Miniature Nutrient Plant Sensor

DESIGN DOCUMENT

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List of Definitions

1. **ADC:** A device that converts Alternating Current (AC) into Direct Current (DC).
2. **Biofilm:** A thin film of organic matter, that is formed by secretions from decaying plants and insects, in a habitat.
3. **CSV**: Comma Separated Values.
4. **Etching:** Here, the use of strong acids and bases, to dissolve parts of a silicon wafer.
5. **IP:** Ingress protection standard
6. **ISM**: Ion Selective Membrane that allows NO_3 to pass through.
7. **Lifetime:** The number of days a sensor can last in the field, without requiring a change of batteries.
8. **LoRa/ LoRaWAN**: Long Range Wide Area Network used for long range communication.
9. **Margin**: The edge or border of a leaf.
10. **MCU:** A microcontroller unit like an Arduino.
11. **Midrib**: A large strengthened vein along the midline of a leaf.
12. **mm:** Millimeter ($1/10^3$th of a meter).
13. **NaCl/KCl**: Sodium Chloride or Potassium Chloride layer on the reference electrode.
14. **Needle sensor**: A sensor that is 2.5 mm thick and 12mm long, and is inserted either at the stalk or root of the plant.This is the device that records the nutrient levels in plants.
15. **nm:** nanometer ($1/10^6$ th of a meter).
16. **Nutrient levels:** Here, we are concerned with Nitrogen, Phosphorus and water levels in a plant.
17. **PCB:** An electrical board with a circuit printed on it.
18. **ppm**: Parts per million.
19. **Sensor**: A 3 inch silicon wafer with 100 needle point sensors (of various sizes) printed on it.
20. **Unit**: Here, the seven sensors and one Arduino, make a unit.

1. Introduction

1.1 Acknowledgement

We would like to thank Dr. Dong for contributing his time and effort in meeting with us weekly, so that we are able to get a better understanding of the project. Aside from that, we would not have managed to complete this Design Document without additional insights provided by Dr. Dong during our weekly discussions.

We are also very thankful for the assistance provided by Yuncong Chen and Xinran Wang. We would have wasted time and resources if it was not for their knowledgeable insight regarding the project design and, the workings and usage of the machineries that we will be interacting with throughout the entire project.

Besides that, we would also like to thank the people who had been working on the project before us. Without them, we would not have the foundation and current understanding of the design process of the plant nutrient sensor.

1.2 Problem and Project Statement

Problem Statement:

Soil conditions are never the same of two patches of land adjacent to each other. One patch could be dense in NO_3 (Nitrates), while the other could be dense in P (Phosphorus). For the best yield per acre, farmers need accurate data about the current nutrient levels in soil, in order to determine the right type and amount of fertilizer required for that acre. However, inaccurate data and the long waiting time on soil analysis results, often leaves farmers with incomplete information about current soil conditions, which has detrimental effects on the harvest of a crop. The unknown or inaccurate measurement nitrate levels in crops leads to excess fertilizer application and lower yields.

Solution Approach:

The solution to the problem is to provide farmers with a portable tool that reads and provides accurate data about current soil conditions on the field at any given time. With this solution in mind, the miniature nutrient plant sensor and its app were made. These sensors can accurately detect NO_3 levels in soil (on a daily basis) to ensure that farmers are well informed about current soil conditions. The data collected by these sensors are readily available on the app.

Purpose of the Project:

Even with the current prototype of the sensor and app, there is room improvement. As of now, the data from the sensors is not fully accurate, as the surrounding temperature and chemical compounds adversely affect the nitrate reading. Furthermore, the sensors also need to be equipped to deal with environmental hazards (dust, dew). Currently, the app only interprets and outputs the readings of the sensors via bluetooth or cellular service.

We are tasked with optimizing the sensors and the app, such that the sensors can read the nutrient levels accurately without being manipulated by their environment, and the app, can perform additional functionalities like sensor tracking or expanding its data transmission range. We are also required to find a way to encase the sensors, in order to prevent them from being damaged by environmental hazards, while ensuring that the integrity of the data is not compromised.

For this project, we are hoping to create sensors that are adaptable to their respective environments and are able to read nutrient levels in the plant accurately, without hindrance from environmental factors. At the same time, we hope to produce an app that provides convenience to the users, such that users will be able to track the location of the sensors and retrieve the data from the sensors from without being at close proximity to the sensors.i.e. long range data transmission.

