Automatic Soil Testing Device for Agriculture

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Abstract. Farm produce is essential to feed growing world population, even as the area of land available for agriculture decreases. Farmers tend to over apply water and fertilizer to maximize crop yield, since knowledge of soil conditions is insufficient for a more targeted application. The over application of water needlessly uses a scarce resource, especially in drier climates. The over application of fertilizer wastes the fertilizer, increases greenhouse gas (GHG) emissions, and degrades downstream water as algae increases and oxygen decreases. The purpose of our project was to develop modules for soil testing and transmitting of data to the hub computer that would be accessible by the farmer. The sensors and transmitter were developed and tested to be mounted on a stake that would be implanted in the soil of the field, and results transmitted to a hub computer that would provide a dashboard of results and control for the farmer to use in making decisions. Prototype modules were developed for soil nutrients and pH. Modules were tested for monitoring moisture and wireless data transmission. Such a system would provide soil condition information that the farmer could use to more apply appropriate amounts of water and fertilizer, and not over apply.

Keywords: soil · moisture · nitrogen · phosphorus · potassium · NPK sensor · agriculture · stake · internet of things · IoT · ESP-32 · ESP-NOW · farm monitor

1 Introduction

Agricultural farming accounts for 70% of freshwater usage across the globe. Of that amount, 40% is used for crops. According to the Organization for Economic Co-operation and Development (OECD), by the year 2050 water demand will increase by 55% due in part to rising populations [1]. The risk of water scarcity will increase and there may not be enough water to distribute adequately between the various stakeholders. The limited water supply may become polluted from the overapplication of fertilizers, and poor management of manure and sludge [2].

Farmers desire to ensure enough water and fertilizer for their plants, so they may tend to over apply. Over application of resources is not only wasteful of those resources but may cause much harm. When fertilizer is overapplied, or if rain occurs soon after application, eutrophication may occur and promote the growth of harmful bacteria and algae [3]. Some soil microorganisms consume and convert excess nitrogen into nitrous

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oxide. Nitrous oxide is a greenhouse gas (GHG) that has a warming potential almost 300 times higher than carbon dioxide [4]. Runoff of fertilizer into surface water, rivers, and lakes can increase overgrowths of algae, or algal blooms. These algal blooms are harmful because they produce toxins and decrease oxygen content in the water [5]. One such toxin is nitrate, which depletes oxygen levels and thus is a risk to health [2]. In the U.S.A., agriculture was estimated to be responsible for about 700 million metric tons of carbon dioxide, methane and nitrous oxide that were emitted into the atmosphere. About 50% of that amount was nitrous oxide, annually released by bacteria in soil and seawater after excess nitrogen fertilizer was applied [6].

The quality of the soil for plant growth is dependent on the criteria of soil parameters such as moisture, pH, temperature, and macronutrient content. Farmers currently attempt to monitor soil quality by shipping a soil sample to a testing laboratory. Soil labs recommend testing every 3–5 years, where the test results are analyzed, and recommendations made for fertilizers to improve the quality of the soil. Farmers may also use at home soil testing kits to determine moisture content and pH. However, these methods are either costly, complicated, or time-consuming [7].

The concept of a stationary soil sensing station has been reported [8]. This concept could be developed to provide the user with real-time data about the soil conditions. Such a device should have the ability to monitor soil moisture content, pH level, temperature, and macronutrient composition, which could be used to optimize application of water and fertilizer, and minimize over application [9]. Automatic transmission of data could be performed from a microcontroller-based soil testing edge node to a hub computer. The hub computer would store a copy of the recommended soil parameters, and act as a web server where the farmer can see summary data, analyze the data, and input control parameters on a dashboard.

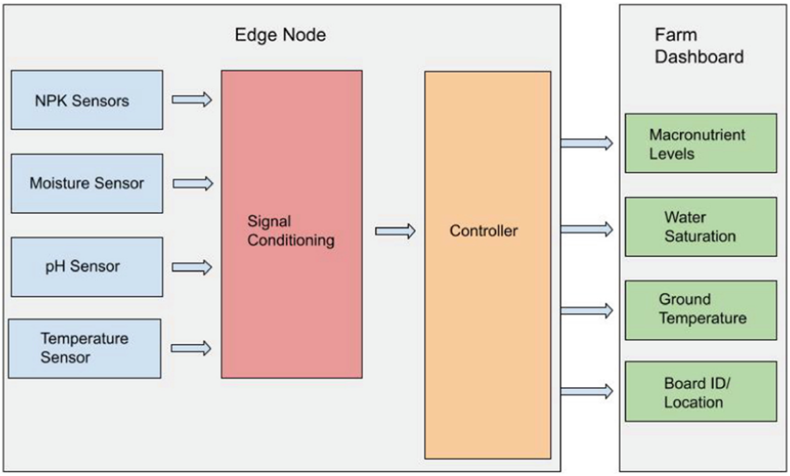


Fig. 1. Block diagram showing the edge node that would be mounted on a stake in the field, and the dashboard on a computer the office or home of the farmer. Communication between units is wireless.

