DEPARTMENT OF BIORESOURCE ENGINEERING

WINTER 2021 BREE 495 – ENGINEERING DESIGN 3

An Enhanced Intelligent Greenhouse Gas Analyzer for Soil Emissions

Professor: Dr. Chandra A. Madramootoo

Advisor: Dr. Viacheslav Adamchuk

Submitted by

Liying Xu

Jinxue Hao

Jing Yu

Minghao Shi

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LIST OF ACRONYMS AND ABBREVIATIONS

AI	Artificial Intelligence
CAD	Computer Aided Design
CH_4	Methane
CO_2	Carbon Dioxide
CPU	Central Processing Unit
FDM	Fused deposit modeling
GHGs	Greenhouse Gases
LoRa	Long Range
LSMT	Long Short-Term Memory
N_2O	Nitrous Oxide
NDIR	Non-Dispersive Infrared Detection
PLA	Polylactic Acid
S	Sulphur
STL	Standard Tessellation Language

ABSTRACT

Greenhouse gas emission increasing pressure on the natural environment, especially the greenhouse gas emission from agricultural soil, which has aroused people's attention to agriculture in North America. As a result, the study of gas emissions from farmland has become a trendy academic topic through a series of experiments and tests. A graduate student at McGill University, Mohamed Debbagh, used the gas sensor method, which combined the infinite sensor network and non-dispersive infrared carbon dioxide (CO_2) sensor. He developed the detection device, measured the carbon dioxide (CO_2) gas, and obtained relatively objective and accurate data. The team made the second development of Mohamed's gas detector, which simultaneously detected and wirelessly transmitted the two gas' concentrations by adding a nitrous oxide (N_2O) sensor, NG2-F-3 sensor. The passive diffusion principle utilized in the original static chamber was maintained in the design, and the pump had been added to help the gas flow in the chamber. Arduino Nano Processes all the sensors in the chamber, and the Raspberry Pi model 3works to transmit the gas data. Simultaneously, a separate gas test was performed on the NG2-F-3 sensor to check the sensor's applicability and accuracy. Data feedback from field tests demonstrated the availability of the NG2-F-3 sensor. The system features include real-time in-situ analysis and wireless remote transmission of greenhouse gas emissions from soil, space and time for pastoral work. In addition, the design components are readily available and effortless to install.

INTRODUCTION

As the increasing occurrence of extreme weather and environment globally and severe pressure of the world population blooming toward nature, as well as people raising concerns progressively to ecological, economic, and social development. In consequence, the world adopted a series of international documents, such as the Paris Agreement, Millennium Development Goals, and the Sustainable Development Goals which was aimed at reducing the pressure of human activities on the sustainability of the environment. Among all the factors that affected the ecology on the Earth, greenhouse gases (GHGs) occupy the main attention of everyone.

The main greenhouse gases are carbon dioxide (CO_2) nitrous oxide (N_2O) and methane (CH_4) (Tremblay, 2005). Greenhouse gases can raise the average temperature of the climate because when the sun's thermal radiation is transmitted to the earth's atmosphere, some of the heat is absorbed by these greenhouse gases. However, this heat is difficult to be evacuated out of the atmosphere, so it enters the earth through the ecological circulation system and raises the temperature (Houghton, 2005). This phenomenon absorbs infrared light and retains heat, and also known as the greenhouse effect (Tremblay, 2005). Some of these greenhouse gases are released from natural aquatic and terrestrial ecosystems, such as wetlands, swamps, and forest forests; the rest of greenhouse gases emissions come from human activities, such as industrial burning and animal husbandry. Part of these greenhouse gases emissions are absorbed by nature, and the rest emissions accumulate in the atmosphere and increase the concentration of greenhouse gases in the atmosphere (Tremblay, 2005). In particular, CO_2 accounts for the majority of industrial greenhouse gas emissions. Carbon dioxide emission is 50 to 66 percent of industrial emissions and this industrial emission is 80 to 85 percent of the world's total greenhouse gas emissions, so the main focus right now is on reducing CO_2 emissions (Tremblay, 2005). Moreover, some wetlands and swamps provide a major source of methane (CH_4) production because of their perennial anaerobic environment (Tremblay, 2005). Furthermore, human activities, especially agricultural activities, have a significant impact on greenhouse gas emissions. For example, in the oil palm fields of Southeast Asia, in order to meet the production growth, the peat bog forest is replaced by palm plantations, which directly leads to the nitrogen in the soil cannot be naturally consumed, so the nitrogen is converted to nitrous oxide (N_2O) and released into the atmosphere in the form of gas (Wollenberg, 2012). Therefore, nitrous oxide (N_2O) emissions are also important in agriculture. Hence, the world is slowly starting to pay attention to nitric oxide emissions from farmland.

Therefore, the research team this semester will continue the design goal of last semester. By retrofitting the existing wireless CO_2 gas flow measurement chamber and combining it with the N_2O sensor to achieve that collecting and transmitting the data remotely to the computer. The CO_2 flow measurement chamber was designed by Mohamed Debbaggh from McGill University. In this report, the actual installation and improvement of the chamber for gas fluid measurement will be described in detail.

Mission statement

Designing and manufacturing an modified automatic wireless carbon dioxide (CO_2) and nitrous oxide (N_2O) gases detecting device for the conveniences and improvement of agricultural researches.

DESIGN APPROACH

This report describes the final design, practical operation methods, design details and test data for retrofitting and testing the infinite gas flow detection device. First, the nitrous oxide (N_2O) sensor selected by the team will be introduced, in particular how to actually use, test, and calibrate the sensor. Moreover, the paper will explain the manufacturing process and assembling information of the design. Meanwhile, to combine the carbon dioxide (CO_2) and nitrous oxide (N_2O) sensors, the team designed a composite base, which was 3D printed. The report would cover 3D-printed information, such as pedestal designs and the printing process. Then, the relationship between the product and society, economy, and environment in design would be mentioned in this paper. Moreover, the report would also give the nitrous oxide (N_2O) measurement data in the modified measuring device. The manufacturing costs analysis was also given in the paper. Furthermore, during the design and producing processes, the team had some challenges; therefore, these challenges would explain in the paper. Finally, through repeated debugging and testing of the final design, the team would give suggestions for improvement and propose future research directions.

LITERATURE REVIEW

NG2-F3 Nitrous Oxide Sensor

The most important component in this gas analyzer is the nitrous oxide sensor. As the previous team mentioned, they reached out to a sensor company named Dynament Company (Berthiaume, 2020). This company has the nitrous oxide sensor that has the sensitivity of 0-1000 ppm range, which is comparably sensitive in the market. As a famous and young technical company in Europe, founded 2011, Novasis-Innovazione provides high-quality design service and product for the automotive and railway field.

Novagas2 is a kind of gas sensor of this company for sale in the market, which is positioned as a measurement module for carbon dioxide (CO_2), carbon monoxide (CO), nitrous oxide(N_2O), and Methane (CH_4). The method used in this type of sensor to detect the concentration of gas is called Non-Dispersive Infrared Detection (NDIR), which is known as the industrial standard method of measuring the concentration of gases like the most common gas CO_2 and N_2O. This method could be described as following: The gas in the sample will absorb some infrared light, which is at a particular frequency; then an infra-red beam will penetrate through a sample cell which containing the sample gas, and the amount of infrared light at specific wavelength absorbed by the gas will be measured; in other word, the light intensity is correlated to the concentration of the measured gas; in this case, precise gas concentration can be measured by the detector (Farano, 2019). In addition, the gas cell has been designed as tough enough dedicatedly to work in harsh environments like agricultural and industrial fields. Furthermore, to make the testing more flexible, a pneumatic pump could be added to the measurement system according to the specific testing environment as well as the natural diffusion. By focusing on the overall technical performance especially precision range and testing environment, NG2-F-3 sensor was selected, which will be discussed in the following in detail (Farano, 2019).

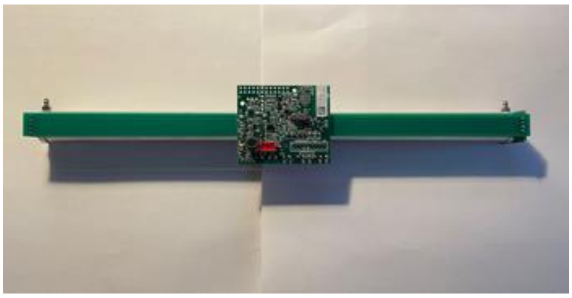


Figure 1. NG2-F-3 sensor

NG2-F-3 sensor, known as a series number of Novagas2 sensor, which is a sensor product for the nitrous oxide gas concentration measurement. This sensor has a overall dimension of 306*48*42 mm with a 56mm*48 mm transmitter board connected to a cylindrical gas measurement chamber by a strip shape supporter. On the gas measurement chamber, there are two input and output gas nipples. And three holes on the transmitter board are applied as fixed functions, which can be customized. Moreover, measuring cycles could be managed by a firmware, which includes “gas inlet through the pneumatic pump and gas concentration calculation” (Farano, 2019).