1.3 Operational Environment

Although the project is tasked with finding the nutrient levels in soil, we will insert the sensors into the stalk, roots and leaves of plants because the plant provides a more stable environment than the soil for sensor implantation. The location of the needle sensors is determined by their lengths. The shorter needle sensors are used to detect nutrient levels in the roots and leaves of the plants, while the longer needle sensors derive data from the stalk of the plant. This implies that the sensor will be exposed to environmental hazards like extreme temperatures, water and dust. Aside from that, the sensors will also be exposed to biofilms, that can develop on the surface of the sensors, and deactivate the data collection capacities of a sensor altogether. The sensor will also be subjected to work in a controlled environment, like a laboratory, for testing purposes, mainly to test the accuracy of the data collected by the needle sensors.

1.4 Intended Users and Uses

Our end products consist of a plant nutrient sensor and an app. One of our intended users are farmers working in fields. By using the sensors, farmers will be able to obtained accurate live data regarding the nutrient content of the soil in the crop field. Researchers/scientists can also use these sensors to obtain real time data from plants, to help their research.

Aside from that, the app will provide a user interface which allows both the farmers and researchers to obtain the sensor data, quickly and effectively. This data can be obtained by the app via cellular network or bluetooth at their convenience.

1.5 Assumptions and Limitations

Assumptions:

1. Each sensor will have an average lifetime of 60 days.
2. The data log of the sensor can be stored in a database.
3. The casing of the sensor provides protection against environmental hazards.
4. The circuit box consists of rechargeable batteries, that can be charged using solar panels.
5. The sensors must be small enough for users to be able to carry it around easily.
6. The sensor will not be constantly exposed to extreme environments. For example, we assume that the sensor will not be submerged in water for an extended period of time.

Limitations:

1. High power consumption of the sensor. (1 W/ unit).
2. The configuration/build of the sensor is based on the environments experienced in the Midwest.
3. The app is only compatible with Android.

1.6 Expected End Product and Deliverables

The end product of our project consists of four main components. These four components are the circuit box, the sensors, a digital wireless data communication hardware, and the app.

The circuit box consists of a microcontroller unit (MCU), filter circuits, amplifiers and power supplies. The sensors are required to measure the nutrient levels accurately, such that they are within the acceptable error margins. Both the MCU and power supplies will remain the same, from its previous design, as they are the best possible options we have available to us. The sensors will be encased in waterproofing polymer coatings, to prevent water damage to the sensors..

As for the digital wireless data communication, we are expected to deliver a calibrated version of LoRa, where it can interact with the sensor, MCU, database, and the app. The expected end product, will allow users to request/retrieve data from the sensors within a 100 KM range, without relying on the bluetooth or cellular data.

Last but not least, we are expected to deliver an app that provides additional functionality to the users to grant additional conveniences. These functionalities include a sensor tracker, which displays a sensor’s geographical location, and an interactive form of data retrieval from the database, which enhances users’ accessibility to the data. The app must be able to interact with the digital wireless data communication (LoRa) as well. The addition of database system will provide a much more efficient system as it provides sufficient memory allocation for storing a large amount of data while at the same time also provide some form of security option where it only allows specific users to access the data. Hence, we are expected to deliver a configured database so that it will store the appropriate sensor’s data correctly.

When these components are combined, the users will interact with the app, and the app will look at the latest data stored in the database and display it. As for the sensors, they will periodically measure the nutrient content and store the data into database with the digital wireless data communication (LoRa) acting as the medium for transmitting the sensors data to the database.

2. Specifications and Analysis

2.1 Proposed Design

The IP64 standard was chosen as a guide for waterproofing our device. IP stands for ingress protection and is used to rate products for water and dust resistance[3]. The IP64 rating is designated as a dust-proof, and water splash resistant rating . The sensor will be exposed to lots of dust and although it will not be immersed in water, it will need to be protected from heavy rain or generally damp conditions. The IEEE-315-1975 standard was used for helping us design our circuit and represents the symbols for specific components used in the design[5]. IEC 60062:2016 will also be implemented in our circuit design as it is the standard used for marking resistor and capacitor values and tolerances including the color code that is familiar to electrical engineers. Unicode 12.0 standard was used to design the app and is used as a standard for coding characters[2].

