Final Design Document

Twin Cities Engineering

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Spring 2023 Semester

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Introduction

A revolution of farmers interested in smart regenerative agricultural practices has blossomed over recent years. Many farmers of these communities are actively seeking stem tools to help monitor soil health and provide feedback to farmers on the quality of their practice. One method to measure soil health is to measure the gases within the soil. Measuring certain gases in soil provides information about the nutrients and microorganism activity within the soil. Commercially available soil pore space gas instruments are costly, with the cheapest systems costing around $100,000. The high costs leave a demand for a low budget system capable of extracting, measuring, and reporting soil gas concentrations.

To address this issue, a team of engineering students from Twin Cities Engineering at the University of Minnesota, Mankato, is planning to develop a low-cost DIY soil sensing unit. The unit will be designed to extract soil gases from four different depths, providing farmers with valuable information about their soil health. The team plans to make all the information about the project available on GitHub, an open-source platform for software development, so that other farmers and researchers can benefit from their work. By developing a low-cost soil sensing unit, the team hopes to make it easier for farmers to adopt smart regenerative agricultural practices and improve the sustainability of their farming operations.

The DIY soil sensing unit will consist of a gas sampling chamber, a vacuum pump, and an electronic sensor for detecting the gases. The team plans to use off-the-shelf components wherever possible to keep the costs low. They are also exploring the use of 3D printing technology to produce some of the components. The device will be powered by a rechargeable battery, which will be recharged with solar power, making it easy to use in the field.

In addition to providing farmers with information about their soil health, the team hopes that their project will also help to raise awareness about the importance of soil health and the role of regenerative agricultural practices in promoting sustainable agriculture. By sharing their work on GitHub, they aim to inspire others to develop similar low-cost solutions and contribute to the growing community of farmers interested in regenerative agriculture.

Current State of the Art

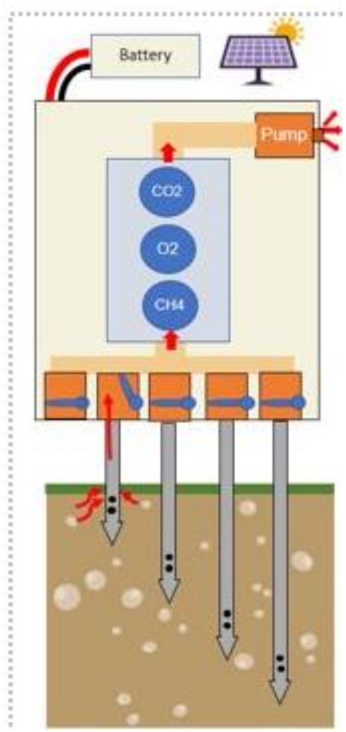
There are a few longstanding methods of acquiring this data from under the soil, one being gas chromatography. This is done in a large lab space where samples of the trapped gas or soil sample are brough to the lab and examined in these large machines. The chromatography machine is, bulky, high-energy cost and high dollar cost. The next champion in this segment is the FTIR.

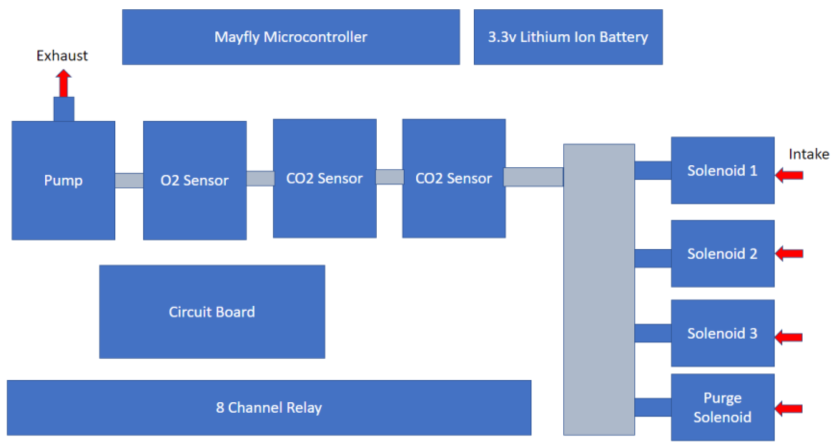
Fourier Transform Infrared (FTIR) spectroscopy is a powerful analytical technique that can be used to analyze the composition of specific gases in soil vapor. The technique involves measuring the absorption of infrared radiation by a sample and then using this information to determine the types and amounts of molecules present in the sample.

FTIR spectroscopy works by passing infrared radiation through a sample, such as soil vapor, and measuring the amount of radiation absorbed by the sample at specific wavelengths. Different molecules absorb radiation at different wavelengths, and the resulting spectra can be used to identify the types and amounts of molecules present in the sample.

When applied to soil vapor, FTIR spectroscopy can be used to identify and quantify the concentrations of various gases, such as carbon dioxide, methane, and nitrous oxide. These gases are important indicators of soil health and can provide valuable information about soil microbial activity, nutrient cycling, and greenhouse gas emissions. So the FTIR is a force. However, this is an industry machine that costs in 100k range and requires a great deal of power. More power than we could get out of a 2ftx2ft solar array

What is the Device:





The images above are diagrams of the system we received from the previous team.

The Device a machine that will stay outside all growing season, it will use a solar panel to charge its batteries. It will be able to accurate a pump to draw gas from under the soil from 4 different depths, run that gas over our sensors and record the concertation of Co2, O2, and CH4. After the reading has been taken, the gas is removed from the chamber via that same pump and ejected through a port in the top of the machine. The data is then saved to an SD card as well as relevant information about Time, Date. Temperature, and Humidity.

Project Tutorial

Project Timeline

- Spring 2022
    - Developed groundwork for entire soil sensing unit design
    - Setup a pump, 8 channel relay and sensor hookup
- Fall 2022

  - Created Sensor caps to connect sensors together
  - Extracted readouts from sensors
  - Programmed framework for device operation
  - Data storage on SD card
  - Eliminated solenoid noise triggering relay issue using snubbers
  - Attempted to implement a methane sensor but fried it
- Spring 2023
  - Created a sensor chamber included with temperature control
  - Created a prototype bulk water removal system
  - Fully implemented entire design into a box for total mobility
  - Implemented a low-cost methane sensor
  - Properly extract gas from probes
  - Completed a GitHub Repository

Device Design

Design Intent

The soil gas sensor device is designed to provide accurate and precise measurements of gas concentrations in soil. It consists of four soil probes of varying lengths (0.25, 0.5, 0.75, and 1 meter) that can be easily attached to the device. Each probe is equipped with holes to extract gas from the soil when a connected pump is activated.

To ensure accurate readings, the four probes are placed in a 1-meter squared area of soil, under the assumption that soil gas concentrations will not vary significantly within this area. The device itself has four ports to connect tubes from the probes to the device. Each port is connected to a solenoid valve inside the device, which can open and close based on the response from a Mayfly microcontroller.

To ensure precise measurements, the device allows for the exposure of one probe at a time while keeping all other valves closed. This process allows the device to accurately measure the gas concentration at each depth, providing valuable insights into the microbial activity and nutrient levels of the soil. By allowing for the measurement of gas concentrations at varying depths, farmers can make informed decisions about the timing and amount of fertilizer application, thus optimizing crop yields while reducing the use of potentially harmful fertilizers.

Behind the solenoids lies the sensor chamber. The sensor chamber houses an Alphasense IRC-AT carbon dioxide sensor, Alphasense O2-A3 oxygen sensor, a TGS2611-E00 methane sensor, a bme280 temperature, pressure, humidity sensor, and a heating element. The heating element is implemented due to our project team’s worry of condensation forming within the sensor chamber and damaging the sensors. The heating element is connected to an H-Bridge and begins heating if dew point is measured from the bme280.