For the specifications, the data refresh rate of this type of sensor is 5 second, which is fast enough for the measurement. In addition, this sensor could have great performance at different testing environments; for example, the temperature range of testing is from 0℃ to 50 ℃ with linear compensation. Moreover, the measurement range and accuracy are the crucial specifications to show the performance of this sensor, which are also the selection basis of our analyzer. For this sensor, the measurement range is from 0 part per million (ppm) to 100 ppm, and the accuracy is +/- 2%, which are very precise and sensitive compared to other N_2O sensors in the market (Farano, 2019).

Sensor Technique

Chamber Measurement

The most common technique to measure the greenhouse gas emission from the field is chamber measurement method. In addition, chamber measurement is economic and simple in the application of research. There are different types of chamber including closed chamber of dynamic or static and open chamber of dynamic or static (Berthiaume et al., 2020). Closed chambers are used as the most common chamber measurement method, which will be introduced following.

In the static chamber method, the chamber is fixed on the study site and collects the greenhouse gases emitted from the soil for the amount of time required. When the gas sample is taken out from the chamber, equal time intervals should be considered. Then the gas could be collected in a gas container for further analysis in the laboratory. In this case, the flux of greenhouse gas emission is calculated by the changes in concentration during the sampling time. (Rao, Sultana, & Kota, 2017). And there are some points that should be noticed before using this method. In order to get stable gas emission, the chamber usually should be anchored at the measuring points; therefore, the top layer of the surface should be cleaned and excavated. Moreover, a blade is always installed at the open end of the chamber because it could easily insert into the ground with the help of this sharp structure. In this case, safety should be carefully concerned when this method is applied. Furthermore, when the gas is collected, gases are not allowed to enter or remove from the chamber in order to keep the accuracy of data.

On the contrary, in the close chamber of dynamic method, during the sampling time, air would flow through the chamber. The flux of greenhouse gas emission could be calculated by measuring the gas concentration in the exhaust gas and air flow rate (Rao, Sultana, & Kota, 2017). In conclusion, chamber methods could easily collect the data of gas emission and do further analysis with lower cost. On this basis, more testing could ensure the accuracy of data analysis (Rao, Sultana, & Kota, 2017).

Non-Dispersive Infrared Detection

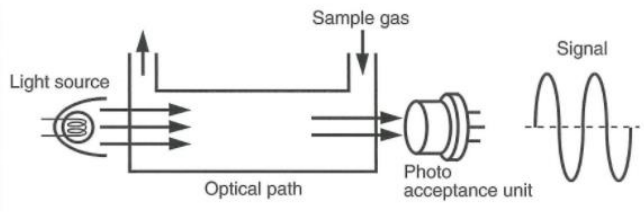


Figure 2. Structure of Non-Dispersive Infrared Detection

Non-Dispersive Infrared (NDIR)detection is commonly applied in the analysis of concentration of greenhouse gases according to the characteristic infrared absorption of the target gases. Specifically, after the gas is collected in the chamber, the gas in the sample will absorb some infrared light, which is at a particular frequency; then an infra-red beam will penetrate through a sample cell which containing the sample gas, and the amount of infrared light at specific wavelength absorbed by the gas will be measured (Tan et al., 2020). Taking carbon dioxide as an example, when the carbon dioxide gas is testing, the infrared light emitted periodically. In this case, only a few amounts of CO_2 in the gas sample could absorb the infrared detector at a wave of 4.3µm. Then the detector is only sensitive in the wavelength band centered on 4.3µm, emitting an electric signal according to the concentration of testing carbon dioxide gas (*Non-Dispersive infrared ABSORPTION SENSORS*, 2021).

In today's market, a multiplexed NDIR gas sensor needs several pairs of bandpass filters and detectors which make the sensor heavier and more expensive compared to the conventional NDIR gas sensor. The infrared detector is paired with just one bandpass filter to do the gas emission testing in the conventional NDIR gas sensor (Tan et al., 2020).

Machine Learning Prediction

Machine Learning is the substream of Artificial Intelligence (AI), and a general designation of several algorithms that support the computers to learn without programming (Wittek, 2014). Machine Learning models are increasingly used in different areas including environmental data analysis, artificial neural networks, stock market prediction, etc.

In the study of Hamrani et al. (2020), three categories of Machine Learning regression models, including classical regression, shallow learning and deep learning were exploited for predicting the greenhouse gas emission from the agricultural field. The research site of this study was in Saint-Emmanuel, in the region of Côteau-du-Lac, Quebec, Canada, and the measurements of greenhouse gas emission which includes nitrous oxide(N_2O) and carbon dioxide (CO_2) were taken at three plots during the growing seasons of five years: 2012, 2013, 2014, 2015, and 2017.

After collecting the sampling gases, the data was sent to the laboratory for in-depth study. In this study, three classes of Machine Learning models were applied: classical regression (SVM, RF, and LASSO), shallow learning (FNN, RBFNN, and ExNN), and deep learning(LSTM, DBN, and CNN) (Hamrani et al., 2020). Then the analysis of correlation, stepwise regression, neighborhood components analysis and minimum redundancy maximum relevance algorithm were applied to determine which parameters affect the prediction of greenhouse gas emission the most during the period of 2012 to 2015(Hamrani et al., 2020).

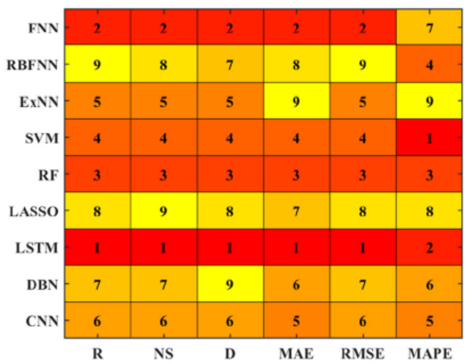


Figure 3. Heatmap Ranking of Comparative assessment of the ML model for N_2O flux

The results show that the LSTM model has the outstanding performance in most analysis, and it is the best model to predict the future carbon dioxide and nitrous fluxes. For example, even though the LSTM requires more intensive training time like most Deep Learning models, the comparison of results of LSTM model with Root Zone Water Quality Model (RZWQM2) showed the better predictive performance of LSTM (Hamrani et al., 2020). In conclusion, the machine learning predict method is becoming a useful method to help to improve the data analysis and prediction.

Sensor Application

Agriculture is the crucial element of the development of civilization, and the cultivation and farming support the living of people. With the development of technology, the production efficiency of crops is dramatically increasing. However, this kind of improvement also causes damage to the environment including climate change, global warming, deforestation, air pollution, etc. (Alexander, 2021).

To minimize the negative impact, more techniques are applied to assist agricultural production in the way of being environmentally friendly. Among these techniques, gas sensors are the common devices used in the productivity of agriculture and the analysis of data for research. There are several applications of gas sensors in the agriculture field. Firstly, the gas sensor could be applied in the commercial greenhouse control system. This system helps measure and control temperature and CO_2 concentration for the growth of optimal plants. In addition, carbon dioxide, nitrous oxide, or methane concentrations could also be tested by CO_2 gas sensors and controlled in the dairy farm or crop fields. Moreover, the quality and status of stored crops in the barn could be detected by the measurement of gas. Furthermore, during the production of biogas, the process of anaerobic digestion could be detected by the measurement of carbon dioxide and methane gas (*Agriculture sensors: Sensors used in agriculture: Gas detection,* 2012).

Sensor Coding

Arduino

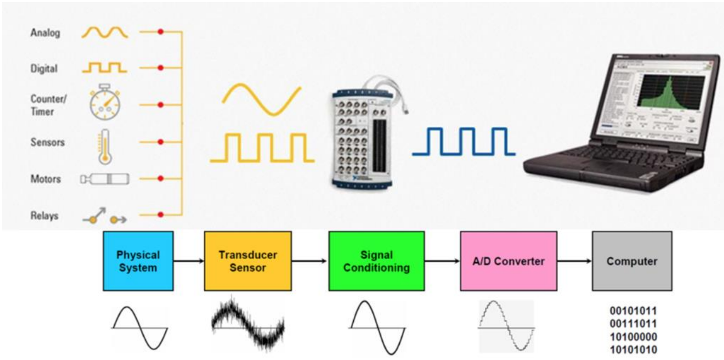


Figure 4. Digital Data Acquisition System (Lange, 2017)

Arduino is a programmable circuit board that is open source and could be integrated into a plenty of simple or complex makerspace projects. In order to sense or control the object, a microcontroller on the circuit board could be programmed. After the Arduino received the data from the sensor, it could interact with outputs like robotics or some display. The whole process of digital data acquisition system is shown in the Figure. 4 (Lange, 2017). In addition, the flexibility and cheap price make it the most competitive and popular product for the makers to create interactive hardware projects.

Arduino Uno and Arduino Nano



Figure 5-6. Image of Arduino UNO (left) and Arduino Nano (right)

Uno is a type of Arduino, which is the most popular among all the types of Arduino. An Atmega 328 processor operating at 16MHz provides power for the board, which includes 32KB of program memory, 2KB of RAM, 14 digital I/O, and 6 analog inputs with 5 volts and 3.3 volts power rails (Mitchell, 2021). Nano is another type of Arduino. In the board of Nano, an Atmega 328 processor is also operating at 16MHz, and other specifications are the same as Uno. The difference between Uno and Nano is the size. As shown in the figures above, Nano is way smaller than Uno. The smaller scale of Nano could make it convenient to place in a tight layout. In addition, the overall weight of the devices might need to be reduced in some projects; in this condition, Nano could make it possible (Mitchell, 2021). The following figure is shown as an example of possible portable gas sensor signal condition and interfacing with Arduino Uno (Mane et al., 2020).