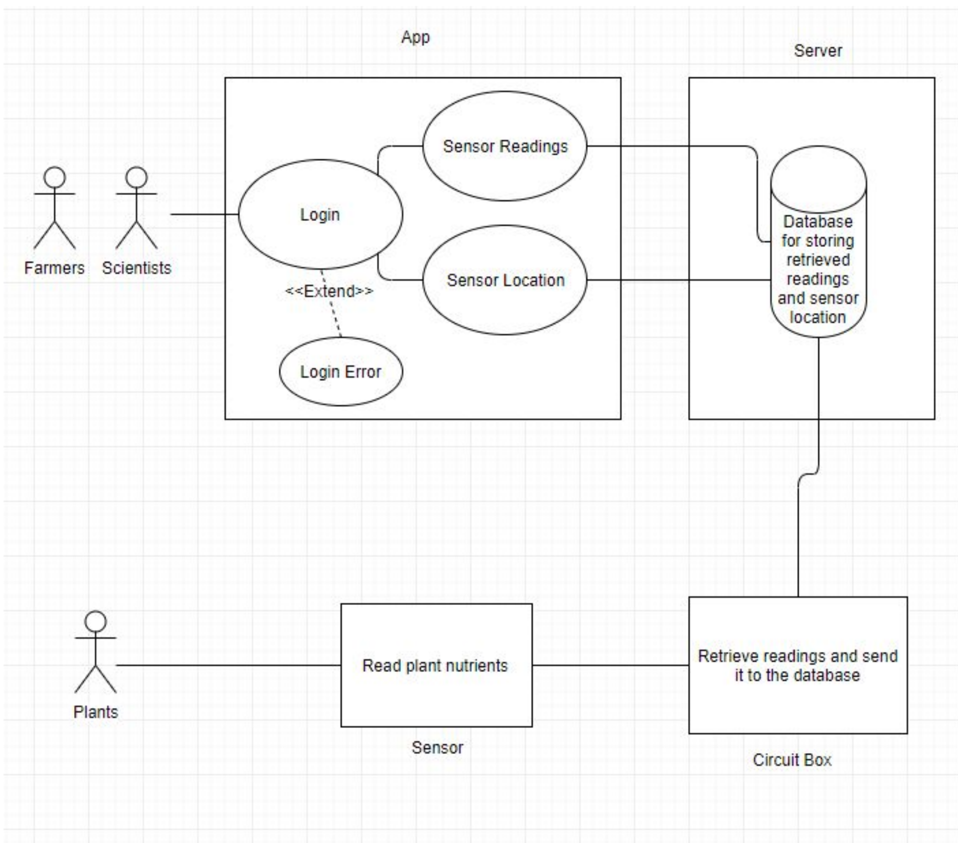

Fig 1: Use Case Diagram

Use Case:

The solution to the problem is to provide farmers with a portable tool that reads and provides accurate data about current soil conditions on the field at any given time. With this solution in mind, the miniature nutrient plant sensor and its app were made, where the sensor can accurately detect NO_3 levels in soil on a daily basis, and to ensure that farmers are well informed about current soil conditions, data collected by these sensors are readily available on the app.

Top Level Design:

The sensor:Arduino: Phone ratio is 7:1:1. i.e. Every circuit box has seven sensors connected to one Arduino, which transmits data to one phone (via Bluetooth/ cellular data). Each of these units (7 sensors and 1 Arduino), consume 1W of power..

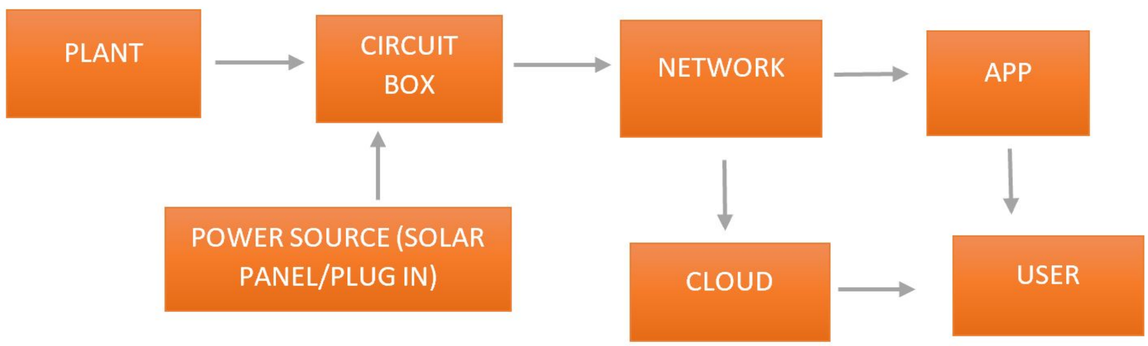

Fig 2: A diagram showing the components of the system.

Working:

1. The system consists of a plant from which we receive data.
2. A sensor is placed to the circuit box, that is attached to the plant. The circuit box consists of an Arduino board, a Bluetooth Board, filter circuits, power amplifiers and AC - DC converters.
3. The circuit box receives power through rechargeable batteries (which are charged by solar panels), when in the field.
4. Data from the circuit box goes into the power read out circuit (which is controlled by an Arduino).
5. From here, it goes into the network (currently via Bluetooth and cellular data) and gets uploaded in ISU's Cloud Storage and the app.
6. The user can now access this data easily.