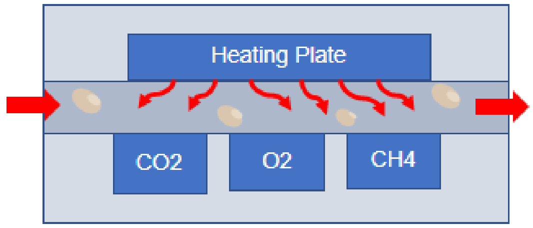


Figure 1

Figure 2

The Alphasense sensors were chosen due to professor suggestion in the reliability of the brand. Each Alphasense sensor is powered with 12V. To measure the sensors a load resistor of 230 ohms is used for both sensors. The voltage drop across the resistor is measured using an Analog Digital Converter (ADC) to read oxygen and carbon dioxide. The Alphasense IRC-AT has two signal wires. Sig+ connects to one end of the resistor while Sig- connects to the other end. The Alphasense O2-A3 however connects in series. 12 volts powers the O2-A3. The output current is an ADC measurable current of 4-20 mA. The load resistor is placed in series with the O2-A3 sensor for the ADC to measure the voltage drop.

The TGS2611-E00 was chosen due to its low cost and abundant literature claiming the sensor to be a capable low-cost sensor for methane detection. Our team lacks the ability to perform proper laboratory calibrations. Our team assumed we could use equations derived from literature [1] [2], to tune an algorithm to compute relatively accurate ppm readings from measured voltage drop across a load resistor. Our assumptions were wrong.

To compute the TGS2611-E00, ohms law is used to measure the resistance inside the methane sensor. The equation displayed in Equation 1**Error! Reference source not found.** is used to compute sensor resistance R_s. For context the sensors circuitry is displayed in Figure 3. The Mayfly ADC measures voltage drop (Vout) across the load resistor R_l.

$$R_s = R_L\left(\frac{Vc}{V_{out}} - 1\right) \qquad \text{Equation 1}$$

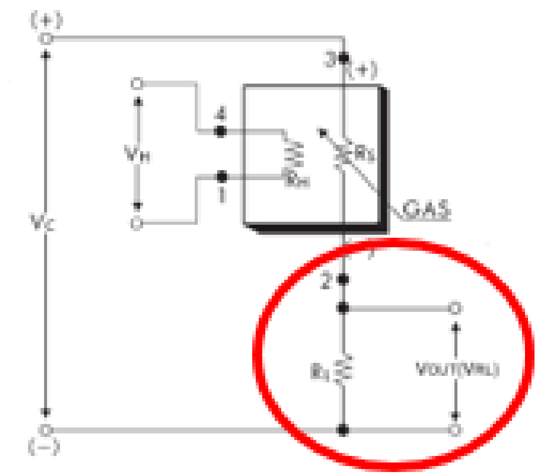


Figure 3: TGS2611-E00 Sensor Circuit

To convert the ADC's measured voltage to methane parts per million our team attempted to use equations from Van den Bossche et al [1]. In their paper, Equation (11) converts sensor resistance to methane ppm using a value R_0 and measured R_s displayed in Equation 1. R_0 is the sensor's resistance value at a reference point concentration of methane ppm. We recorded R_0 in an ambient setting to be equal to 23,250 Ω. Our team recognized we had no way to control environmental factors such as temperature and relative humidity, but we could reference them using measurements from the BME280. When using the equation, we found the trend to compute confusing results. The equation also did not compute an expected trend.

The BME280 was chosen due to its ease of installation. The device has two total BME280s installed with addresses (0x76) and (0x77). (0x76) measures ambient temperature, pressure, and relative humidity within the container of the device. (0x77) measures temperature, pressure, and relative humidity within the sensor chamber. Both the BME280s are used to compare the difference between the ambient environment and inside the sensor chamber. If the temperature is excessively cold out, condensation could occur. Thus, the mayfly continually monitors the temperature and relative humidity inside the sensor chamber to acknowledge when to turn on the heating element.

Device's Program Flowchart

Shown in Figure 4, the Mayfly microcontroller first reads if any of the bme280 sensors or the external ADC is properly connected. If any of the components are not connected, then the device will not operate. If all components are connected the code will reach Arduino's loop function. Inside the loop function is a for loop intent on opening one solenoid valve out of four, pumping gas from the solenoid through the device, measuring data, heating the sensor chamber if necessary, and storing the data on a SD card located on the microcontroller itself.

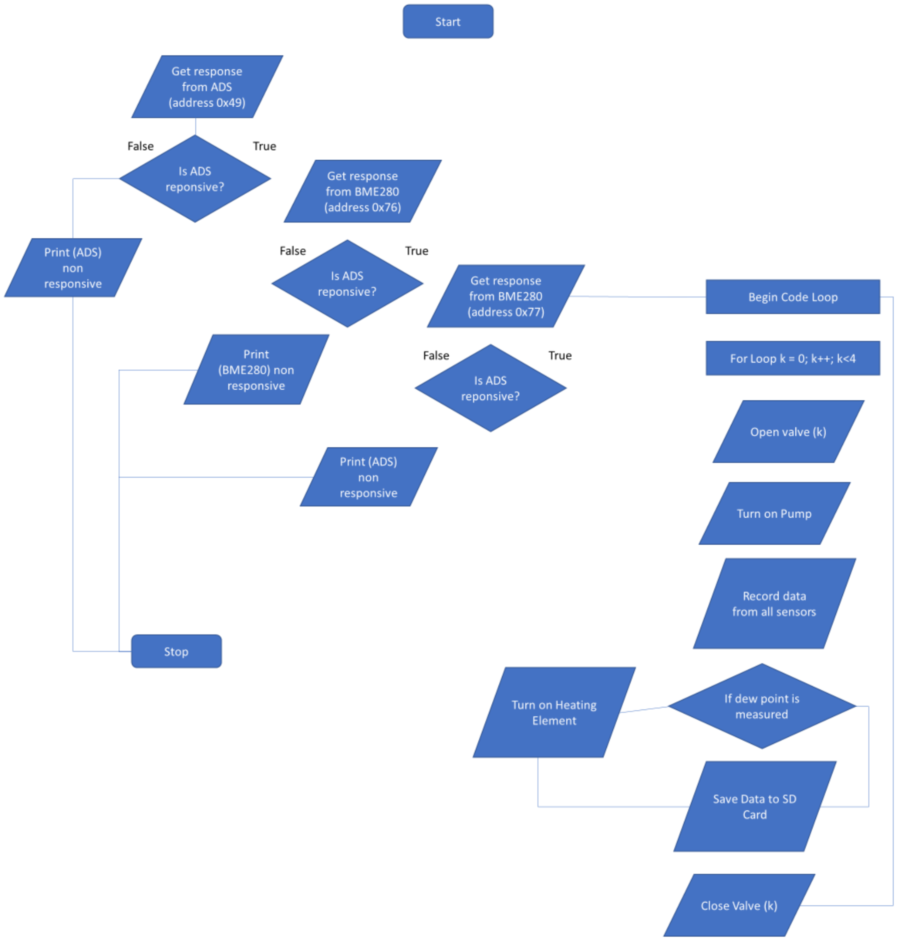


Figure 4: Program Flowchart

Device Electrical Schematic

The electrical schematic displayed in Figure 5 shows all electrical components wired in the device. At the center of it all, a Mayfly v1.1 microcontroller controls all the operations of the device. Both the Alphasense O2-A3 and the Alphasense IRC-AT voltage readouts are measured using an onboard ADC. An external ADC component, the ADS1115 measures the voltage level of the battery, and measured voltage drop across the load resistor of the TGS2611-E00 methane sensor. The solenoids are controlled with an 8 Channel Relay. Each solenoid is connected to the normally open position. Connected in parallel with each solenoid is a resistor and capacitor in series. These are snubbers intended to dampen AC noise generated when the solenoids are opened or closed. Our project team had a significant problem controlling the relays until the snubbers were installed. To control the pump and heating element, an L298N H-Bridge was used. The H-Bridge can limit voltage supply to the components used Pulse Width Modulation (PWM) from the Mayfly microcontroller.