Raspberry Pi 3

Raspberry Pi is a cheap computer in the size of a card. It can be plugged into the monitor or television, with the application of keyboard and mouse. In addition, it can be used as a learning tool to learn how to program using language like Scratch or Python as described in its official website. Overall, Raspberry Pi is a functional and useful device that could help people solve different problems.

Raspberry Pi 3 is the third generation of raspberry. Compared to its predecessor, Raspberry Pi 3 is faster. In addition, it has more advanced capabilities. For example, The Central Processing Unit (CPU) of Raspberry Pi 3 has 50% better performance than that of Raspberry Pi 2. The improvement could be shown in video playback, applications processing speed, data procession, etc. Furthermore, wireless internet out of the box with connection of Wi-Fi and Bluetooth is allowed in Raspberry Pi 3, which provides more convenience for some remote-control projects.

Additive Manufacturing

3D Printing Technologies

Additive manufacturing, also known as 3D printing, is a transformative approach to industrial production which could create lighter and stronger systems. In other words, additive manufacturing solves the problems that the customized components could not be easily produced or purchased. For example, if sensors or electronics are placed in a chamber, considering the layout of the inner chamber, a component used to support the sensor is needed with a specific dimension; in this case, 3D printing could solve this problem with lower cost and high efficiency. Therefore, nowadays, in the market, more production needs additive manufacture like eyeglasses, furniture, dental products, architectural scale models, reconstructing fossils, and etc. In addition, 3D printing technology allows the inner or outer structure remain integrity, which makes desired components in different appearances.

The first step of 3D printing is focusing on making three dimensional solid objects in the software which provide 3D drawing function. In the market, there are many software tools available for the drawing. The most common applications are AutoCAD, Solidworks, 360 Fusion and so on. After we draw the components in three dimensions, the drawing should be exported as an STL file, which is the place to store all the information about the conceptual 3D model. Then, we should select the material for the printing. In the market, there are many kinds of material available. The most common materials are Polylactic acid (PLA), Polyvinyl chloride (PVC), and Acrylonitrile butadiene styrene (ABS), which will be discussed in the following section. After the materials are selected and the parameters of the object are decided, the G Code should be created. The STL files will be imported into slicing software, like Slic3r or BCN3D Cura. Then the slicing software tool will transform the files into G code, which contains the instructions for the 3D printer. Last, the 3D printer will produce the object layer by layer. After several minutes to several days, which depends on the size and shape of the objects, the object could be produced.

Materials

One of the most common in the market of material for 3D printing is Polylactic Acid (PLA), which is used as the 3D printing material of our inner components. Polylactic acid is a type of polymer made from renewable resources. In the production process, it is fermented under controlled conditions of carbohydrate sources. These sources include corn starch, sugarcane, beans, and etc., in which its building blocks could be lactic or lactide monomers (Gutierrez, 2021).

In addition, there are plenty of valuable properties to support the polylactic acid plastic to become the most common and user-friendly material for 3D printing on the market. Compared to the petrochemical based plastics, PLA is more eco friendly because of its biodegradable property (Gutierrez, 2021). Specifically, PLA has a reduced carbon footprint because the crops absorb carbon dioxide when it grows, and the whole process produces less greenhouse gases to produce polylactic acid than that of petrochemical based plastic.

Furthermore, PLA melts easily because of its low melting point; therefore, it requires less energy to transform the raw material to the shape designed compared to other fossil fuel-based material. As for the environmental effects, taking petrochemical based plastic and PLA as example, when they are both incinerated, PLA emits less toxic material. (Barrett, 2021). In this case, these characteristics make PLA easily occupy the market share of 3D printing material and become more competitive.

DESIGN PROCEDURE

Previous Design

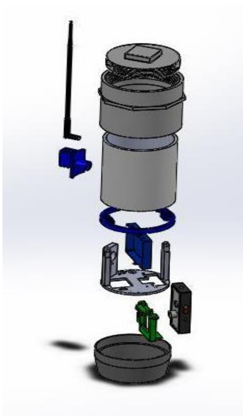


Figure 7. Previous Design

The previous design as shown in Figure 7, is the basis of current design. This design has a similar outer appearance with the current design. In the main chamber, it contains the sensor circuit box, sensor platform, fan, fan holder, and CO_2 sensor. Due to the lack of N_2O sensor, the inner layout remains the space for the future installation of high sensitivity N_2O sensors. In this design, the tube is 6 inches diameter PVC pipe, and most components in the main chamber are 3D printed like support platform and fan holder, which are considered to lower the cost as the previous team mentioned (Berthiaume, 2020).

DESIGN CONSIDERATIONS

The product is proposed to the user group of academic and professional researchers, with interests toward studying GHG emissions from agricultural soil. As an engineering design project, it must meet the criteria and standard of law. In addition, sustainability is playing an important role in any plans and practice of engineering projects. Therefore, besides the fundamental requirements for the projects, the impacts on the sustainability of the environment, social demand, and economic development and living standard should be considered. The specific design considerations of the design will be discussed in the following part.

Environmental

The overall design is environmentally limited in the choice of materials because the product is required to be used outdoors, and at the same time to make sure that it can resist extreme weather, such as snow, rain, and long periods of sun exposure, so PVC pipes were chosen. At the same time to ease the installation of the product, the bottom of the product added metal blame. Therefore, the materials used in the overall design of the product all need the input of non-renewable resources, which put a certain pressure on the ecological environment. However, due to the durability of PVC materials and metal, the product can be recycled and reused through refurbishing techniques (sanding, polishing). Thus, the input of raw materials will gradually decrease in the subsequent stage. Meanwhile, internally, the design uses 3D printing technology with polylactic acid. This is a renewable material that is biodegradable. By using crops such as corn starch and bagasse, polymer products are fermented in a restricted environment. Therefore, although the structure of 3D printing is difficult to be reused, the material can still be recycled and degraded into fertilizer and put into agriculture, and polylactic acid is not only biodegradable, but also carbon neutral material (ALL3DP, 2021).

Metal components and plastic are the main material used in this design, which is non-renewable resources. If these materials are disposed improperly after the lifespan of this analyzer, they will have a great impact on the environment, putting more burden. In terms of pollutions, they might cause severe greenhouse gas emission like carbon dioxide (CO_2), sulphur (S), methane (CH_4), and even nitrous oxide (N_2O), which would result in the acid rain, influencing the ecosystem and survival behavior of wildlife like migration; in addition, if some non-renewable components burn, it will produce pollutant to the air, which might be deposited to the water body like river and lake, threatening the life of species; furthermore, the process of disposal involves surface land construction, which changes local ecosystem to some extent. Therefore, to minimize this kind of influence, in the user manual, there should be a specific section to inform the user to dispose of the component properly after the lifespan of this analyzer.

In addition, extending the lifespan of the analyzer could help minimize the negative impacts on the environment. Regular maintenance is important to reach the goal. Therefore, the maintenance section in the user manual should be more detailed like informing the user maintenance period and replaceable components. Moreover, the selection and recycling of materials used in the analyzer are the crucial part of sustainability. For example, degradable plastic could be applied in the shelter of replaceable components; used plastic tubes for the main chamber with light damage or color faded could be recycled and returned to the production line for future manufacture. Additionally, when the user applies the analyzer on the soil, the topsoil will be damaged because of the blade in the bottom of the chamber, which is unavoidable during this process. Therefore, proper placement of the device should be informed in the user manual.

Social

From a social perspective, this analyzer could test the gas emissions in very precise specifications, which would provide the source data for the modeling or prediction in the research of environmentalists or engineers. In addition, the results of testing and research might alert the government and society to pay attention to the GHG emission and make further regulations on this issue. As for the devices, the uses of remote control could provide the user great convenience when the testing is processed. As a result, the users could get precise measurements without bringing the gas to the laboratory for further analysis compared to some traditional devices. In this case, users could save more time, increasing the efficiency of research.

Even though this design could provide many conveniences during the testing process and a positive influence of the society, the potential risk should also be considered. An engineer should take the safety of society and users as the most important role when designing the products or project. For example, in this device, most parts of the main chamber and internal components are assembled. Assembly should be informed properly in the manual to avoid damage to devices. In addition, correct application could avoid various safety issues. For instance, minor electrocution would occur if the wires and circuit board are installed improperly; furthermore, when placing the chamber to the soil in the process of testing, the blade might harm the users. To avoid this safety issue, in the user manual, there must be a safety and health section clearly informing the risks might occur during the testing process. Moreover, the maintenance of devices should be informed properly in the user manual, especially the gas sensors in the main chamber because of their high precision property.