Structure of the sensor:

The sensor consists of a 3 inch silicon wafer, which is treated with ions to reduce its resistivity (within acceptable limits) . To make it compatible with biological materials, the wafer surface is coated with 115 nm thick layer of Gold, 250 nm thick layer of Silver and 22 nm of Silver Chloride. The sensor is then wrapped in a waterproof polymer from the sides. 8 mm of this wafer forms the current collector, the remaining 2 mm is uncoated for the entire process. Needle point sensors of varying lengths (between 5mm and 12mm) are etched into the sensor. Shown below in Fig 2 is the sensor and all its basic components. The purple layer on the bottom is the silicon substrate with the gold and silver layers printed onto it. The black pads and lines are the conductors that act as connectors or vias to the circuit box. Wires are attached to the three pads. The blue pads represent the ISM that is deposited onto the gold pads. This is a selective membrane that filters out all ions that are not nitrates. The orange pad represents a NaCl/KCl that is added on top of the silver chloride pad. These pads are used to add extra chloride to the silver chloride layer as it is depleted. The silver chloride layer slowly depletes itself as it produces current for the circuit box. The green layer represents a watertight glue that has yet to be determined. The glue helps hold down the edges of the ISM because over a few days of constant contact with the water in the plant, the ISM begins to detach from the gold plating. The glue helps keep water from getting underneath the ISM layer. The ISM, NaCl/KCl, and glue are deposited using the Nordson Dispensing Robot and the thicknesses of the layers are measured with the same machine.

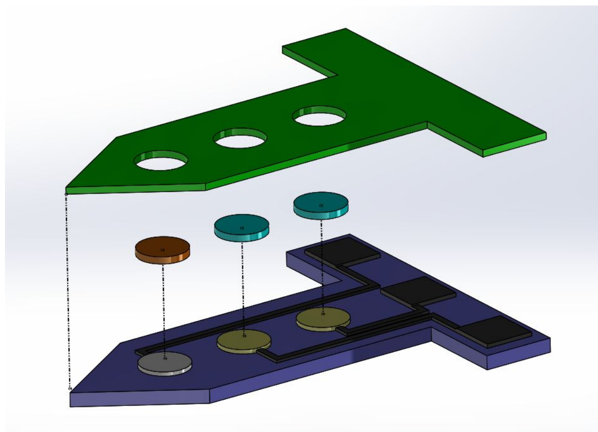

Fig 3: A diagram showing the components of the sensor.

Circuit box:

The circuit box is a 6 inch metallic box, with the top screwed on to the bottom. This provides a certain degree of water resistance and also prevents foreign entities (weather conditions, farm animals) from tampering with the sensitive equipment. The box has a port (on the outside), that connects to either a power outlet (to charge the battery in the lab) or solar panels (to charge the batteries in the field). There is a switch on the side of the box that is used to test the response of the circuit components, to the presence of electricity.i.e. if the components switch on when current flows through the system. If a component does not switch on (in the presence of current), it is taken out for debugging.

The power source (plug in AC wall power source/ solar panels) is connected to the charger. If the circuit box is plugged in, a demodulator circuit is in place to convert the 110 V down to the 5V, required for the functionality of the circuit. Solar panels are used to power the batteries in the field, so that the batteries can last as long as possible without being replaced. As of now, the batteries are good for 2 months (60 days).