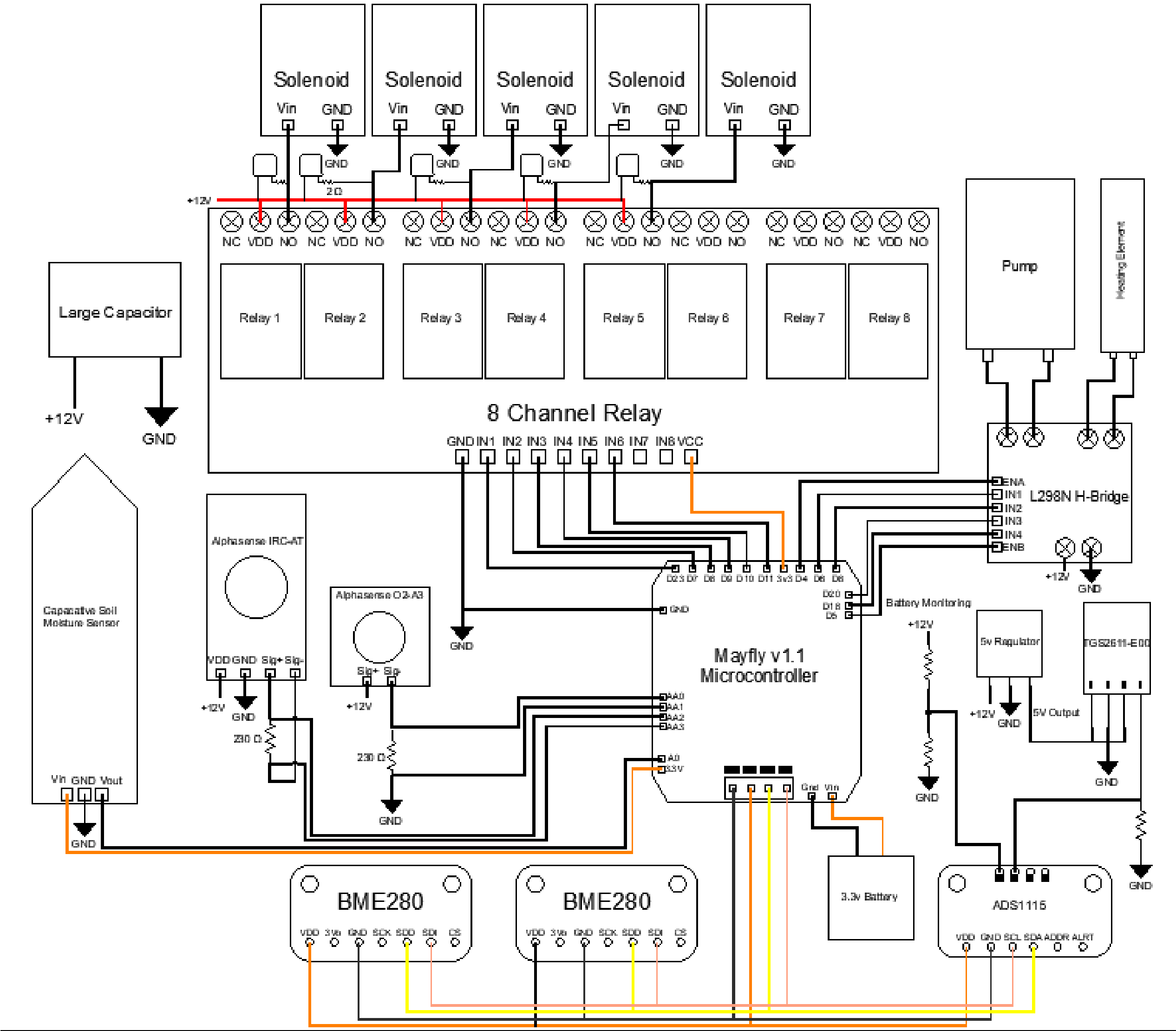


Figure 5: Electrical Schematic

The Mayfly Microcontroller was chosen due to its capabilities and the microcontrollers focus on being used to monitor environmental conditions in a DIY environment. The EnviroDIY community is behind this device. The Mayfly Microcontroller is based on Arduino and uses the Arduino IDE software for programming. The microcontroller is pivotal for our device because of its range of capabilities. The device uses I2C communication, Analog Digital Converters (ADC), pulse width modulation, and one of the most important points is the number of available pins. In total our device requires 23 individual pins to operate the device leaving the mayfly as a great option.

The solenoids are powered using 12V and controlled from the 8 Channel Relay. Placing the snubbers in parallel with the solenoids is important due to noise generated from the opening and closing of a relay. The noise generated would retrigger the relay even though there was no input. The relay would begin to spasm uncontrollably until the power was turned off. The snubbers absorb AC signal noise and prevent a commonly known issue of the relays going haywire. The solenoids themselves consume a lot of power, about 600 mA per solenoid. The solenoids have been used in all three semesters of this project because the solenoids met the need for testing and designing. All project teams were focused on function and not worried about power consumption.

The L298N H-Bridge is used to control the current supplied to both the pump and heating element using PWM from the Mayfly microcontroller. Both the pump and heating supply are wired to the same H-Bridge but are separately controlled to meet the necessary power consumption. In software the pump is operated at maximum speed to fill the sensor chamber as quickly as possible. For the heating element, about 2 volts was enough to heat the sensor chamber adequately but can be adjusted in the code to either increase or decrease heat output.

The ADS1115 is an Analog Digital Converter (ADC) used to measure the voltage at different points in a circuit. The Mayfly has four onboard ADC pins. Our team is using all four pins to measure the voltage drop across the load resistors of the carbon dioxide and oxygen sensor. Other components we need to measure are the TGS2611 – E00 methane sensor, and the battery voltage. Since our device is planned to eventually be powered by a solar panel, a battery monitoring system has been implemented. The ADS1115 measures from 0 – 5V, but we have it measuring up to 3.3V max due to a warning in the component's documents. A 100,000-ohm resistor is placed in series with a 10,000-ohm resistor. Using the voltage divider equation and measuring the voltage drop across the 10,000-ohm resistor, the ADS1115 can safely measure voltage and the Mayfly can compute the total voltage supplied by the battery. Lastly the ADS1115 also measures the voltage drop of the TGS2611 - E00's load resistor and an algorithm are used to convert and compute methane ppm.

The Capacitive soil moisture sensor is used to detect water inside the bulk water removal trap. The Mayfly measures voltage from an analog pin. Currently the program has not implemented any response to water level besides taking measurements. We suggest using measurements from the soil moisture sensor to operate designed water trap.

Water Trap

We chose to use the method of 3D printing to create a water removal unit for the soil project. Full well understanding two things that this method will be able to get a basic design or best shape but the difficult learning curve of the solid works software as this semester is the first time we have engaged with that software.

We started this off by disassembling a commercial water filter, the intent was to use a portion of this, and just print a coalescing tray that we could attach an actuated removal of the water. We took all the measurements of the parts we intended to replace.