Economic

The overall cost of the analyzer might be influenced by the nitrous oxide sensor, carbon dioxide sensor, and other electronic devices in the main chamber. The cost of the nitrous oxide sensor and carbon dioxide sensor in our design is much higher than that of other sensors, especially the nitrous oxide sensor, which is imported from Europe with the highest precision in the testing field of nitrous oxide. After the manufacture, when this product is selling in the market, the overall price is always considered by the customer. Therefore, in order to lower the overall price while maintaining the quality of this analyzer, most components are 3D printed and assembled like a support platform and circuit box; in this case, the overall price could be maintained in a reasonable range, which makes this analyzer more competitive in the market. In addition, reasonable recycling will reduce the cost of purchased parts to some extent; for example, some plastic material like PVC pipe for the main chamber of the analyzer could be recycled for repeated use if it is only damaged slightly or just has color faded. Furthermore, proper maintenance for the inner device could extend the lifespan of this analyzer, which would reduce the cost of the purchase for the user. Therefore, the user manual of the analyzer should properly inform the user of maintenance like replacing battery regularly or cleaning soil and small rock remaining in the chamber after use.

COMPARISON OF DESIGN ALTERNATIVES

This figure shows the alternative design of this analyzer. This design is based on the existing CO_2 gas flow measurement Chamber. The original carbon dioxide sensor is kept, but the position of the carbon dioxide sensor is changed. The carbon dioxide sensor and nitrous oxide sensor are combined and placed in the middle of the chamber using 3D printing technology. At the same time, a filter net is added at the bottom of the chamber to filter the air, so as to avoid small particles of soil and organisms in the soil entering the sensor. A fan was added to create a flow of air inside the chamber, helping sensors detect carbon dioxide and nitrous oxide in the air. Moreover, the length of the tube of the main chamber is extended because of the new coming nitrous oxide sensor, which is 306 millimeters.

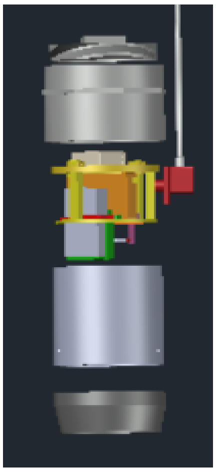


Figure 8. Alternative design

However, after the NG2-F-3 sensor was received, we found that the main chamber layout design of the last two alternative designs was not suitable for the N_2O sensor because the wires were much more than we estimated, and also a sensor battery came with the new sensor. In this case, there is no space for them to be installed if we still use this alternative design. In addition, the filter net is a circular platform, which should be fixed on the tube with nails. In this case, when the analyzer is testing in the moisture or raining environment, the inner devices might be damaged because of the water ingress. In the current design, the filter net is installed in other locations to solve this problem, which will be discussed in the following. Also, the upper chamber platform just provides the support for the battery, which would cause the waste of material. In the current design, the layout of the inner chamber is redesigned in order to avoid the waste of 3D printing material, while maintaining the desired functions. Therefore, an advanced design was proposed which will be discussed in the following in detail.

The Pugh chart was considered as a very useful tool to select the best design. In this chart, the designer could easily know how to rank the design according to the criteria. As shown on the Pugh chart in the appendix**,** the best design is selected based on the seven criteria. Comparing the five designs, the current design is the best in ergonomics because the blade on the bottom side of the chamber can help the analyzer easily insert into the soil when testing. On the side of the second design, although it has a fan, it can easily intake crops or insects during the testing. The cube shape characteristic of the first design makes it difficult to achieve uniform forces on the sides when testing. For the durability, the chambers of these designs except third design and current design are open directly to the soil when testing. Therefore, the chamber could be the habitat of insects and rocks may damage the inner devices in the main chamber. However, in the third design and current design, a filter net is applied to avoid this problem as well, which increases the lifespan of the analyzer. As for the cost, the first and second design have lower cost than the third and current design. The cost of the current design is reasonable because the N_2O sensor has more precise sensibility, and other materials are carefully selected by considering the price-performance. In terms of portability, the first design is difficult to carry because of the cube shape. The current design involves remote control by applying Arduino and Raspberry Pi 3, which provide more convenience than other designs when testing.

In addition, the current design concept's benefits lie in the material, assembly, and ease of outdoor use compared with other previous designs. The latest version of the design was based on food-grade PVC material, which is better suited to outdoor environments than typical PVC. The 3D-printed parts were made from PLA material, which is lighter than PVC and more environmentally friendly. The overall design assembly was completed using machine screws and threads. The 3D printed parts were designed with a mortise and tenon joint structure to assist the assembly of the parts, making the internal structure more integrated and facilitating assembly. The chamber used a six-inch tube more extensive than the four-inch tube used in the previous design but can contain all sensors, fans, pumps, batteries, and data cables. Therefore, from the appearance, the overall design is more concise and convenient for outdoor use to avoid damage caused by exposed accessories. Furthermore, a control switch is set outside the top lid to constrain the design's operation and facilitate manual operation. In conclusion, the current design has the best performance among these five designs in the perspective of these seven criteria as shown in the Pugh chart.

PROPOSED DESIGN - The Gas Analyzing Chamber

Sensor Configuration

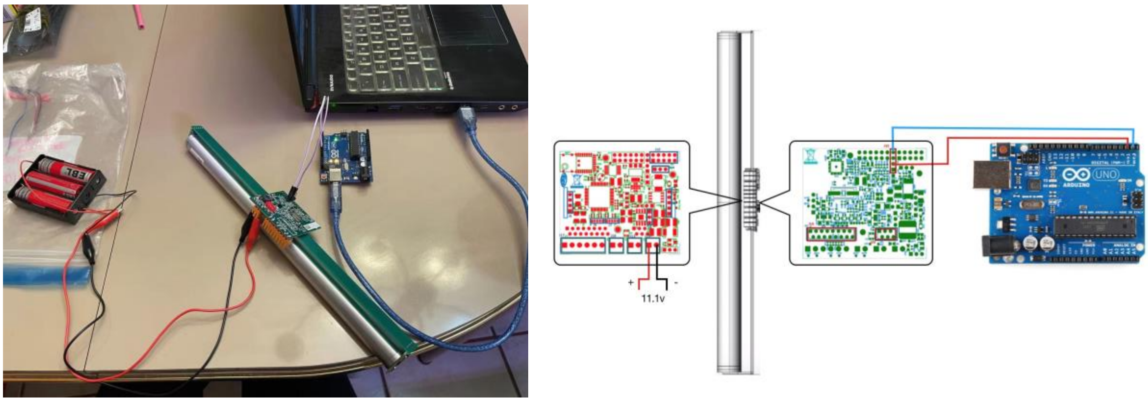


Figure 9-10. Connection of NG2-F-3 and Arduino UNO with PC (left) and the schematic circuit diagram (right)

Since the NG2-F-3 is the core modification that has been made on the device, the independent data transmission process and general communications with the rest of the system requires certain experiments and adjustments. Debbagh's thesis has provided a substantial number of instructions and examples on the circuit board and wiring arrangement, which has been extensively consulted by this part of the report.

Firstly, the NG2-F-3 sensor was separately configured with an independent Arduino UNO board, as a test of its fundamental functionality, as illustrated in Figure 10. According to the NG2-F-3 user manual, connector port J19 is responsible for UART 9600-115200 Baud transmissions, which corresponds to Digital PWM pin 0 and pin 1 on Arduino UNO. For the power option, connector J15 is applied for 9-24 V DC input, therefore the same battery standard as the power supply for K30 is selected, which is a set of 3 lithium-ion 18650 3.7V batteries.

For the software codes, several library functions were created, with basic operations such as initializing the port to build communication with the computer, requesting N_2O concentration and temperature data from the sensor. The codes are only for testing the functionality of NG2-F-3 independently and are attached in the appendix for reviewing.

To add the N_2O detection feature to the original device, the configuration circuit board was studied. The data processing was done by Arduino Nano, a small and complete micro-controller installed on the board. All the sensors included in the device are connected to Arduino Nano and analyzed by the pre-programed codes as an entity. The long-distance transmission from each node is designed to be received by a mobile gateway, developed by Raspberry Pi 3 Model B (Debbagh, 2019).

After careful examination on the wire diagram and the circuit board of Debbagh's design, pin TX1 and RX0 on the Arduino Nano processor were selected for transmission and receiving form NG2-F-3, respectively. An additional battery power supply is required for the new sensor, which is the same aforementioned standard as the power supply for the K30 sensor. A suggested wire diagram with NG2-F-3 integrated into the system is presented below in Figure 11, which is modified based on the diagram in Debbagh's thesis. A synthesized code that has included the new functions (i.e., detecting N_2O concentration and the surrounding temperature with NG2-F-3) is attached at the end of the report. Since the NG2-F-3 sensor has a built-in temperature-detecting module, the original DHT 11 temperature is no longer required, therefore the part of the codes involving DHT 11 was removed.

