi-Fi signal range. Since the sensor is usually placed in exterior places, the Wi-Fi signal may be blocked by a variety of obstacles, which may cause the sensor to lose signal frequently and miss some data. Meanwhile, in the battery energy aspect, the sensor will keep sending the request to connect to Wi-Fi until the Wi-Fi connection is established. Such a constant-connection mode costs a huge power consumption and may lead to a brownout problem. To prevent the aforementioned problems, two modifications were applied to the firmware. The first is to add a voltage-checking procedure after the first connection is failed. A boot count is used here to save the connection failure. In the beginning, it will wake every 30 seconds for a consecutive of four times to make the connection. This prevents data loss due to some Wi-Fi signal fluctuations. After four continuous connections in two minutes, if the sensor still cannot be connected, we considered the Wi-Fi signal itself has a problem, which means the Wi-Fi either have a weakened signal or be removed or lost the connection. Based on the voltage, if the voltage is in good condition which is above 3.5V, the sensor will attempt to make a connection every two hours. If it is not, the sleep interval will adjust to 12 hours to preserve energy. The second implementation is to store the measured data locally and send all saved data to the next valid connection. The data is stored in the internal memory in ESP32, and the data can be kept even after a restart. After connecting to the Wi-Fi and finishing the one cycle of measurement, the device will deep-sleep for 25 minutes, following the regular scheduling, until the next wake up.

The new optimized firmware was then applied to both Wi-Fi air version and Wi-Fi soil version. Figure 5 shows the four combined sensor performances. The voltage was protected to touch low voltage points, and at the same time, the data measurement was stable and continuous. As a result, it successfully eliminates the brownout problem through the Wi-Fi connection and voltage optimization.

Strong evidence here is shown in Fig. 6 when I-Canopy is tested during the winter, the air temperature falls around -10°C, which is 10 degrees below the operation limit of the battery. The battery had a lower capacity and received much less solar energy. The firmware optimization prevents the brownout problem occurs and had a frequent measurement at the same time.

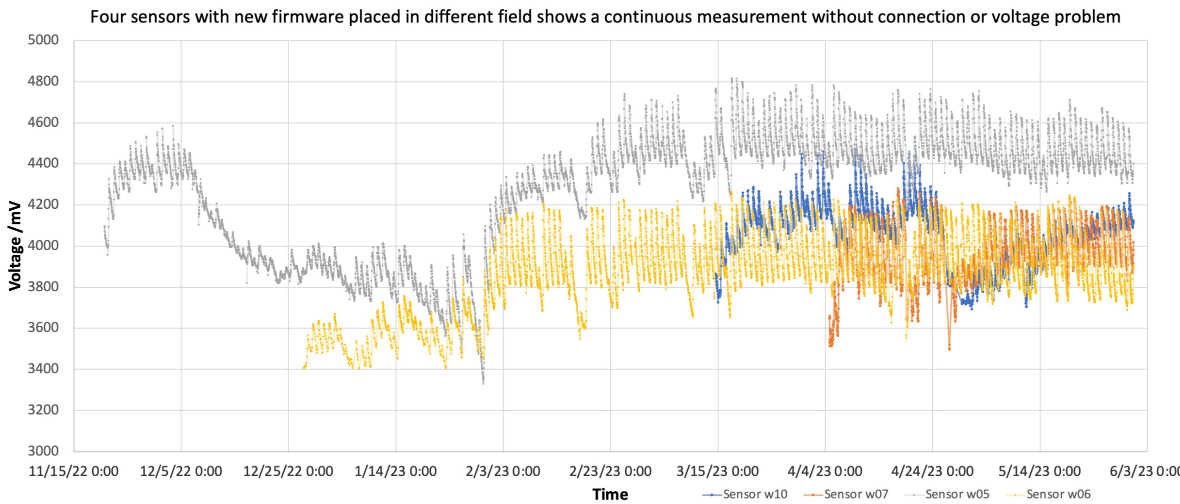

Fig. 5 The data of four installed sensors with the new firmware

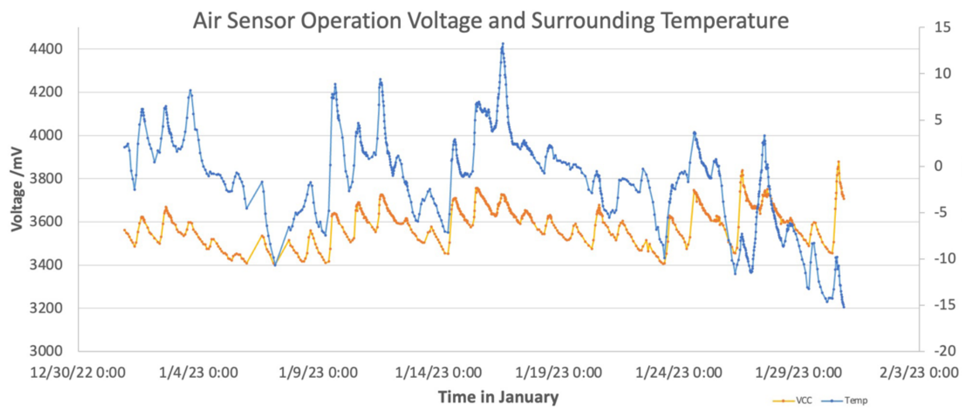

Fig. 6 Winter performance with the voltage control firmware

Conclusion

I-Canopy sensor provides a precise measurement of soil and air properties and supports Lora and Wi-Fi transmission to meet different IoT environments under different weather conditions. A recent voltage research along with the firmware update pushes the operation limit even further. The voltage check function ensures the sensor to go through the low voltage condition and still be resilient. The Wi-Fi connection logic prevents unnecessary energy loss and improves connection efficiency. The local data storage enables the possibility to run under poor Wi-Fi environments. Furthermore, in the next stage of development, we are planning to adjust the Wi-Fi connection interval based on the data storage to save more energy, and remote firmware update to simultaneously update all sensors under the system without physically reinstalling.

Acknowledgment

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Reference

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