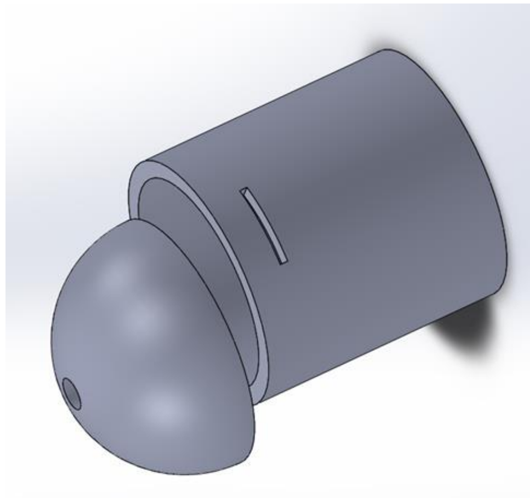


Figure 6: Screen capture from SOLIDWORKS of the first iteration

The plan at this point was to attach this to a commercial object that had a similarly shaped plastic container over a filter. Our design included a hole in the bottom of the dome, here we would attach the connection to the pump for the water removal. On the side of the Cylinder there is an area for the sensor to communicate the water height has reached its limit, stopping pumping gas in.

It was at this point that we realized the cost saving in just modeling and printing the whole thing ourselves. The whole unit could be assembled ourselves for ~$6.00 of PLA and $10.00 for off the shelf coalescing filter. The commercial filter was currently around $100.00.

*Figure 7: Example of the water trap (not the exact one) *image from Amazon.com MID FLOW PARTICULATE FILTER/WATER TRAP*

printing the top portion came with new learning challenges. The first models are just the basic shapes and I couldn’t even figure out how to make one shape on another without making then separate parts.

The new design was going to incorporate two ports that connect to the hoses using the current iteration of the soil sensor prototype. One the intake port will be in the middle above the coalescing filter and the second will to the side of that this will be the exit port for the air now free of liquid water (at current temp).

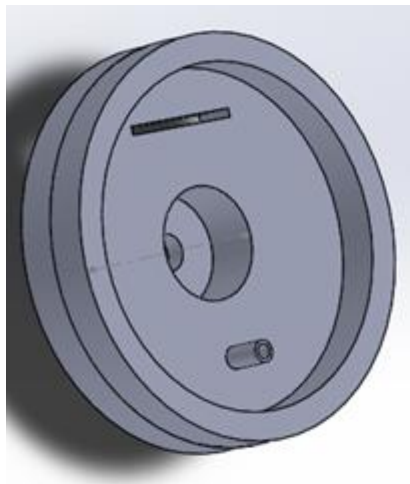


Figure 8: Screen captures from SOLIDWORKS; Figure is the underside the part.

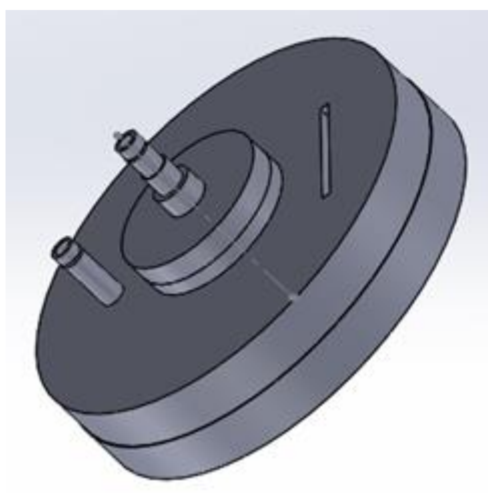


Figure 9: Screen captures from SOLIDWORKS; Figure is the top of the part.

At this point the plan was the inner walls around the center hole much thicker than the program would have had them as well as made the hole undersized for current purposes. The intent was to bore the proper threads in. A port was added to the top since now we could mount that water level sensor in the top.

The first prints suffered from my not building a design that print easy the large gaps of “ceilings” that this design had a high percentage of failure on the first layers trying to bridge those gaps. This more or less self-corrected after the first layer and the choice to make all the walls slightly thicker for water-tight consideration came in clutch.

Also on the second print the failure in the first layer tipped the interior outlet port over and failed to connect properly. After a few more iterations and the realization that the boring technique that was previously mention was not well understood and we then chose to try to print the threads to attach to the commercial filter

We took all the appropriate measurements of the threads: .771in Diameter of the connector with the threads .767in Diameter without threads (thread width was ~.004in), the connector was .28-inch-tall and displayed roughly 4.1 turns of the threads.

Using this data and the tools on SOLIDWORKS I was able to resize the whole to proper size and add the threading necessary to connect to the filter.

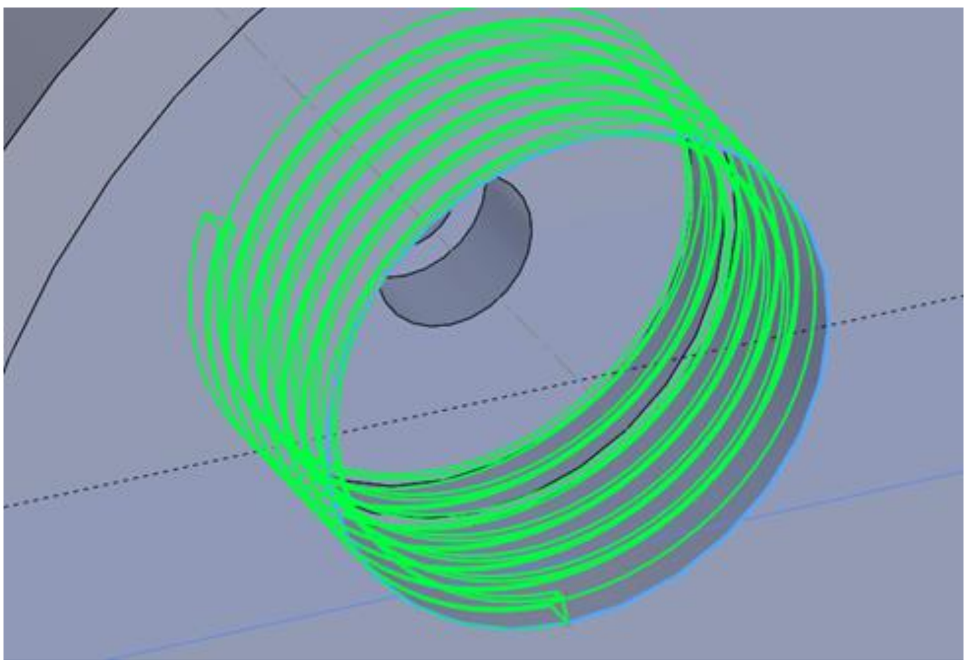


Figure 10: Screen captures from SOLIDWORKS the thread tool set to 16 thread per inch with .004 thick threads.

The Hosing connections were more just by trial and error (the inner diam of the tubing is not what you want if you want a good seal). During these last iterations I sized up the fittings on the top as well to create a nice seal and added a few ridges to them to help secure and prevent leakage.

Though this design technical works and worked for our demonstration, there is still need for iteration. A large flaw in the current design is that all the OD specs where create to allow attachment to another device we are no longer using. The greater the volume within the chamber the more water can be trapped before the machine will turn off (the more data it can gather) however the greater the volume of the trap the greater the volume of the whole system a system that. The added volume accounts for 80ml of air and needed to be flushed out with 3 times that volume. To guaranty with even a 95% accuracy that we can say “we know where the gas came from”.

So, in future iterations I will need to run simulations on the air flow, with the goal of reducing the volume in the chamber while still allowing for an acceptable amount of water to build before the machine has to turn off and purge the trap.

The 3D printing process has proven to be a great choice for prototyping and developing the water removal unit. This is because 3D printing enables fast production of parts, allowing for multiple iterations and testing of designs with minimal costs. As described in the methods section, the top and bottom parts of the unit required several iterations to optimize their design and ensure they meet the requirements for the project. The ability to make rapid design changes and improvements allowed us to achieve a functional unit that performs well in collecting water from gas drawn from under the soil.

This process was done over about a weeks' time, if I had tried to get this injection molded or vacuum formed, not only would it have costed hundreds if not thousands for the proper mold to be fashioned to create my part. It would have taken weeks to get those molds made. Each iteration the same costs and time would apply…perhaps for a larger print run of the final iteration that way would could insure that the final iteration would be air and water-tight. Until then 3d printing is the best option.