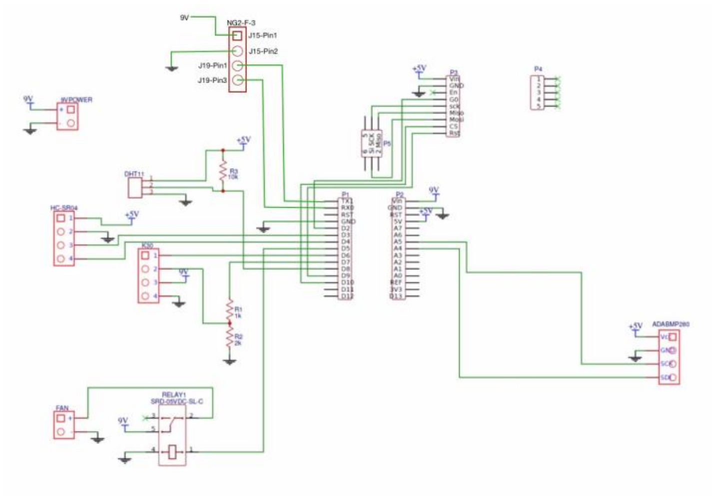


Figure 11. Proposed wire diagram of the sensor node circuit board (with NG2-F-3 added) (Debbagh, 2019)

Outer Shell

The outer shell of the gas analyzer designed as a cylindrical robust chamber. This design is originated by Mohamed Debbagh. In Mohamed's design, he placed the host of sensors inside the chamber, and housed the configuration unit and communication unit in a box and fixed on the surface of the shell using cable ties. Despite placing the configuration and communication unit will increase the convenience of repairing and making adjustments. However, installing the configuration unit at the surface of the chamber leads to the exposure of wires and batteries. Since this device is also designed for outdoor purposes, this kind of design would cause potential risks such as electric shock and damage of the configuration units due to different weather conditions. Although there were some imperfections in Mohamed's design, among all the shapes we considered, the cylindrical shape has no sharp corners which prevent the safety risks. The cylindrical shape is also easy to store and save spaces as well as convenient to carry. Therefore, our team decided to follow Mohamed’s cylindrical design and modify it on top of it.

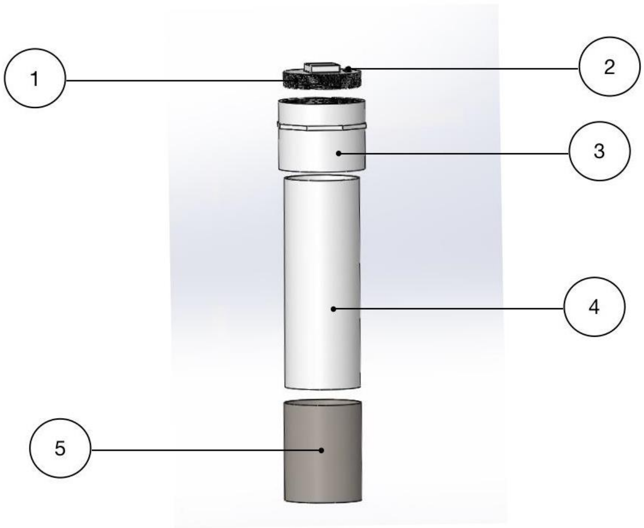


Figure 12. Exploded outer shell demonstration

Component Number	Component Name
1	Cap
2	Switch
3	Cap Adapter
4	Pipe (6 inch)
5	Soil Blade

Table 1. Outer Shell and components number labels and corresponding names

According to the requirement of this new chamber, a N_2O gas sensor was added and worked together with the CO_2 sensor; thus, the outer shell tube of the new gas analyzer was enlarged for the modified arrangement. The exploded view showing in Figure 12 demonstrated main parts for the outer shell and the corresponding names are in Table 1. The cap of the chamber can prevent dust and rain from entering the chamber. The reason why the chamber was not sealed is because it saves for changing the batteries for the sensors. There was a hole for the antenna on top of the cap, and a switch inlaid in the cap. The material of the pipe is PVC which is suitable for outdoor purposes and easy to purchase. The switch is to control the batteries instead of the sensor directly.

Due to the limitations and rules of the pipe manufacturers, the cap required an adapter to connect with the pipe. As the result of COVID, our team encountered issues with purchasing adapters from the sellers; thus, the final prototype was manufactured by 3D printing technique. The pipe is the main supporting part of the outer shell, and the interior structure will be fastened at this part. The size of the pipe is 6 inches* 45cm, and the pipe is made from PVC which is the same material as the cap. The mater of soil blade is 304 stainless steel, and this part is mainly for fixing the chamber into the soil which allows soil gas emissions in the enclosed chamber with unlimited soil type. This cylindrical gas chamber is perfect for on-site gas sampling, and it greatly reduced the inconvenience and weather limitation for gas sampling.

Interior Structure

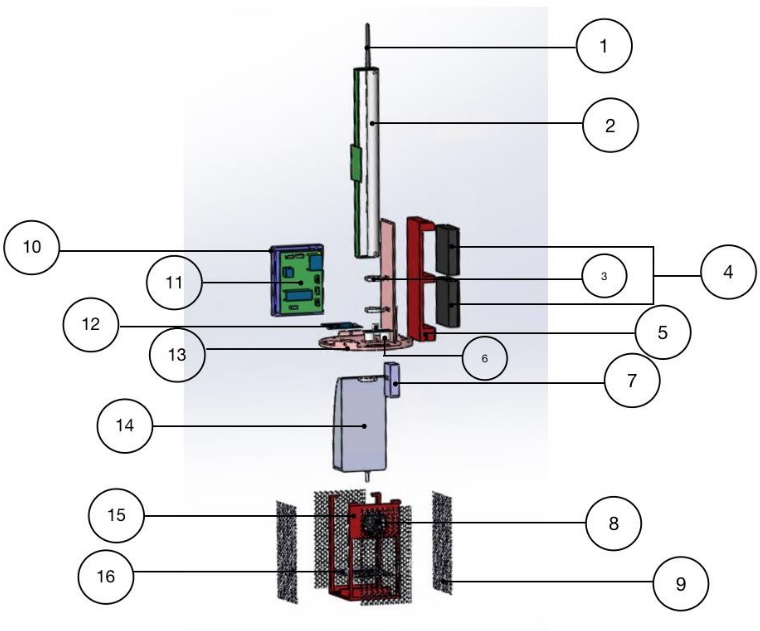


Figure 13. Exploded interior structure and components of the device with number labels

Component Number	Component Name
1	Antenna
2	NG2-F-3 Nitrous Oxide sensor
3	NGS-F-3 clip (3x)
4	Battery holders (2x)
5	Battery holder support
6	Ultrasonic sensor
7	Bottom NG2-F-3 support block
8	Fan
9	Filter wire screen (5x)
10	Configuration unit holder
11	Configuration unit board
12	K30 Carbon Dioxide sensor
13	Upper support
14	Pump
15	Lower support
16	Detachable pump bottom support

Table 2. Interior structure and components number labels and corresponding names

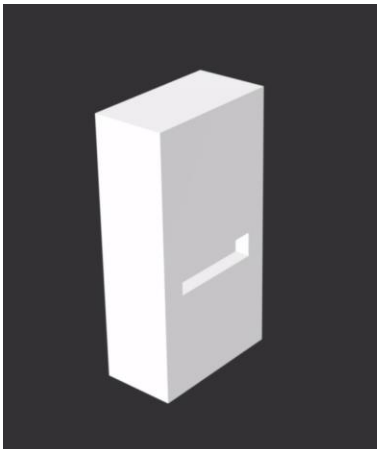


Figure 14. Bottom NG2-F-3 support block (#7 in Figure 13)

This structure is designed to be attached on the bottom of the main upper support (#13 in Figure 13) with. A grove on the block was created for installing one of the NG2-F-3 clips (#3 in Figure 13), which provides a third pivot support for the cylindrical gas analyzer tube. This block can be attached on the upper support by two different ways: glued together directly or attached with a set of hook-and-loop fasteners. For this design project, the team chose to use fasteners to join the two parts, which is more flexible for adjustments and disassembly. The unit is purposely built thicker than the supporting panel on the upper part, to provide a stable fixation of the sensor.

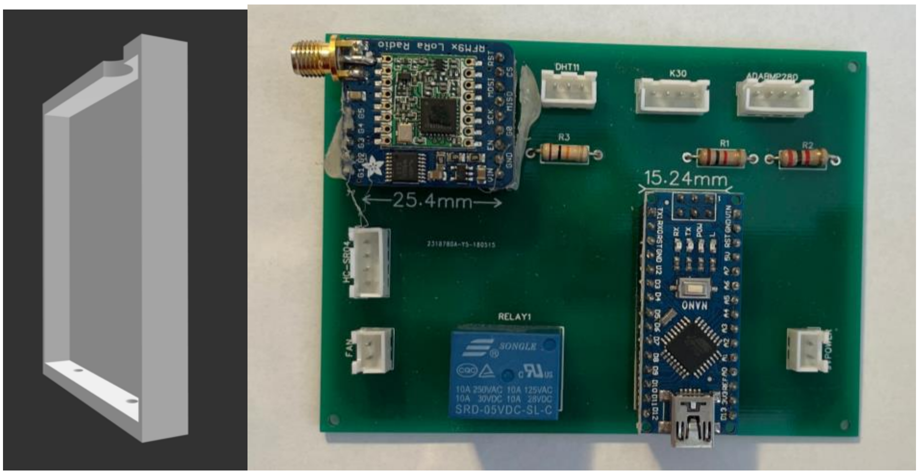


Figure 15-16. Configuration unit holder (#10 in Figure 13, left) and the configuration unit (right)

The configuration board has the dimension of 101 mm × 73 mm with connecting ports and data transmission modules on the surface. Since one of our design objectives is to rearrange the wiring and the general components placement, we have made the decision to set the configuration unit inside the cylinder. The holder is designed to be screwed on to the main upper support, and as shown on the image, two holes for 6-32*1-1/4 size screws (size 6 screw has 32 thread per inch with 1-¼ inch long length) were created for the assembling purpose. An opening on the top aligns with the LoRa (Long Range) antenna port, which provides enough space for installing the antenna. Upon the assembling process, the holder allows the front of the configuration board to face the other components, such as the sensors, that are for connections. It gives the connecting ports easy access to the sensors through wires.