The purpose of our project was to develop modules for soil testing and for transmitting of data to the hub computer that would by accessible by the farmer. The collected data of soil conditions could be analyzed to improve soil conditions in order to increase crop yield while conserving resources. This could result in a more optimal application of water and fertilizer, reducing the harm of overapplication.

2 Materials and Methods

The full design of the system had three units: an edge node mounted on stakes in the field, a hub computer and a web server with a dashboard accessible by the farmer (Fig. 1). One or more edge nodes would be mounted on stakes (Fig. 2) in the field to monitor soil and crop conditions. The edge nodes would wirelessly communicate to the hub computer. The farmer would interact with the web server through a dashboard.

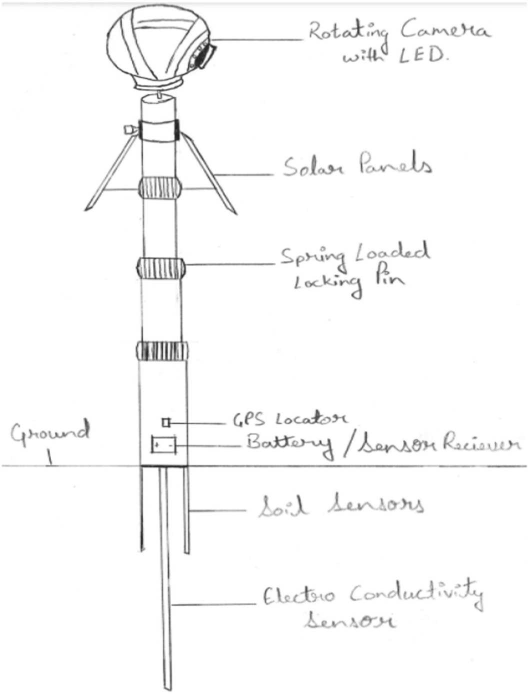


Fig. 2. The design concept has 3 below ground sensors and solar panels that would be externally mounted to the stake. All electronics and power supply for the edge node would be stored internally to stay protected from the weather. The prototype would be height adjustable, allowing for the solar panels to remain above the height of the crop and receive direct sunlight.

The edge node had sensors, including a water moisture sensor, a nitrogen, phosphorus and potassium (NPK) sensor, a pH sensor, a temperature sensor, and a camera. The edge node also had electronics for signal processing, microcontroller, wireless communication module and power management module. The hub computer had a corresponding communication module to receive that data from the edge nodes and transmit to the web server, which hosted a dashboard accessible by the farmer.

Modules of the design concept were implemented and tested as a prototype. The modules are seen in the system block diagram (Fig. 3).

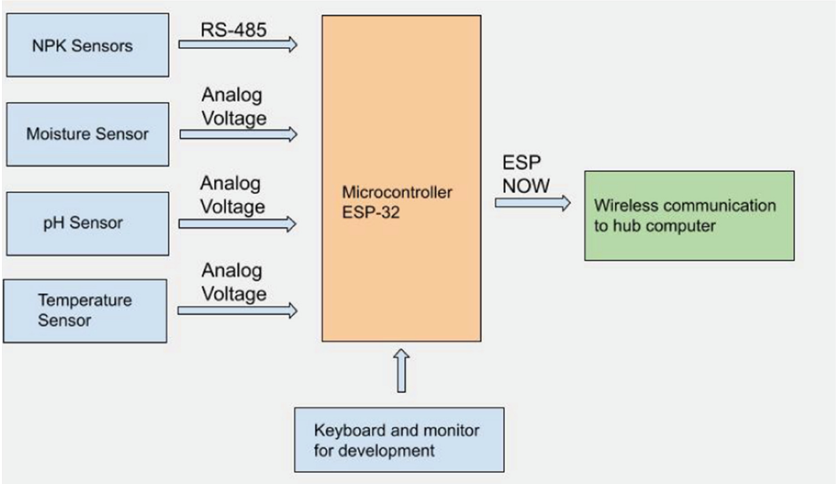
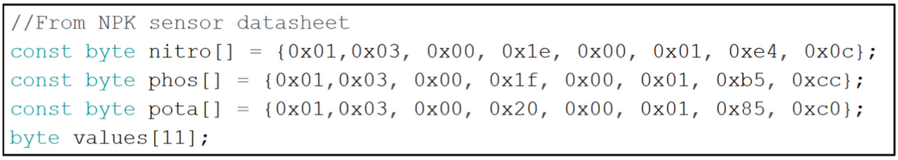