Calibration protocol

We designed a method for cheap calibrations last semester and even though the hand make calibration gas was within +/- 4% the amount of gas created was 100ml each time. For our calibrations this semester we intended to use a more established method.

The process of making calibration gas using flow meters typically involves the following steps:

1. Select the appropriate gas mixture: The first step in making calibration gas is to select the appropriate gas mixture that matches the gas you want to calibrate. This is usually done by consulting the specifications or requirements of the instrument or sensor being calibrated.
2. Assemble the equipment: Once the gas mixture has been selected, the next step is to assemble the equipment needed for the calibration process. This typically includes a gas cylinder or source, a pressure regulator, flow meters, tubing, and a gas mixing chamber.
3. Set the flow rates: The next step is to set the flow rates of the individual gases using the flow meters. This is typically done by adjusting the flow control valves on each flow meter to the desired flow rate. The flow rates are typically specified in the instrument or sensor calibration documentation.
4. Mix the gases: Once the flow rates have been set, the individual gases are then mixed in the gas mixing chamber. The mixing chamber is typically designed to ensure that the gases are thoroughly mixed to achieve the desired gas mixture.
5. Verify the gas mixture: Once the gases have been mixed, it is important to verify the gas mixture to ensure that it matches the specifications of the instrument or sensor being calibrated. This is typically done using a gas analyzer or other measurement equipment.

It is important to note that the specific process for making calibration gas using flow meters can vary depending on the specific instrument or sensor being calibrated and the gas mixture being used. It is also important to follow proper safety procedures when working with gas cylinders and other equipment to prevent accidents or injuries.

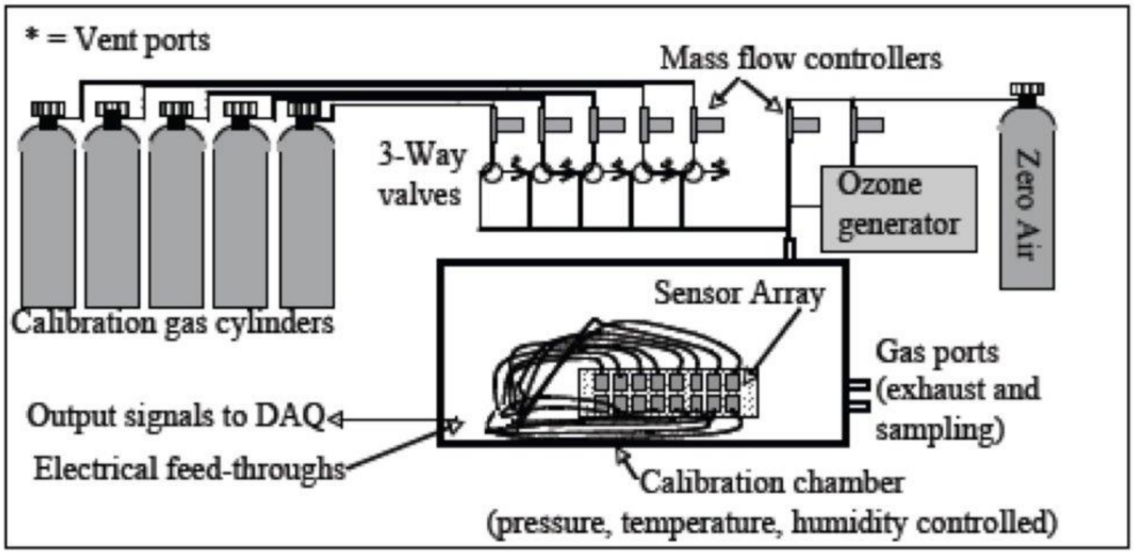


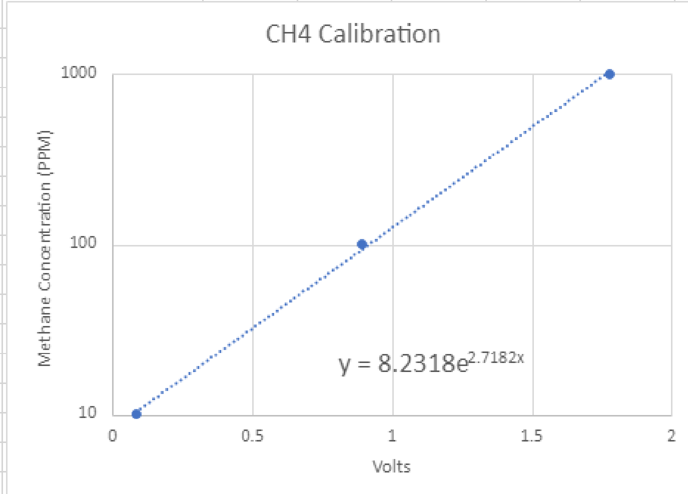
Figure 11: Calibration Setup Diagram

The Mass flow controllers are between $1500-$2000 a piece and the current layout has at least 4 of them. The good new TCE has many of these flow controllers! However, we did have any of the wires, instructions, or "Controllers" that allow humans to interface with the flow controllers.

We did a good deal of research, found all the instructions, and concluded that this set up would not only cost 2 weeks' time to assemble but that the setup was so cumbersome that few people that would be interested in this DIY project would have the aptitude or resources to invest with this set up.

Because of these set back and realizations we rescoped and went back to the 3-point tests for calibration using the method from last semester using this we got our methane senor calibrated and created an algorithm for turning the output from the sensor to a PPM scale.

Index when Begun	Methane Voltage Measured	PPM	Notes
16-22	1.75	1000	
39-46	1.84	1000	
Purge: 49 - 94			
97	1.71	1000	
108	1.85	1000	
340	0.86	100	
405	0.89	100	
460	1	100	
540	0.93	100	
572			
597	0.92	100	
646	0.53	10	
712	0.52	10	
769	0.51	10	
827	0.51	10	



Last semester's (Fall 2022) calibration method is attached as an appendix(i)

Motivations

The health of soil plays a crucial role in the success of agricultural production, and farmers can improve crop yields and reduce the use of fertilizers by understanding the level of microbial activity in the soil. Soil gas sensors are useful in this regard as they can detect methane or carbon dioxide which are byproducts of microbial decomposition, an essential process in the soil nutrient cycle. The concentration of these gases provides information about the level of microbial activity and the rate of decomposition, which helps farmers make informed decisions about the timing and amount of fertilizer application.

The use of soil gas sensors enables farmers to reduce their dependence on expensive and potentially harmful fertilizers by applying them only, when necessary, thus reducing the environmental impact of agriculture. Furthermore, optimizing fertilizer use promotes soil health and leads to increased crop yields, ultimately contributing to improved food security.

Results

Our team attempted to perform experimentation on our soil sensing unit while it was operating. We found during calibration; we could not achieve accurate repeatable values with the installation of the new sensor chamber. Our team also desired to test gas extraction from soil, but since we failed to calibrate properly, we did not investigate the functionality of gas extraction from soil.

Discussion

Challenges and Solutions

Mayfly Microcontroller Driver Issue

Our team faced a problem with the Mayfly Microcontroller near the end of the semester. In some way shape and form the on-board ADC stopped operating as expected. Only a week later the USB connector on the mayfly suddenly felt loose and would not snap in as normal. The problems prevented us from uploading new code or reading measurements from the current Mayfly installed in our system. Luckily, we have backup Mayfly Microcontrollers, but we were unable to get use out of them. We found while attempting to upload a program on the different Mayflies, an error “stk500_recv(): programmer is not responding” would repletely display in the output terminal of the Arduino IDE if verbose was turned on in IDE settings. Tracing the error on forums, our team found the issue was likely related to FTDI drivers needing to be installed. However, in our attempt to install the drivers the issue persisted. Our team can only assume we installed the drivers incorrectly. Since our semester is ending, the new semester will have to solve this issue to get the soil sensing device operational again.