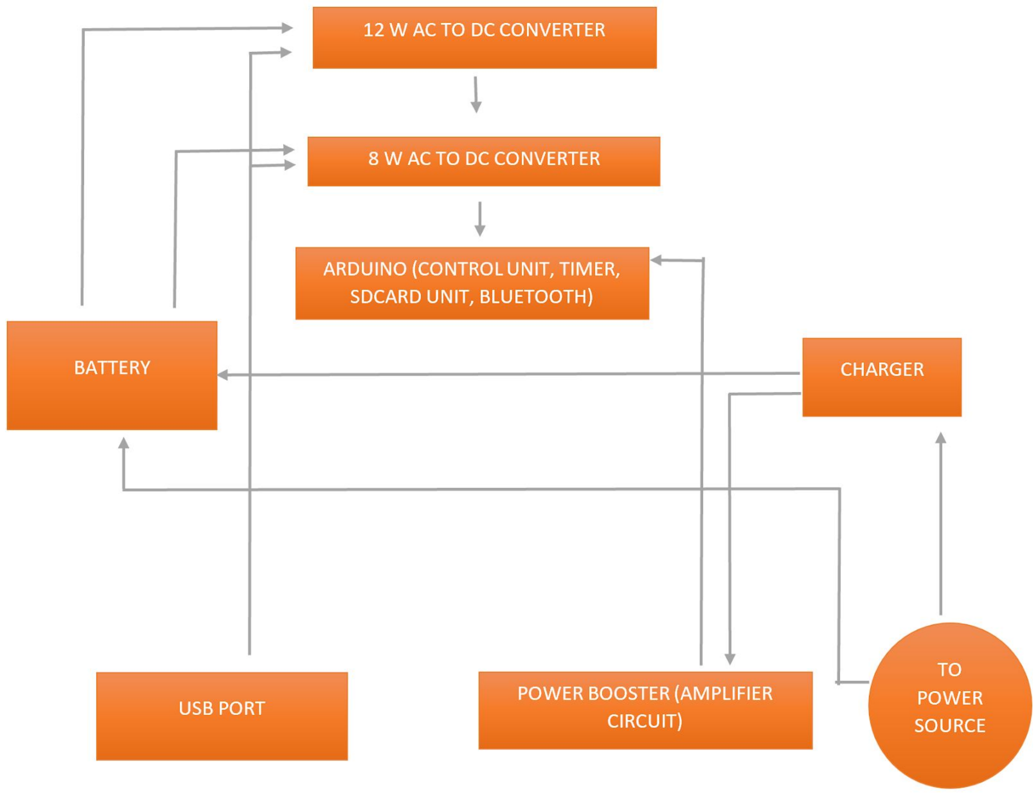

Fig 4: Flowchart of components in the circuit box

<u>Working:</u>

1. The charger supplies current to the battery and power booster circuit, when the battery is not fully charged. When fully charged, the battery supplies power to the circuit and the charger supplies power to the power booster circuit. At night, the battery supplies power to the circuit and the power booster as well.
2. The battery unit is two Li-on batteries connected in series, each of which provides a charge of 3500 mAh.
3. The USB port uses a micro-USB to USB cable to transmit data from the sensor (attached to the plant) to the circuit box. The micro-USB side connects to a micro- USB port on the PCB, onto which the sensor is glued.
4. The data from the sensors come in at different power levels. Therefore, we have two ADC units (12 W and 8 W respectively). These units are connected to the Arduino.This system is mounted in the order shown in Fig 2 (12W ADC at the bottom, 8W ADC in the middle and Arduino on the top), and is connected via pins. The 12 W ADC, forms the power read out circuit.
5. The data is now stored in the Arduino. The Arduino puts timestamps on the data. However, the Arduino does not have enough power to transmit the data over Bluetooth by itself. So, a power booster (buffer amplifier circuit) is connected to the Arduino to help with data transmission over Bluetooth. Data is also stored on the SD card.

Software (app.) component:

The software component of the system consists of the app, the cloud (database), and network.

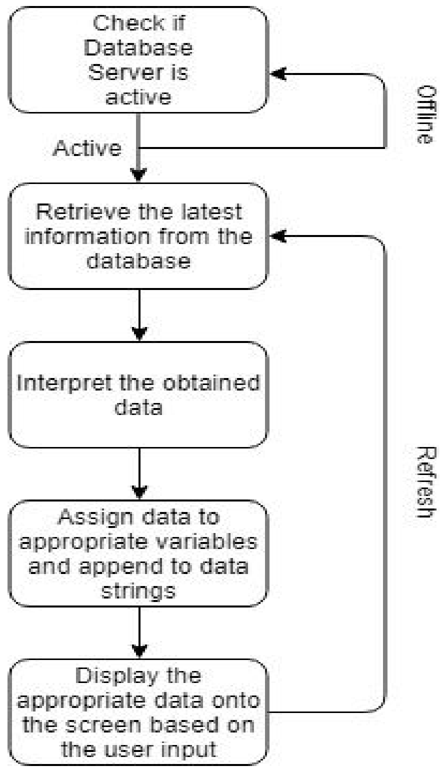

Fig 5: Software Flow Diagram

The diagram above portrays the sequence of steps that occur when a user wishes to retrieve the nutrient measurements from a sensor in the fields. Fig 3 assumes that all of the necessary hardware/software is calibrated properly and is working correctly. For example, we assume that the database is up and running and the sensors is able to store the data into the database correctly. Initially, when the user retrieves the data, the app will try to connect to the database. If the database is offline, the app will constantly refresh its access into the database until the user cancels their request or the database is online. If the server is online, the app will retrieve the latest measurements of each sensors based on the timestamps. Upon retrieving the measurements, the app will interpret it in such a way that it is readable to the user. Once the measurement is interpreted, the data is assign to their appropriate variables and is appended to the data string. The appropriate data strings is then printed/outputted onto the screen of the terminal of the user. If the user wishes to refresh the results, they can click on the refresh button on the app to retrieve the latest results. When the refresh button is pressed, the app will retrieve the latest measurement from the database again and the process is repeated again.

Database Structure:

Login Table	
User Name	String
Salt	String
Password Hash	String

Sensor Data Table	
Owner	String
Sensor ID	String
Sensor Lat	Integer
Sensor Long	Integer
Date of Data	Integer
Sensor Data	Integer

Table 1: Database Structure

As of now, we have decided to use either mySQL or Etg Database to store the sensors' data and PHP language to retrieve the data from the database to the app. With the sensor tracker functionality, we have decided to use Google Maps API for tracking the sensors' location. As for the app itself, we have decided to use android studio instead. The reason for this is because android studio provides convenience to us with its wide variety of libraries.