Fig. 3. System block diagram for the prototype showing communication methods between each component

In the prototype, the microcontroller for control, data acquisition and communication was the ESP-32 S3 (Espressif Systems, Shanghai, China). The ESP-32 S3 was programmed in C using the Arduino IDE.

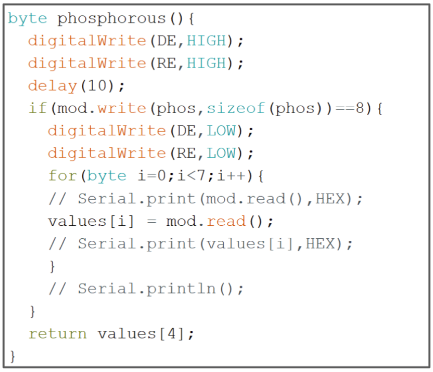
The design concept has the edge node mounted on a stake with the soil sensor probes in the ground. For the prototype, an NPK sensor (Taidacent, Shenzhen, China) was used, which has 3 electrodes, one for each element to be inserted into soil. An alternating current voltage was applied to excite the electrodes. An increase in conductivity would signify an increase in concentration of nitrogen, phosphorus, or potassium.



```
//From NPK sensor datasheet
const byte nitro[] = {0x01,0x03, 0x00, 0x1e, 0x00, 0x01, 0xe4, 0x0c};
const byte phos[] = {0x01,0x03, 0x00, 0x1f, 0x00, 0x01, 0xb5, 0xcc};
const byte pota[] = {0x01,0x03, 0x00, 0x20, 0x00, 0x01, 0x85, 0xc0};
byte values[11];
```

Fig. 4. Inquiry frame for all elements of NPK sensor, used to interpret RS-485 into analog values for the ESP-32 to read data values from the response frame for each element.

To communicate from the NPK sensor to the microcontroller in the edge node, the half-duplex RS-485 serial communication was used. Figure 4 shows the inquiry frame for the NPK sensor elements. The inquiry frame was used in the software that ran on the microcontroller for serial communication over RS-485. The RS-485 serial communication sent and received the data one bit at a time. Figure 5 shows the software function used to read the phosphorus concentration from the NPK sensor.

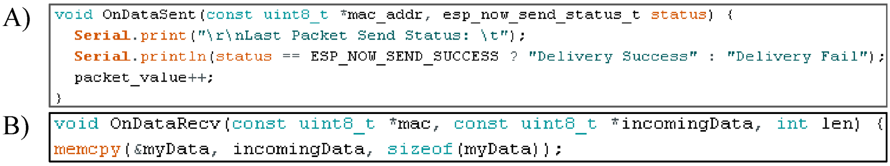


```
byte phosphorous(){
  digitalWrite(DE,HIGH);
  digitalWrite(RE,HIGH);
  delay(10);
  if(mod.write(phos,sizeof(phos))==8){
    digitalWrite(DE,LOW);
    digitalWrite(RE,LOW);
    for(byte i=0;i<7;i++){
    // Serial.print(mod.read(),HEX);
    values[i] = mod.read();
    // Serial.print(values[i],HEX);
    }
    // Serial.println();
  }
  return values[4];
}
```

Fig. 5. Function to read phosphorus concentration.

A module was developed to measure moisture content in the soil. The water sensor (ICStation, Shenzhen, China) used in the prototype had 2 metal prongs and returned an analog value based on how resistive the soil was. Resistance decreased as water content increased. The analog voltage value was then converted by the microcontroller into a percentage to display on the dashboard.

The pH sensor (Atlas Scientific Environmental Robotics, Long Island City, New York, U.S.A) used in the prototype was made of a single probe consisting of a glass electrode, made from a special glass containing metal salts and a reference electrode, which had a potassium chloride wire suspended in a solution of potassium chloride. By measuring the potential difference between a known solution and the soil, the pH was returned as an analog voltage value to the microcontroller.