Calibration problems

Calibration of methane sensors involves adjusting the sensor's output to match the expected readings for a given concentration of methane gas. This process typically involves the use of specialized equipment, such as gas mixers and calibration standards, which can be costly. In this case, the team decided not to proceed with the calibration because of the cost involved. This decision may have been based on a variety of factors, such as budget constraints, competing priorities, or a belief that the sensor would still perform inadequately. It's worth noting that the decision not to proceed with the calibration of the methane sensor can have consequences beyond just the cost involved. Failing to calibrate the sensor can lead to inaccurate readings.

Use of sintered steel probes

Sintered steel is a type of porous metal material that is commonly used in filtration applications where it is necessary to block particulate matter while allowing gases or fluids to pass through. In the context of soil gas sampling, sintered steel can be used to create a course filter that prevents soil particles and other debris from entering the metal probe while still allowing gas from beneath the soil to pass through.

The sintered steel filter is typically located at the tip of the metal probe and acts as a barrier that prevents soil particles and other debris from entering the probe. The filter is composed of a network of interconnected pores that are small enough to block particles but large enough to allow gas to pass through. This ensures that only clean gas from the soil is sampled, without any contamination from soil particles or other debris.

The use of sintered steel filters in soil gas sampling is an effective way to ensure that samples are representative of the gas present in the soil without any interference from particulate matter. This is important because particulate matter can alter the composition of soil gas samples, leading to inaccurate readings and incorrect conclusions about soil health or other factors of interest.

When sintered steel filters are welded to a solid steel tube, there is a risk of compromising the overall strength and durability of the probe. Welding can introduce weak points in the probe that may break or deform under pressure or resistance, potentially causing damage to the probe or affecting the accuracy of soil gas measurements.

In some cases, sintered steel filters have been found to break at the weld when they come into contact with great resistance. This can be a serious issue in field applications where probes may encounter resistance due to soil conditions or other factors.

To mitigate the risk of structural failure in soil gas sampling probes, it is important to carefully design and construct probes with the appropriate materials and techniques. This may involve using stronger materials or alternative welding methods to ensure the overall strength and durability of the probe.

Overall, while sintered steel filters offer many benefits for soil gas sampling, it is important to consider the potential downsides of welding them to a solid steel tube. Careful attention should be paid to the overall structural integrity of the probe to ensure accurate and reliable soil gas measurements in the field.

Flowrate loss with current solenoids

During experimentation with our device, we tested our tubing for extracting gas from the solenoids to the sensor chamber and then to the pump. We found a large pressure drop from the solenoids which we believe diminished the device's gas extraction rate. This semester we do not have the time to replace the solenoids with more efficient ones, so we are left with extracting at a very slow flow rate even with maximum pump rate.

Methane sensor oxygen dependence

One key issue with the current Figaro TS2611-E00 methane sensor is the strong oxygen cross sensitivity. We recognized our sensor will operate in an anoxic (low oxygen) environment. We also expected the TS2611-E00 to have a cross sensitivity to varying oxygen concentrations. We tested the issue using argon to purge the oxygen from the sensor chamber. We did not expect the oxygen cross sensitivity to be many times larger than the humidity and temperature cross sensitivities. This strong oxygen cross sensitivity means the sensor will be least accurate when the methane concentration is potentially high enough for the sensor to measure. This severely limits any possibility of collecting any useful data with the Figaro TS2611-E00 methane sensor in a soil gas sampling application. Two possible solutions are discussed in Future Recommendations.

Device Wire Management

The circuitry of the device was soldered onto a smaller soldering board. When installed our team had a lot of trouble getting access to components inside the box with the circuit's wires in the way. A new larger soldering board was added, replacing the old one. This soldering board has terminals to allow users to change wires around easily and without hassle. Still the board is large and wires inside the box still do not have much room.

Future Recommendations

Methane Sensor

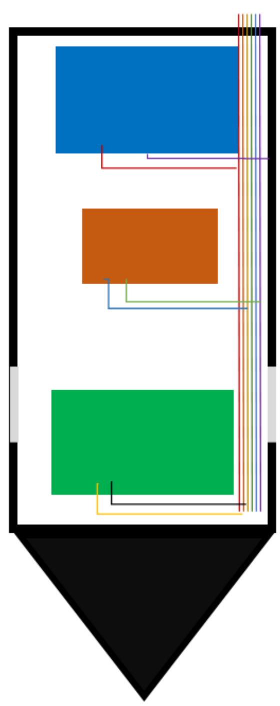
In the Challenges and Solutions we discussed the TGS2611-E00's strong oxygen dependence and how it does not fit our purpose due to the accuracy severely worsening in the target anoxic environments. Our team found a possible replacement, the Cubic brand Gasboard2502 TDLAS methane sensor. The price is $2,300 per sensor with an accuracy of +/-5ppm and a repeatability of +/-1.6ppm. This may not be accurate enough for useful methane measurements in dry soil with methane in the 2-10ppm range, but it will almost certainly have adequate accuracy for anoxic conditions with methane in the 25-100ppm range. The Gasboard2502 sensor will double the device component cost.

No Methane Sensor

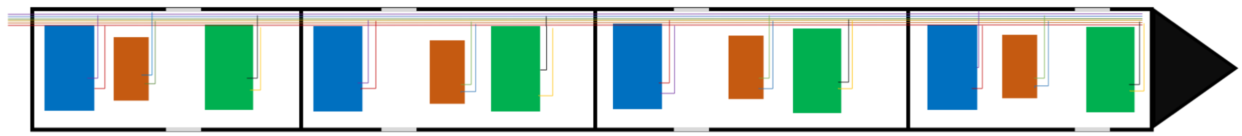
The other option is to not include a methane sensor. This allows an attractive alternative design, the "sensors in probe" design. This design almost certainly requires not using a methane sensor. The sensors in probe design eliminates many components, including the air pump, air solenoid valves, air manifold, water valve, water separator, sensor chamber, heater, and plumbing. This leads to advantages in reduced power use, lower design complexity, and fewer points of failure. The main challenge with the sensor in probe design is keeping the liquid water out of the sensors. This is the most likely point of failure. This design may use hydrophobic membrane filters, plugs made from sintered hydrophobic material, or some other method to keep water out (grey sections of exterior shell).

"Sensors in probe" description

The CO2, O2, and temperature humidity combination sensors are removed from their circuit boards and inserted into the soil probe. The sensors are connected remotely to their circuit boards with ribbon cable. Liquid water is prevented from entering with a hydrophobic filter or similar. The hydrophobic filter allows soil gases to diffuse through it. The probe has duplicates of each sensor in separate chambers at each soil depth. The sensors may be assembled onto a frame that in slid into the tube as one piece. A seal of caulk or an O-ring between each set of sensors would prevent soil gas mixing vertically in the tube.



Sensor in probe design detailed view.



Sensor in probe complete probe layout.

Applying regression to create a calibrated algorithm

Based on the actions from literature, using statistical analysis tools such as regression improves algorithm calibration. We recommend using two-point calibration and linear regression to improve calibration results. Setting up an experiment to calibrate the methane sensor alongside a temperature, humidity sensor could allow better calibration even in environments with changing temperature and humidity. Our recommendations come from work done by Bastviken et al [2].

Design Issues

Currently the sensors installed in the device are connected to the 12V supply or 5V supply without any on or off switch. In the future wire the sensors to connect to relays. Wiring the sensors to a relay could reduce power consumption for a long time simply by turning the sensors on or off when needed. Keeping in mind the sensors do need time to warm up. The sensors warm up in about 30 seconds, but more accurate measurements are possible at 30 minutes. Weighing the cost benefit is necessary if making this change.