The standards that we will be using for the implementation of the app is GNU and JCP while the standards for the PHP language that will be using falls under PHP license itself. If we choose to implement the database with mySQL, the standards will fall under GNU and under a variety of proprietary licenses.

2.2 Design Analysis

So far, we have:

1. Arduino as the control unit. Not only is this unit economically beneficial, it also consumes lower power than other microcontroller units.
2. Narrowed down the polymer used for waterproofing the circuit box, that is also compatible with biological material. Having a material that satisfies both these parameters are vital to the efficiency of our sensors and the accuracy of their readings.
3. Discussed how the data could be transmitted over long distances using LoRa. For fields that are outside cell coverage areas or have poor cell connectivity, but are within the 15 mile radius of LoRa, these sensors can still be used to transmit data to the users efficiently.
4. Discussed how voltage levels correspond to Nitrate levels, and how these results are interpreted. To understand the efficiency and accuracy of new sensors, it is vital to have a good point of reference.
5. Discussed how to make the app more user friendly and easier to access. However, security issues may arise due to the ease of accessibility of the data.

Strengths :

1. The data collection unit works effectively. No glitches have been reported so far.
2. The sensor helps collect the most up to date values for nutrients present in the soil, and the app ensures that the data is available almost immediately.
3. The sensors are sensitive to the temperature and nutrient levels in soil, and collect data effectively.
4. The system is self- sustainable (upto 60 days), and has a low carbon footprint.

Weaknesses:

1. For now, we have decided to use the most basic model of our nutrient sensors, the ones without temperature sensors in them. Although this helps narrow down the function of this device and test the data's accuracy, we will have no knowledge of the range of temperatures for which the sensor can work effectively.
2. The slightest change in power levels (even 0.01 W) changes the data by at least 1000 ppm. Maintaining a constant power supply is difficult in fields because the amount of solar energy available is not constant at all times.
3. Data collected by the sensors is not within the acceptable error margins.
4. Data can be transmitted using cell signals/ Bluetooth, within Ames, but not over long distances or in areas with poor connectivity. Purchasing LoRa for economic long distance data transmission, although effective, is also very expensive, and surpasses our budget.
5. The rarity of the polymers that are compatible with our sensor and the biological matter, make them not only difficult to purchase, but also, expensive. Without a good budget for this project, it will be difficult to develop a sensor for the required levels of efficiency and accuracy.
6. The 12 W ADC, is a homemade circuit. Therefore, its efficiency functionality and efficiency cannot always be guaranteed. It is the only component that has to undergo extensive debugging (compared to all the other components) before every use.
7. Given the structure and the materials on the sensor, they are very expensive to manufacture, and accuracy cannot always be guaranteed.
8. The data collection program does not always execute when prompted.

3. Testing and Implementation

3.1 Interface Specifications

The 3 major interfaces that we will be testing will be the sensor itself, the sensor-database network, and the database-Application connection. The sensor interface will be tested functionally as specified in 3.3. The sensor database connection will be tested using standard methods, i.e. Unit testing, edge testing, etc. The application-database interface will be tested via a predefined database with known data.

For the case of our sensors, we transfer all of the previous measurement data into the microcontroller, convert it into a CSV file and create a graph in Microsoft Excel based on the data.The resulting graph displays the voltage vs nitrate level correlation. The graph is then use as a guideline for the calibration and testing of the sensors.

3.2 Hardware and software

The test equipment will be specific to each portion of the device.

1) Sensor Testing Equipment:
    A) Nitrate calibration and test equipment. This will be used to define and test the Sensor itself, and define the characteristic curve of the device. Similar equipment will be used for the temperature and differentiation properties.
    B) Environmental simulation. A set of devices used to simulate an environment including rain, humidity, temperature, and dirt. This will be used to ensure stability and reliability of the device in the field.
2) Database Testing Equipment:
    A) Mock Sensor. This will be used for testing the database input capture. It will likely be software based
    B) Database visualization software. MySql database visualization to view what is being saved and isolate the database software for testing
3) Application Testing Equipment:
    A) Mock Database. Used to isolate application for unit testing, hosted local to the testing machine and with known data
    B) Variety of Smartphones: Used for UI testing and to ensure wide compatibility.
4) Additional Testing equipment:
    A) Nordson Fluid Dispenser. This machine is used for accurately dispensing microscopic layers of polymer resins on the sensor substrate. This machine is also used for inspection of the seal that is meant to be achieved. This machine is used for both fabrication and inspection[6].

Fig 6: Nordson Fluid Dispensing Robot

B) Multimeter. This will be used for checking various voltage outputs of the sensor and estimating power consumption.