Figure 17. NG2-F-3 clip (#3 in Figure 13)

The shape of the clips was created based on the cylindrical gas-analyzing tube on the NG2-F-3 sensor. There are three of the clips on the interior structure, two on the upper part and one on the bottom. Three supporting points prevent the sensor from shaking or sliding during transportations, since the sensor has a relatively long and fragile structure (30.6 cm). Slots are prepared on the main upper support and on the bottom support block, and the clips can be directly inserted into them. This structure allows flexible assembling and detaching the Nitrous Oxide (N_2O) sensor, while maintaining a firm grip when installed.

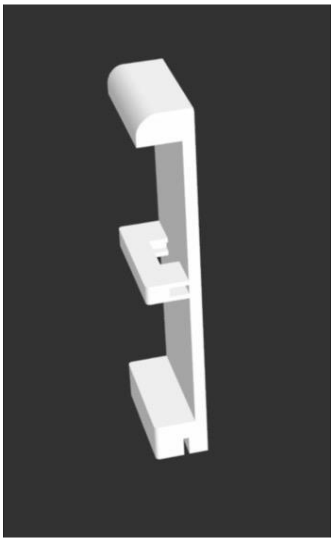


Figure 18. Battery holder support (#5 in Figure 13)

This battery holder unit is designed to be installed at the back of the supporting panel on the upper support. It provides sufficient space for two 3×18650 3.7 V battery cases, one for the K30 CO_2 sensor and one for the NG2-F-3 N_2O sensor. Unlike the other assembled components on the interior structure, the battery holder is especially built for the convenience of battery-changing, therefore easy detaching and reassembling process is necessary. On the bottom of the unit, a groove was created, matching with the perpendicular plane on the main upper support. In this way, when the batteries require recharging, the user can remove the cap on top of the outer shell (#1 in Figure 12) and easily draw out the holder and reinsert it back into position. There is a partition in the middle of the unit, to separate the two battery cases. A tunnel was created on the partition, which allows the wires to pass through, and ensures the tidiness of general wiring arrangement. The direction of the battery wiring aligns with the location of the switch (#2 in Figure 12) on the cap, allows the switch to connect to and directly control the device powering from outside. In addition, the top of the battery holder is designed into a curved surface to avoid sharp corners, which might result in incidental injury on the user during battery changing.

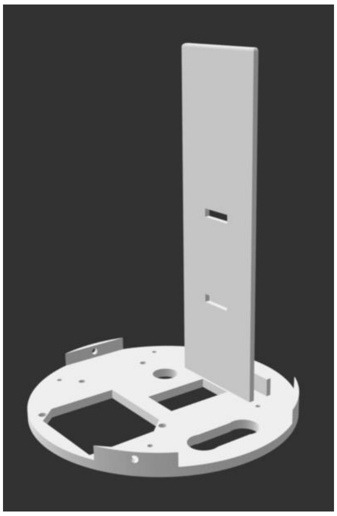


Figure 19. Upper support (#13 in Figure 13)

The upper support is the core structure in the interior design. It sustains the major loads of the components on the inside. The K30 CO_2 sensor and the ultrasonic sensor are designed to be installed on the circular platform, parallel to the ground and facing downward, for the purpose of detecting CO_2 emission from the soil and detecting distance to the ground, respectively. The K30 sensor is installed with two #4-40*½ screws and the ultrasonic sensor is attached with glue. The cylindrical NG2-F-3 N_2O sensor is placed perpendicular to the platform, passing through the smaller rectangular opening, with the transmitter board facing toward the center of the platform. The configuration board is installed vertically and facing the center as well, right across the platform on the opposite side of the ultrasonic sensor. Differing from the original design of Debbagh (Debbagh, 2019), the temperature module is excluded in this design, since the NG2-F-3 sensor has a built-in temperature-detecting function. Hence, the arrangement allows all wires to be placed on the upper chamber, with the minimal wiring distances in general. The only unit that requires wiring on the bottom-half chamber is the fan, which is located below the platform. Therefore, a round opening is designed in front of the configuration unit, allowing the fan to connect to the board. There is a tall plate standing on the platform, providing support to the NG2-F-3 sensor, and backing to the battery holder behind. Three load-bearing screw holes were created on the edge of the platform, in order to install the entire structure on the wall of the outer shell (#4 in Figure 12).

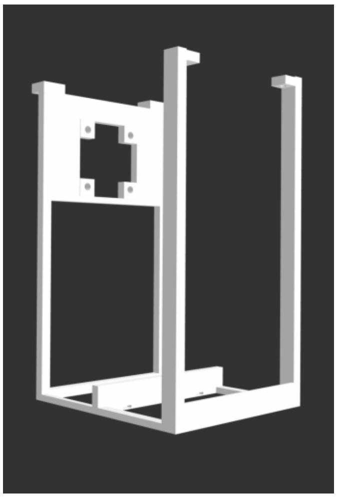


Figure 20. Bottom support (#15 in Figure 13)

The bottom support is installed below the platform of the upper support with four #4-40 ½ screws. This unit is primarily responsible for bearing the load of the pump. It also provides a frame for installing the filter screens, which creates a semi-closed chamber for the sensors and prevents gravel and other matters from being drawn in. The four side faces and a section of the bottom face allows air-circulation through filters, maintaining a state of constant air-exchange with the effect of the fan on the upper part. The vertical partition on the bottom efficiently stops the pump from sliding, with the support from the detachable bottom support (#16 in Figure 13). This design not only includes required features, but also minimizes the usage of printing material.

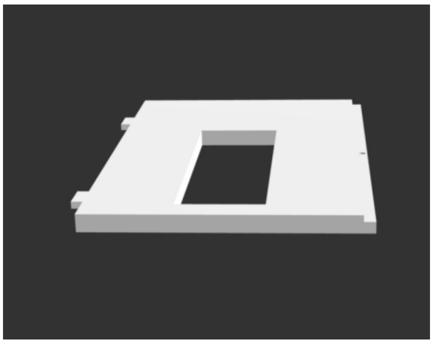


Figure 21. Detachable Pump bottom support (#16 in Figure 13)

For the portability of the device, a battery-powered air pump was selected for supplying air to the NG2-F-3 sensor. Therefore, a detachable bottom support for the pump is designed for the convenience of retrieving the pump when it needs battery changing. This unit is installed by inserting the two mini boxes into the slots on the bottom support (#15 in Figure 13) and attach the other side by joining the holes with an iron wire. A rectangular opening on the unit is designed for accessing the switch on the pump's rear without unnecessary disassembly.

PROTOTYPE MANUFACTURING

Outer shell Manufacturing

The outer shell was divided into four parts: the cap, the adapter, the pipe, and the soil blade. The cap, the adapter, the pipe was all made of PVC material in the original design. Food grade pipes were used in the selection of pipe body material to meet the needs of outdoor use. In addition, failing to find a matching adapter in the market due to the size of the tube; therefore, 3D printing was selected to complete the project. The soil blade was made of a 304 stainless steel plate because of consideration for outdoor use and durability. The cap is an industrial standard six-inch diameter with threads. The pipe body was selected with an inner diameter of 6 inches and a wall thickness of 0.25 inches and a length of about 1 foot to facilitate subsequent length cutting. The forming process of the soil blade was helped by the clamps which could shape the steel plate to fit the curved surface of the pipe. This process could also be done using a rolling forging machine.

In order to acquire the designed size of the PVC pipe and 304 stainless steel metal sheets, they were cut by a mechanical band saw. The PVC pipe was cut to a length of 45 cm, and the steel plate was cut to a rectangular shape with the of 21 * 17.24 cm. For the sake of fixing the interior supporting structure, a drill was used to create holes which match the 6-32*1-1/4 size screws (size 6 screw has 32 thread per inch with 1-¼ inch long length) on the pipe wall. Moreover, the 3D printed parts were sanded with sandpaper to achieve the best assembly size. Next, reserved a steel plate width of 5cm, and then used a drilling machine and screws to fix the contact area between the steel plate and the pipe wall. Figure 22 below shows the actual semi-finished product.