A)

```
void OnDataSent(const uint8_t *mac_addr, esp_now_send_status_t status) {
  Serial.print("\r\nLast Packet Send Status: \t");
  Serial.println(status == ESP_NOW_SEND_SUCCESS ? "Delivery Success" : "Delivery Fail");
  packet_value++;
}
```

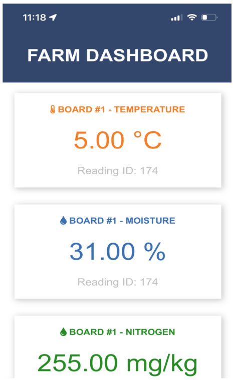
B)

```
void OnDataRecv(const uint8_t *mac, const uint8_t *incomingData, int len) {
memcpy(&myData, incomingData, sizeof(myData));
```

Fig. 6. ESP-NOW software callback functions to A) send and B) receive data.

Wireless communication was achieved using the ESP-NOW protocol. For the user to view data remotely, a chain mesh network would be used to pass sensor data along a series of edge nodes until a computer hub was reached in the network. Then the data would be uploaded from the computer to a web server. To pass the data along the chain mesh network, the MAC address of the receiving edge node was altered as shown in Fig. 6 according to the successive edge node in the network. The data from each edge node was passed as a C program struct with a device ID so that the location the data was coming from would be known.

The dashboard of the prototype was hosted on a web server from an ESP-32 hub (Fig. 7). The dashboard was made using HTML to display the data from the edge nodes. As the data was uploaded to a web server hosted on the ESP-32 hub computer, it could be accessed remotely from any device with a network connection.



11:18

FARM DASHBOARD

BOARD #1 - TEMPERATURE

5.00 °C

Reading ID: 174

BOARD #1 - MOISTURE

31.00 %

Reading ID: 174

BOARD #1 - NITROGEN

255.00 mg/kg

Fig. 7. Example of the dashboard of the prototype to display values from the sensor modules. This dashboard could be accessed on the phone or PC of the farmer. The displayed data was simulated on an edge node and then transmitted to the hub node, which published it to the web server.

Two power sources were used in the prototype: a 12-V source for the NPK sensor, and a 5-V source for all other modules.

3 Testing and Results

Two of the modules of the prototype were tested using the ESP-32 microcontroller: the soil moisture sensor and the wireless communication modules.

3.1 Soil Moisture

The moisture sensor was utilized to assess whether the module could classify soil between wet, good, and dry soils. First, the moisture sensor needed to be calibrated. The prototype module for soil moisture testing consisted of the moisture sensor and ESP-32 microcontroller. Results were displayed on an attached laptop computer display during testing.

The procedure to evaluate the moisture sensor was to progressively add water to a sample of soil, mix and measure. A plastic tumbler with a diameter of 7 cm was filled with loam soil, such that the bottom 13 cm of the tumbler was filled with loam. The loam was obtained at a consumer gardening store, and was used as the soil for this test procedure. The first measurement was made prior to any water being added, so the loam was considered dry. Thereafter, known amounts of water (multiples of 5 mL) were added and mixed with the loam, then moisture was measured again. Prior to each measurement, the sensor electrodes were wiped clean with a cloth, inserted into the freshly mixed loam, 30 s were allowed to pass prior to recording the moisture value to ensure the sensor reached a steady state. Two moisture sensors were used for each trial. The ICStation sensor used in the prototype and a commercial moisture sensor (Sonkir, MS02, Ashland City, Tennessee) were both used. The Sonkir sensor values were reported on a scale from 1 to 10, with 1 being dry and 10 being moist. The commercial sensor was used to help classify the soil as dry, good and wet.

Five samples of dry loam had this testing procedure done. The total number of trials was 30. The number of trials for one loam sample ranged from 2 to 10. The results of the measurements are shown in Fig. 8, a scatterplot of the raw reading on the microcontroller for the moisture sensor vs. the known amount of water mixed into the soil. The raw sensor values decreased as the amount of water increased. An equation for linear fit and a R^2 values were determined for the measurements in Fig. 8. The R^2 value was only 0.67, so the relation was not strongly linear.