Fig 7: Multimeter

C) Greenhouse located in the Plant Sciences Institute on the Iowa State University Campus. This facility will be used for testing the sensor in “real world” conditions. Rainfall and other moisture, temperature, dust, insects, and chemical resistance can be tested here in a semi-controlled environment.

Fig 8: Plant Sciences Institute

3.3 Functional Testing

The tests will verify the accuracy of the sensor based on the requirements of the client.

Test Number	Test	Desired Result
1.A	Measure Nitrate Between 1 to 5000 ppm	± 10%
1.B	Temperature Invariance	± 5%
1.C	Differentiate From Other Nutrients(e.g Phosphorus)	± 10%

Table 2: Functional Testing

<u>Test 1.A Measure Nitrate Between 1 to 5000 ppm</u>

1. Obtain or dilute nitrate solution to between 1 and 5000 ppm.
2. Insert needle sensor into solution and connect to readout circuit box.
3. Obtain voltage value from arduino adc pin.
4. Compare value to calibration curve for nitrate concentration.
5. Repeat steps for various solutions in concentration results.
6. If data is outside error range adjust the calibration curve and repeat steps.

The goal of the test is the have the sensor box read the nitrate concentration within 10% error.

<u>Test 1.B Temperature Invariance</u>

Repeat test 1.A, but vary the temperature between 1℃ - 40℃. After the sensor needle is inserted into the solution, the system should be moved to a temperature chamber. The calibration curve will be adjusted with the temperature values and voltage value from the sensor. The error for temperatures in the range should be within 5%.

<u>Test 1.C Differentiate From Other Nutrients(e.g Phosphorus)</u>

Repeat test 1.A, but after preparing the solution add other plant nutrients like phosphorus. If the test isn't within 10% error the printing of the needle will need to be adjusted to only provide a voltage for nitrate ions. The goal of the test is to ensure the sensor materials are only responding to nitrate within 10% error.

3.4 Non-Functional Testing

These tests will fulfill the user requirements for the sensor.

Test Number	Test	Desired Result
2.A	Waterproof	The sensor operates after exposure to moisture
2.B	Transmission Range	Transmission Without Cell Network
2.C	Operational Lifetime	3 (Months)
2.D	Power Consumption	< 2 (Watt)

Table 3: Non-Functional Testing

Test 2.A Waterproof

The sensor will be set up in a test field. The sensor will be setup to continuous transmit data to the server. The sensor should continue to transmit data after rainfall has occurred in the field. If the sensor fails the seal on the sensor needle will need to be adjusted. The sensor can be tested under various water conditions including a mist spraying continuously on the sensor. The sensor should have an adequate seal to prevent moisture creeping underneath the ISM and NaCl or KCl coatings located on the needle. The spray mist test will determine if the glue has properly sealed around the wires bonded to the vias. The plant will be wet for the duration of the use of the sensor and the glue will have to prevent water from penetrating underneath the ISM layer for the life of the sensor. We will also test various mounting orientations of the sensor to ensure that the sensor performs under a variety of conditions. The sensor can be mounted near the midrib of the leaf or on the margin. It can also be mounted on top and underneath the leaf.

Test 2.B Transmission Range

The sensor is currently operational using cellular network. The goal is to have an alternative transmission method to the cellular network using LoraWAN. The sensor should be able to transmit data from the test field using only LoraWAN.

Test 2.C Operational Lifetime

The sensor box will be deployed in a greenhouse environment. The sensor should provide continuous measurements for a three month period of time. The three month lifetime is only for ideal greenhouse environments. The sensor will also be deployed in a test field. The goal for the test field sensor is a 1-2 week operational period.

Test 2.D Power Consumption

The current sensor operates on 0.8 Watts. The goal is to keep the power consumption of the circuit box under 2 Watts. The power will be measured using a multimeter. The goal of the test is to ensure the continuous operation of the sensor with the current solar power source. The test will be conducted under full power consumption where the sensor is collecting data and during the transmission of the data.