Currently, the mayfly microcontroller in the device is supplied by a separate 3.3v battery. In the future, connecting the mayfly to the main power supply would prevent the risk of the mayfly running out of power. Eliminating the 3.3v battery would also eliminate the need for a person to continually replace the battery when servicing the unit. Lastly, eliminating the battery could increase space inside the unit. If necessary, incorporating the 3.3v lithium-ion battery as a backup could be useful. The current design recognizes the method for analyzing supply battery voltage, but no work has been done to implement a stop mechanism for when battery voltage reaches a certain low.

The current installed Solenoids are a problem for the device for three reasons. 1) the current solenoids are bulky and difficult to connect to. 2) The solenoids consume an abundance of power, way more than necessary. 3) The solenoids cause problems with the flow rate of the device. With different solenoids the device may be able to extract gases better, consume less power, and be easier to install. Overall, the solenoids are to expensive in terms of space, and power. Other smaller solenoids exist with much less power consumption making the current solenoids obsolete.

The current sensor chamber and pipe system for delivering gases extracted from probes has problems. The sensor chamber leaks due to being printed from PLA, and its inside volume is much larger than necessary. To resolve these issues, we recommend creating a sensor chamber with a leak-proof material and optimizing its inside volume to maximize gas contact with the sensors. Reducing the sensor chamber volume will also decrease pumping time and lead to long-term energy savings.

Our team implemented a battery level monitoring system using a voltage divider and a single pin from the ADS1115 ADC. However, we created a new circuit board for the system including terminal screws instead of hardwired soldered connections. The new circuit board lacks the voltage divider created on the previous circuit. Reimplementing the battery monitoring system would be useful. The voltage divider can be seen in Figure 5: Electrical Schematic. When a battery operates, its terminal voltage decreases when losing power. Performing a power drain test with the battery monitoring system will show at what voltage the battery is at low power. The device can then be programmed to perform actions based on low battery voltage.

In the Fall 2022 semester, time readouts were implemented into the Arduino program. In Spring 2023, our team did not focus on time. Slowly the time measurements became inaccurate and unusable as the internal clock drifts. Perhaps time could be adjusted using Fall 2022 program found in the GitHub repository. Our team recommends correcting the time readouts for useful context when datalogging. Instructions should be made for the client to periodically correct the internal clock time.

During this Spring 2023 we found calibration difficult and expensive. To perform proper laboratory calibration requires a lot of resources. Our team found our calibration procedure using a 10 ml syringe to be cost-effective and useful. Despite the absence of advanced laboratory equipment or specialized knowledge, our method has demonstrated efficacy in conserving resources and time. Nevertheless, the project is an open-source DIY resource for people. The syringe calibration method could be useful to the open-source community, but perhaps finding a commercial resource could provide value to next semester's team and the open-source community.

Gantt Chart for Fall 2023

Our team created a Gantt Chart we expected would be reasonable for next semester's team. The Gantt Chart includes objectives and tasks already scoped for a team to reasonably finish the objectives by the end of the Fall 2023 semester. However, this is a template and created a lot of value for our team in the Spring 2023 semester. Using a Gantt Chart provides accountability for your team to accomplish tasks in a timely manner. Our team recommends using our Gantt Chart and altering it to accommodate the problems faced during the semester.

Conclusions

In conclusion, The Spring 2023 soil sensor team focused on developing a low-cost, DIY soil sensing unit that can extract, measure, and report soil gas concentrations from four different depths. This project addresses the high cost of commercially available soil pore space gas instruments, which can hinder farmers' ability to monitor their soil health. The project has been ongoing with Spring 2023 being the third semester of the project. The Spring 2023 team created a prototype sensor chamber and a prototype water trap. Our team was able to implement the sensor chamber into the design and implement program logic to operate the heating element inside the chamber. The water trap design was 3D printed, but unfinished and untested. Our team installed a TGS2611-E00 methane sensor into the soil sensing unit but found and later validated the sensor reacted improperly to anoxic environments. A new circuit board was implemented with screw terminals to improve wire management and improve a user's ability to change around components. The conversion to a new circuit board eliminated the battery monitoring feature installed on the previous circuit. Our team explored what resources would be necessary for proper calibration of our device and found the resources to be very expensive. Our team stuck with a syringe method because of the low cost and easy applicability. Our team created a Gantt Chart for the Fall 2023 semester for the next team to use as an outline. The Gantt Chart supports a lot of our recommendations for the next team to perform in the future.

Program and supporting Resources

The program and supporting resources such as STL files, a condensed Final Design Document, Technical Poster, and more information about the project can be found on our GitHub repository with the link provided. https://github.com/TheGreatBuddo/Soil-Sensing-Device.git

Appendix i - Calibration

This Calibration Protocol will be run using the existing concepts of volumetric measurements and serial dilutions to correctly create our own calibration gas. This step is necessary to confirm the data sheet information and set up our equations to convert the output to proper percentages and ppm. We will do this by passing 100ml of our calibration gas over the sensors. We will first cover the Items necessary for calibration, The warmup time of the sensors, then cover O2 Sensor calibration then the CO2 Sensor, and lastly the CH4 Sensor.

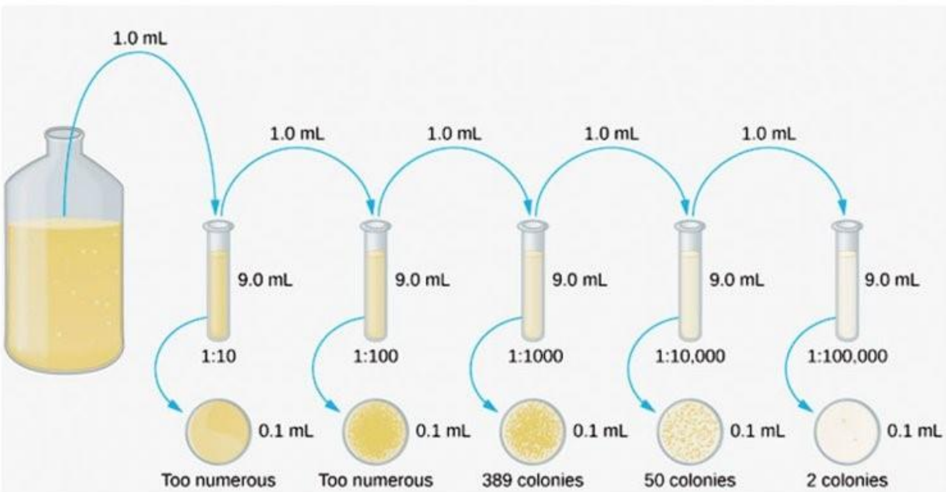
> Note: This Method was tested against 2 off the shelf handheld CO2 Stafty sensors, Accuracy of method was withing ±20ppm

The Required Objects

- Blackburn, 16g Threaded CO2 refills
- Blackburn Inflator
- One Tank of Argon, Compressed
- Methane Calibration Gas (1000 ppm, Nitrogen Balance, 17 Liter
- 100ml luer lock plastic syringe
- 10ml luer lock plastic syringe
- 2 male to female luer lock tips .167 in OD (M2F-ll)
- 3-inch section of .25 OD soft plastic tubing
- 0.50-inch section of .25 OD soft plastic tubing
- ~15 Balloons (Container for our gas CO2 and Argon)
- Soil Vapor Device

The first test is the Warmup time of the sensors. In this Test we will set up the system and turn on the pump and the sensors in series, as well as have the mayfly logging the data. Allow the system to run uninterrupted for 1 hour. While the systems are running, all the ports are drawing from the “same” ambient air not placed in the ground. The intent is to look at the data afterwards and find the point at which the values stabilize. Then compare those results to the values on the data sheet.