Figure 22. The chamber and metal blade

Interior Structure Manufacturing

3D printing needs the required parts are drawn by the design team with the help of CAD software and then converted into a standard tessellation language (STL) format file and sent to the 3D printing office. The stl. file allows input print settings such as resolution, filling material, print speed, etc. Appendix B figure B-1 lists the Settings entered for printing. Once the printing setup is completed, the total time spent on printing and the printing sequence are generated for the user's reference and code is generated for conversion to machine printing. Fused deposit modeling (FDM) is selected for 3D printing, which is suitable for printing small parts, and the materials used are suitable for engineering models. In the FDM printing process, there were two materials used, a modeling material and a support material. During the printing, both modeling and support materials were formed in plastic threads or filaments and were unwound from a coil. From the coil, the materials squeezed out through the extrusion nozzle to the build table, while the extrusion nozzle was melting the filaments. The computer transformed the dimension of the design into X, Y, and Z coordinates in order to make both the nozzle and the build table to follow in the printing process. In the FDM system, the extrusion nozzles moved over the build table horizontally and vertically, printing a cross section of an object onto the platform. During the printing, the thin layer of material cools and hardens, immediately binding to the layer beneath it. Once a layer had completed, the build table was lowered for the next layer of materials. After finished printing, the object came off the printer, its support materials were removed by snapping by hand.

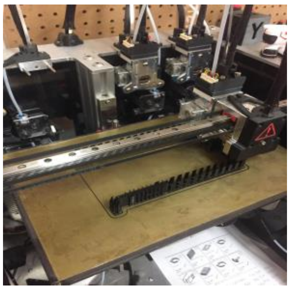


Figure 23. The 3D printing Machine

ASSEMBLY PROTOCOL

The detailed assembly protocol is illustrated in Appendix D. The protocol demonstrated the assembling sequences with instructions. The electronic design graphics could also be provided by contacting our team. The figures below show the final assembly device.

Figure 24-26 The final assembled interior structures

Figure 27. The assembled outer shell

COST ANALYSIS

The cost analysis table is attached in the appendix, which demonstrates the detailed manufacturing costs for this gas analyzing device. During the manufacturing process, the majority costs are nitrous oxide sensors and 3D printing. The nitrous oxide gas sensor took up the dominant part of the costs, not only because it has accurate measurements in low-concentration gas emission conditions, but also it was imported from foreign country which led to a higher shipping costs and import taxes. The total manufacturing time of the 3D printed parts (excluding adapter) was 96 hours. The total volume of PLA consumption was 76.04 units. Due to the travel and shipping restriction of COVID, our team was not able to find a suitable adapter, the 3D printing method was chosen. The printing cost of the adapter was $228.1. For the CO_2 detection, a K30 sensor, the same model from Debbagh's design was selected. The cost of the K30 sensor shown in appendix E. was referred to the price as of 2019. Moreover, the cost analysis below does not include labor and transportation costs. According to the data provided by another design group, the cost of manually detecting the gas sample is $2,470.19, while the cost of the sensor gas detection given by them is $1,970.28 before tax (Berthiaume et al., 2020). In contrast, our team's design and manufacturing costs are lower than the other two which is $1932.89 with tax.

TEST RESULTS ANALYSIS

In order to test the NG2-F-3 sensor could respond to variation in the testing environment, several independent tests have been done in different locations in Macdonald Campus Farm. The results are shown in the following graphs.

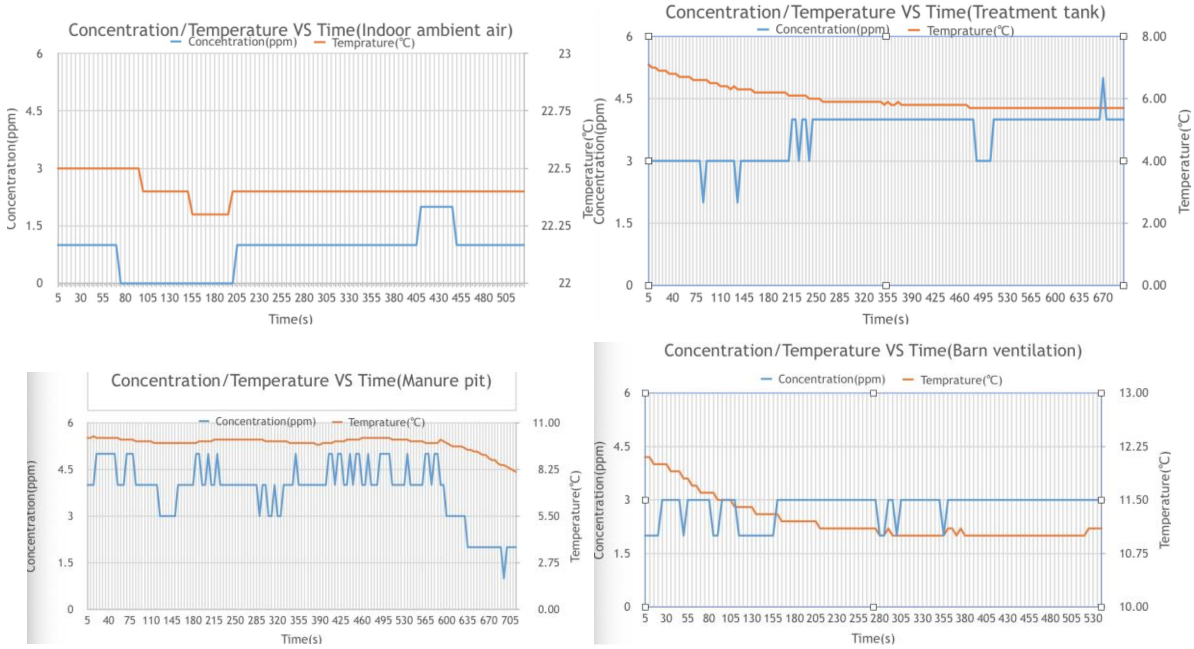


Figure 28-31. Concentration of N_2O and Temperature vs time of 4 different locations.

Four tests of N_2O concentration near four locations have been implemented. As shown in the Figure 28-31 the concentrations of N_2O are in the range of 2 to 5 ppm, which shows stable data output in the main testing time. At the beginning and the end of these tests, both the concentration of N_2O and temperature have unstable output. The reason for this phenomenon might be the improper operation and ventilation system.

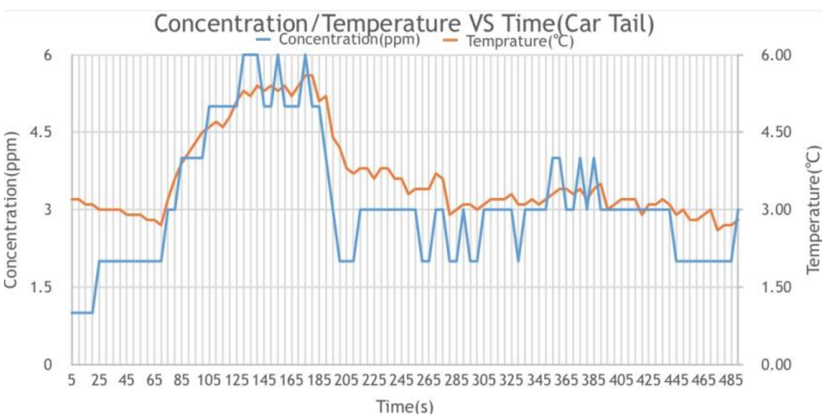


Figure 32. Concentration of N_2O and Temperature vs time near car tail.

The tests were done in the barn and outdoor circumstances to show the performance of N_2O gas sensor. We tested the N_2O concentration near the car tail which was shown in Figure 32. The concentration of N_2O is in the range of 1 to 6 ppm near the car tail, which fluctuates, so does the temperature. The reason might be that the wind influences the gas into the sensor, which results in a very high concentration in a certain time and lower concentration in other times. Overall, the performance of the NG2-F-3 sensor has a great performance in the indoor and outdoor testing environments with precise and sensitive data output.

After calibrating the sensor, which has a great performance in different environments, the sample we got could be further analyzed, and the N_2O gas flux could be calculated as described in the following. Firstly, the raw data of N_2O gas emission should be converted from ppm to mg per m^2 of N_2O using the following equation:

$$Cm = \frac{CvMP}{RT} \qquad \text{……. Eq. 1}$$

Where C_m represents the mass/volume Concentration in mg per m^2; C_v is the concentration (v/v) in ppm; M represents the gram molecular weight (For N_2O, M=28 mg/mol); P is the atmosphere pressure; R is the universal gas constant; and T is the Room temperature.(Crézé & Madramootoo, 2019)

In addition, with the mass/volume concentration, the flux of N_2O gas could be calculated as following steps. To begin with, using the median flux method (MFM), five concentrations taken at time of 0, 15, 30, 45, 60 minutes are applied to calculate the flux of N_2O over the one-hour sampling time. In this case, ten possible slopes of linear regression could be calculated with five concentrations over the one-hour sampling time, in which the slope of linear regression could be generated for each two gas concentrations (Crézé & Madramootoo, 2019). The equation is shown in the following.

$$ft = H\left(\frac{\Delta C}{\Delta t}\right)_{\text{median}} \qquad \text{……. Eq. 2}$$

Where f_t represents the N_2O flux in mg/m^2/hr; H represents the chamber height; ΔC represents the difference in gas concentration in mg m^{-3}; and Δt represents the difference of time in hours. After the flux of N_2O gas is calculated, we could further apply it in research activities like using ArcGIS to present the distribution of N_2O gas emission in corn fields after fertilization or analyzing its influence by the water table management.