3.5 Process

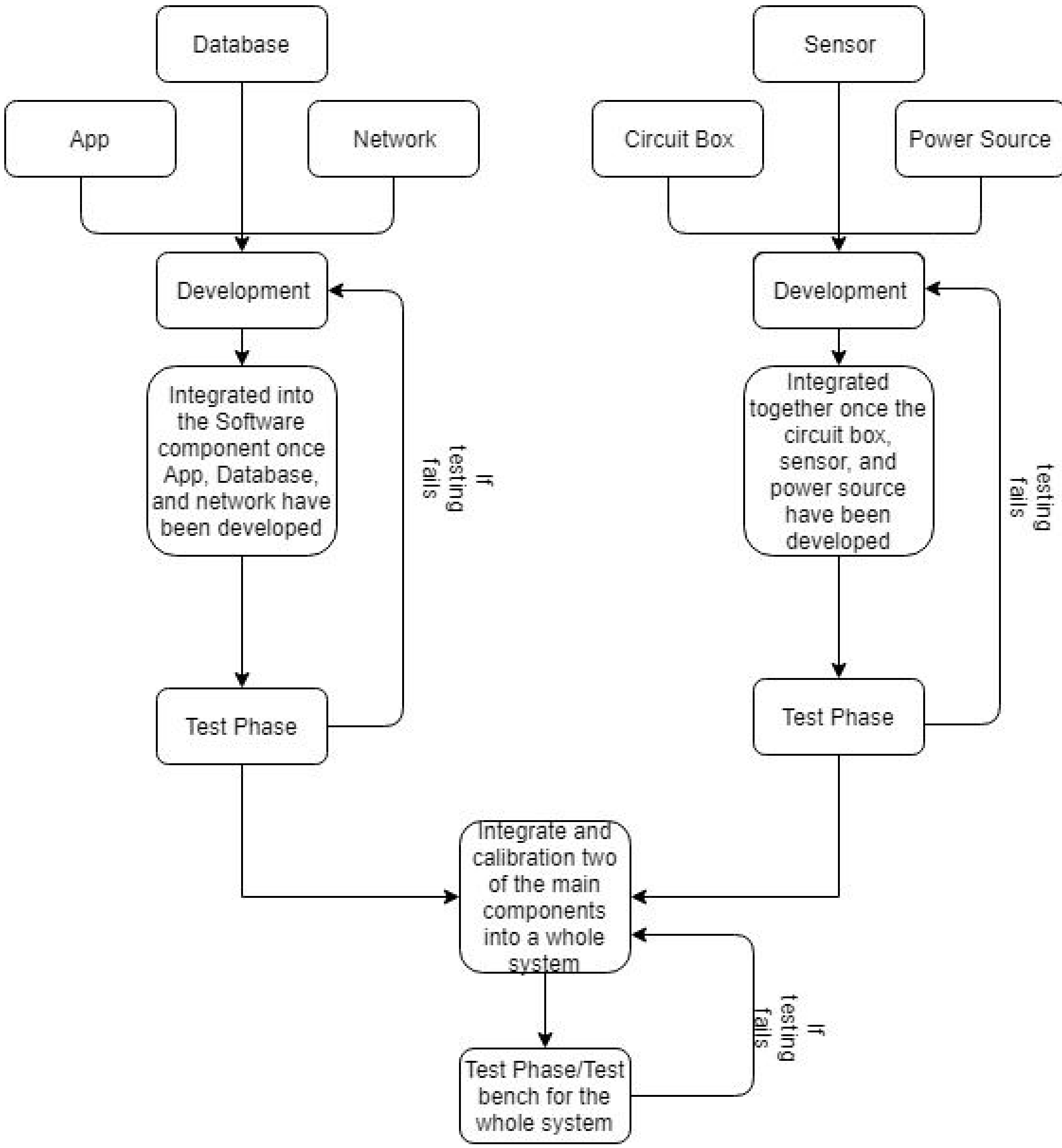

Fig 9: Process Flowchart

Based on Fig 7, we started out developing/optimizing each of the components individually and perform tests on it to ensure that it is working as intended. The specific test that is performed on these components are described in section 3.2 Hardware and Software. Once each of the components have passed its respective test, the components will be integrated into a larger component and will also have its specific test. This process continues until all of the components are integrate together into the whole system and passed the testing phase.

3.6 Results

3.61 Implementation Issues and Challenges

1. The sensor cannot differentiate between Nitrogen and other particles in the soil precisely.
2. The sensors have no estimated range of temperatures, under which they work without any glitches.
3. The accuracy of the data is directly proportional to the amount of incoming power. A slight change in power has detrimental effects on the accuracy of data.
4. The units, when embedded correctly in plant stalks, can run for 60 days, without needing a change of batteries.
5. Data can be transmitted effectively from the field to the app, within Ames.

4. Closing Material

4.1 Conclusion

So far, the team has a good understanding of the current state and functionality of the sensor. We have met with the grad students and have begun to look at how each aspect of the system will be optimised. We have familiarized ourselves with how the sensor printing machine is operated. Also, we have obtained the current software for the project, and understand how it currently operates.

The goal of the project is to improve on all the components of the sensor system. The sensor needle needs to be made more reliable and be invariant to other stimuli. The sensor box will be made more weatherproof. The transmission will be made to not rely on cellular networks. The app will be updated to be easily accessible by the uses. The goals will be accomplished by isolating each component to be optimised separately. The separation of each component will allow us to work on our specialized areas. After improvements have been made, the components can be connected with our established interfaces.

4.2 References

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