The first calibration test was performed to check the 0 values on the sensors. This was achieved by venting some gas from the compressed Argon into a balloon for storage. Then the balloon is attached to the top of the 100ml Syringe by pinching 1 inch from the inlet and stretching the remaining balloon over the syringe. Draw 100ml out of the balloon, because of the pressure in the balloon this will affect the size of the balloon less than one would think. Once you have the 100ml pure Argon calibration gas, we will attach the M2F-ll tip to the 3-inch tube and then affix the other end of the tube to the sensors. Attach the syringe to M2F-ll (some of the Argon will expel as the pressure equalizes between the syringe and the ambient air pressure- this is expected and will not affect current process). Turn the power on the pump off. Mark the time for reference and push the 100 ml of gas over the sensors for 10 seconds. Log the data and track the lowest values that are output from the sensors. After 0 value test, reattach the pump to clear the line back to ambient values. Repeat this calibration step 2 more times and use the lowest values. This data will be used as the zero value to detect change. ie: if 1.1v is the 0 value then and the next tested value is 1.3v that is a change of .2v) this will be used later for ppm calculations.



The second calibration test will be testing the O2 sensor with 5%,10%,15% concentration of O2. Each of these calibration values will be tested 3 times for repeatability and accuracy. To create our calibration gas for O2 we will need to assume that ambient air is ~20.9 O2. Then we can set up the equation y=20.9x where y is the goal for the % of o2 being tested.

Ie: @5%

$5=20.9x \Rightarrow 5/20.9=x \Rightarrow x= 0.239$

So, with this we can convert that into 23.9% of the 100 ml of gas in our syringe.

First Draw 76.1ml of argon from the balloon into your 100ml syringe. Remove the balloon and attach the M2F-ll. At this point the argon will decompress to ambient pressure and you will begin to draw in the remaining 23.9ml of air. This is now a 5% O2 concentration of calibration gas. Turn the pump off and attach the 100ml syringe to the sensors in series and mark the time. Administer the 100ml over a 10 second period. Log the data and then attach the pump again to purge the system with ambient air until normal values return (~20-30 seconds).

The same math and method can be applied to each of the other values:

@10%

$10/20.9=x \Rightarrow x= 0 .478$

Thus, start with 52.1 ml Argon and then draw in 47.8 ml of air to creating 10%

@15%

$15/20.9=x \Rightarrow x= 0.718$

Here, start with 28.2 ml of Argon and then draw in 71.8 ml of air to create 15%

Note: First iteration of the calibration test used CO_2 as the balance gas for the O_2 sensor however O_2 sensor has a CO_2 sensitivity, if the CO_2 is above 5% (50,000 ppm) these levels are unexpected in the field use of this device however when exposed to even the lower value of 28% CO_2 the sensor itself would output roughly 37% expected amperage.

The Next sensor to calibrate will be CO_2. We will use a similar method to the O_2 sensor however we will need to employ a process called serial dilution to achieve the smaller required values of 1000 ppm, 2000 ppm, 3000 ppm, 4000 ppm and 5000 ppm. Start out with one balloon of argon gas, and then create a second balloon with CO_2 gas. To do this screw one of the 16g threaded CO_2 cartridges into the Blackburn Inflator, pull the balloon over the dispenser nozzle and over the back of the dispenser. Pinch around the neck of the inlet again and pull the nozzle back slowly to release some of the CO_2 from the cartridge. Once both balloons are ready, then prepare the 0.5-inch soft plastic tube with both M2F-ll tips inserted on either side of the tube (ideally touching inside the tube to reduce contamination) hereafter referred to as “docking tube”. After that, use the 100 ml syringe to draw 95 ml of argon. Then use the 10 ml syringe to draw 5 ml of CO_2 out of the other balloon, attach both syringes to the connecting docking tube to draw the 5 ml CO_2 into the 100 ml syringe. At this point we have a 5% concentration or 50,000 ppm, allowing time for diffusion (~5-10 second). Now implementing the serial dilution process, if we want to reduce the current concentration by a factor of 10, we can transfer 10 ml of the 5% concentration back to the 10 ml syringe. Then expel the remaining gas in the 100 ml syringe. Next, draw another 90 ml of pure argon from the balloon and reattach it to the docking tube. Return the 10 ml 5% concentration to the 100 ml syringe and now a 0.5% concentration of CO_2 or 5000 ppm. Lastly remove the 100 ml syringe and one of the M2F-ll tips to attach to the sensors in series, turn off the pump and mark the time. Administer the gas over the standard 10 second window. Log data, turn the pump back on to clear the line and return to ambient values. Then repeat 2 more times for 5000 ppm. Note: the 5000 ppm should be the max the sensor will detect thus should receive max output.

This same method will be used to get other values

@4000 ppm

Start with the 100 ml syringe with 96 ml of argon and the 10 ml syringe with 4 ml of CO_2 attach both to the docking tube draw 4 into 96 and allow time for diffusion. Transfer 10 ml back to the 10 ml syringe @4% concentration then dilute into another 90 ml argon to achieve 4000 ppm

@3000 ppm

Start with the 100 ml syringe with 97 ml of argon and the 10 ml syringe with 3 ml of CO_2 attach both to the docking tube draw 3 into 97 and allow time for diffusion. Transfer 10 ml back to the 10 ml syringe @3% concentration then dilute into another 90 ml argon to achieve 3000 ppm

@2000 ppm

Start with the 100 ml syringe with 98 ml of argon and the 10 ml syringe with 2 ml of CO_2 attach both to the docking tube draw 2 into 98 and allow time for diffusion. Transfer 10 ml back to the 10 ml syringe @2% concentration then dilute into another 90 ml argon to achieve 2000 ppm

@1000 ppm

Start with the 100 ml syringe with 99 ml of argon and the 10 ml syringe with 1 ml of CO_2 attach both to the docking tube draw 1 into 99 and allow time for diffusion. Transfer 10 ml back to the 10 ml syringe @1% concentration then dilute into another 90 ml argon to achieve 1000 ppm

Mark the time of each calibration run and its value being tested for later reference against the logged data.

Lastly The CH_4 Sensor calibration will be very similar to the CO_2 calibrations we will be using the argon balloon but now we need to create the CH_4 gas balloon by attaching the balloon to the value and expelling some gas into the balloon. The CH_4 gas is 1000 ppm to start with and the goals are to archive values for 10 ppm, 50 ppm, 100 ppm, & 150 ppm. Using a similar equation to the first calibration $y=1000x$, where y is our desired ending concentration

@100 ppm

$100/1000=x \Rightarrow x=0.10$

Start by Drawing 90 ml of Argon into the 100 ml syringe and then drawing 10 ml CH_4 into the 10 ml syringe attach both to the docking tube and transfer the 10 to the 90 to create a 100 ppm concentration.

@75 ppm

$75/1000=x \Rightarrow x= 0.075$

Start by Drawing 95 ml of Argon into the 100 ml syringe and then drawing 7.5 ml CH4 into the 10 ml syringe attach both to the docking tube and transfer the 7.5 to the 92.5 to create a 75- ppm concentration.

@50 ppm

$50/1000=x \Rightarrow x= 0.05$

Start by Drawing 95 ml of Argon into the 100 ml syringe and then drawing 5 ml CH4 into the 10 ml syringe attach both to the docking tube and transfer the 5 to the 95 to create a 50-ppm concentration

@25 ppm

$25/1000=x \Rightarrow x= 0.025$

Start by Drawing 97.5 ml of Argon into the 100 ml syringe and then drawing 2.5 ml CH4 into the 10 ml syringe attach both to the docking tube and transfer the 2.5 to the 97.5 to create a 25 ppm concentration

Note: the CH4 calibration gas is at 1000 ppm or 20% of LEL. This CH4 concentration is not explosive in a normal atmosphere with 20.9% ambient O2 and is within NIOSH (National Institute for Occupational Safety and Health) safety standards for human exposure for up to 8 hours with sufficient ventilation.