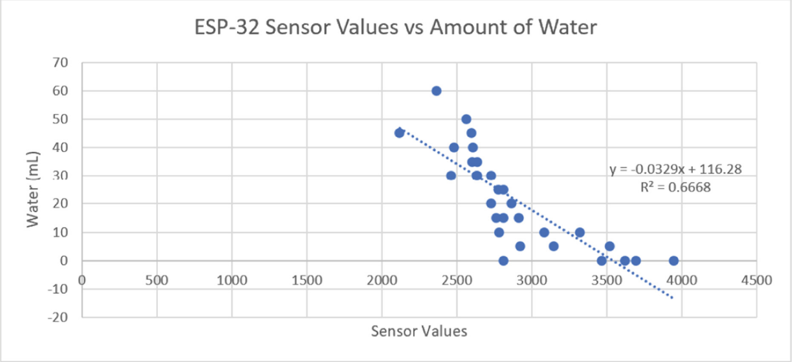


Fig. 8. Uncalibrated Sensor Readings vs. Amount of Water (mL).

A similar plot was made for the values (1–10) from the Sonkir sensor vs. the known amount of water mixed into the soil (Fig. 9). The Sonkir value increased as the known amount of water increased, but the relation also had a moderate R^2 value of 0.67. Based on this analysis, the relation between the moisture sensor readings and the Sonkir values could be determined and used for classification of soil moisture level.

3.2 Wireless Communication

ESP-NOW is a wireless communication protocol developed by Espressif. ESP-NOW is compatible with ESP-32 boards, inexpensive and may have a higher transmission range in comparison to some other protocols. The ESP-NOW communication protocol had a specified range of 76 m. To assess the effective range of ESP-NOW in a natural outdoor space, a test was conducted by sending 30 data packets at various distances and determining the packet error rate (PER). Each packet contained 250 bytes of data, which was the maximum packet size. For each distance, 30 data packets were sent. The

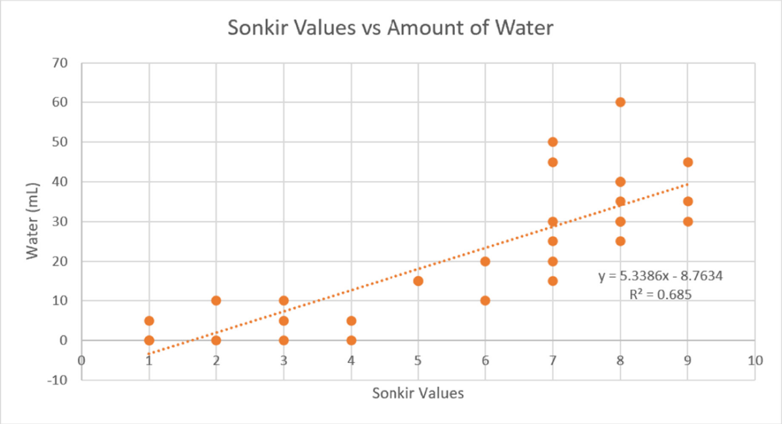


Fig. 9. Sonkir Readings vs Amount of Water (mL).

tests were conducted at a park on the university campus. Distances of 46 m, 76 m and 107 m were tested for the 30 data packets and the average PER was determined for each distance. The assessment was to count how many packets were received, and compare that to the number sent. The difference in number of packets was considered the error.

Table 1. ESP-NOW Packet Error Rate (PER) Tested at Various Distances

Distance (m)	Packets Received			Average Packet Error Rate (PER)
	Trial 1	Trial 2	Trial 3	
46	30	30	26	4.4%
76	28	27	26	10.0%
107	15	10	8	63.33%

Results from testing showed that the ESP-NOW protocol could transmit data over all three tested distances, but the PER of errors increased with increasing distance. Results are shown in Table 1. Performance on a farm may be no worse than the tested conditions, since testing was conducted in a large park in an urban environment. Since there were some errors at all the tested distances, the software should add an error detection and retransmission scheme.

4 Discussion and Future Directions

Prototype modules were developed for measuring in the soil the following: nitrogen, phosphorus and potassium (NPK), pH, temperature and moisture. Testing was done toward calibration of the moisture sensor with moisture content in the soil. A communication module was developed and tested using the ESP-NOW wireless protocol. This could be used in a mesh network to pass messages from the soil monitoring stakes back to a hub computer. A prototype hub was made with the ESP-32 microcontroller that hosted a website that displayed a dashboard of sensor values. The farmer would be able to view the website to make decisions about application of water and fertilizer.

The design and testing results appear promising. More development to complete the envisioned system and testing would be required toward full implementation. Development of such a system would help farmers monitor soil parameters and assist with the application of appropriate amounts of water and fertilizers, reducing the need of over application of these resources. Minimizing over application of fertilizer would reduce the amount of pollutants downstream.

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