ISSUES AND CHALLENGES

The project went through BREE 490 Design 2 and BREE 495 Design 3, these two courses. During the design process, there were several issues and challenges that our team encountered. For this project it was the first time that the whole capstone project was worked remotely due to the irresistible and unpredictable pandemic around the world which brought numerous obstacles.

Firstly, the main component of this gas analyzer is the N_2O gas sensor which we purchased from Italy and arrived in the middle of February. It was because during the purchasing process, it was the holiday season which decelerated progress, and there was a payment issue and a currency issue occurred from the seller's side complicated the procedures even more. Although we learned numerous details before we got the N_2O sensor, when we actually took the sensor, there was more knowledge required for us to learn in order to use the sensor properly. Since there is nobody who is confident in this type of sensor, we spend a lot of time working on cable connection and calibration of the sensors. Moreover, this sensor requires a new type of software, *Realterm*, to calibrate and record data, it took us about two weeks to communicate with the manufacturer and figure out the method of using this software. When we finally figured out the proper way to calibrate the sensor, we could not find a proper gas seller in order to calibrate the sensor with known concentration N_2O gas and zero gas. We did contact a company called Linde which was recommended by a PhD student from the department of bioresource. However, the sales representative was not active in this case; hence, the sensor cannot respond with accurate concentration readings yet, and future calibration is required before application of the device. Thus, these obstacles lead to the delay of the whole project process and prolong some works to the future.

In addition, due to the pandemic, one of our teammates was not in Montreal and has 12 hours differences with us. Thus, communication became a major challenge in our team. This issue resulted in the final design and delay of the 3D print process. The postponement of 3D printing led to a pity of insufficient time to fix the manufacturing error. We sincerely hope once we are able to get proper gas to calibrate the N_2O gas sensor and perfect the software configurations in the future.

RECOMMENDATIONS

This design successfully inherited some of the characteristics from the previous design by Cindie Berthiaum's team. It includes a nitrous oxide (N_2O) gas sensor with higher sensibility and a customized functional circuit board. In order to further improve the system, some recommendations are proposed below. First of all, the sensor calibration procedure of the NG2-F-3 requires further actions due to the inaccessibility of gas samples as mentioned in the paragraph above. Furthermore, the main purpose of this project is to enhance the sensibility of sensors; considering maintaining the overall cost in a reasonable range, while the price of the nitrous oxide (N_2O) sensor is expensive, the inexpensive printing plastic Polylactic acid (PLA) is selected as the 3D printing material of this project. In the future, with a larger budget, the 3D printing material Polylactic acid (PLA) could be replaced by other advanced materials like Acrylonitrile styrene acrylate (ASA), Polyvinyl chloride (PVC), and Nylon12. Moreover, after analyzing the economic, environmental, and social considerations, a specific user manual is needed to ensure correct operation, maintenance, and recycle process. This design could also increase its overall portability by adding a foldable handle on the outer shell. In this design, in order to make enough interior room for the core sensors, some of the original features were removed from the design. For future adjustment, Arduino could integrate other sensors like pressure sensors and moisture sensors into the system.

CONCLUSION

This report illustrated the design of carbon dioxide and nitrous oxide emission analyzing and wireless data transmission device manufactured by 3D printing technology. This design combined two gas emission detecting sensors into one chamber. The report also demonstrated the reaction of the nitrous oxide gas sensor through the field gas detection and data analysis at different locations. Despite uncontrollable external force factors, the data performance reached the expectation, which proved the practicability of the sensor. In this design, the use of the Configuration Circuit Board, Arduino Nano, and Raspberry Pi 3 Model B were studied, and a plan for the integrated data transmission was proposed as a wire diagram and Arduino codes. The gas analysis system has specific applicability for field N_2O and CO_2 emission testing. Product advantages are readily available assembly parts and straightforward installation and operation. Simultaneously, the product simplifies the difficulty of gas acquisition and advances gas acquisition efficiency. Furthermore, the design is more portable and provides a more efficient data infrastructure for land research laboratories and land management practices.

ACKNOWLEDGEMENT

We would like to show the deepest appreciation to our mentor, Dr. Chandra Madramootoo, for his continued guidance and supervision and the generous support to our project. Dr. Viacheslav Adamchuk gave us numerous practical suggestions and help on sensor calibration and configuration. We would like to also thank Mr. Paul Meldrum and Mr. Scott Manktelow for their support and John Lan for helping us at the machine shop. Last but not least, we convey our sincere gratitude to Ms. Wendy Ouellette for her time and assistance which helped us organize the sensor purchase.

REFERENCES

Debbagh, M., Adamchuck, V., Madramootoo, C., Mawof, A., Whalen, J., & Prasher, S. (2019). *Development of a Low-cost Wireless Sensing System for Rapid in situ Assessment of Soil CO_2 Emission.* MS thesis. Sainte-Anne-de-Bellevue, Quebec: McGill University, Department of Bioresource Engineering & Department of Natural Resource Sciences.

Tremblay, A. (2005) *Greenhouse Gas Emissions-- Fluxes and Processes: Hydroelectric Reservoirs and Natural Environments*. Berlin: Springer. Retrieved March 14, 2021

Houghton, J. (2005) *Global Warming*. Reports on Progress in Physics 68(6):1343–1403.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., … Smith, J. (2008). Greenhouse gas mitigation in agriculture. *Philosophical Transactions: Biological Sciences*, 363(1492), 789–813.

Wollenberg, E. (2012). *Climate Change Mitigation and Agriculture. London: Earthscan*. Retrieved March 13, 2021

Berthiaume, C., Cox, D., Lugun, L., Adamchuck, V., Madramootoo, C., Enger, M. (2020). *An improved and robust automated greenhouse gas analyzer for agricultural fields.* Sainte-Anne-de-Bellevue, Quebec: McGill University, Department of Bioresource Engineering.

Rao, M., Sultana, R., & Kota, S. H. (2017). Hazardous waste. *Solid and Hazardous Waste Management,* 159-207. doi:10.1016/b978-0-12-809734-2.00005-5

Tan, X., Zhang, H., Li, J., Wan, H., Guo, Q., Zhu, H., . . . Yi, F. (2020). *Non-dispersive infrared multi-gas sensing via nanoantenna integrated narrowband detectors*. *Nature Communications*, *11*(1). doi:10.1038/s41467-020-19085-1

Non-Dispersive infrared ABSORPTION SENSORS. (n.d.). Retrieved April 11, 2021, from https://www.gastec.co.jp/en/product/detail/id=2206

Wittek, P. (2014). Machine learning. *Quantum Machine Learning,* 11-24. doi:10.1016/b978-0-12-800953-6.00002-5

Hamrani, A., Akbarzadeh, A., Madramootoo, C. (2020) *Machine learning for predicting greenhouse gas emissions from agricultural soils.* Retrieved from https://doi.org/10.1016/j.scitotenv.2020.140338

Alexander, D. (2021). *11 devastating ways humans impact the environment*. Retrieved April 11, 2021, from https://interestingengineering.com/11-ways-humans-impact-the-environment

Agriculture sensors: *Sensors used in agriculture: Gas detection*. (n.d.). Retrieved April 11, 2021, from https://edinburghsensors.com/industries/agriculture/

Yashraj Singh Shaktawat. (2020). *What is ArcGIS*. Retrieved April 11, 2021, from https://www.geospatialworld.net/blogs/what-is-arcgis/

Glenn, A. J., Moulin, A. P., Roy, A. K., & Wilson, H. F. (2021). Soil nitrous oxide emissions from no-till canola production under variable rate nitrogen fertilizer management. *Geoderma, 385*, 114857. doi:10.1016/j.geoderma.2020.114857

Nelli, F. (2019). *Tutorial – sending values from PC to Arduino by serial communication*. Retrieved April 12, 2021, from https://www.meccanismocomplesso.org/en/tutorial-sending-values-from-pc-to-arduino-by-serial-communication/

Lange, C. (2017). *Types of data acquisition systems*. Retrieved April 12, 2021, from https://medium.com/daqifi-data-acquisition/types-of-data-acquisition-systems-6ce3d997a2ce

Mitchell, R. (2021). *A comparison of Popular Arduino BOARDS: ARDUINO*. Retrieved April 12, 2021, from https://maker.pro/arduino/tutorial/a-comparison-of-popular-arduino-boards

Mane, S. A., Nadargi, D. Y., Nadargi, J. D., Aldossary, O. M., S. Tamboli, M., & Dhulap, V. P. (2020). *Design, development and validation of a portable gas sensor module: A facile approach for monitoring greenhouse gases*. *Coatings, 10*(12), 1148. doi:10.3390/coatings10121148

Barrett, A. (2021). *Advantages and disadvantages of PLA*. Retrieved April 12, 2021, from https://bioplasticsnews.com/2020/06/09/polylactic-acid-pla-dis-advantages/

Gutierrez, R. J. (2021). *Pla plastic/material: All you need to know*. Retrieved April 11, 2021, from https://all3dp.com/1/pla-plastic-material-polylactic-acid/

Crézé, C. M., & Madramootoo, C. A. (2019). *Water table management and fertilizer application impacts on CO2, N2O and Ch4 fluxes in a Corn agro-ecosystem*. *Scientific Reports, 9*(1). doi:10.1038/s41598-019-39046-z

APPENDIX

Appendix A: Dimensions of Technical Drawings

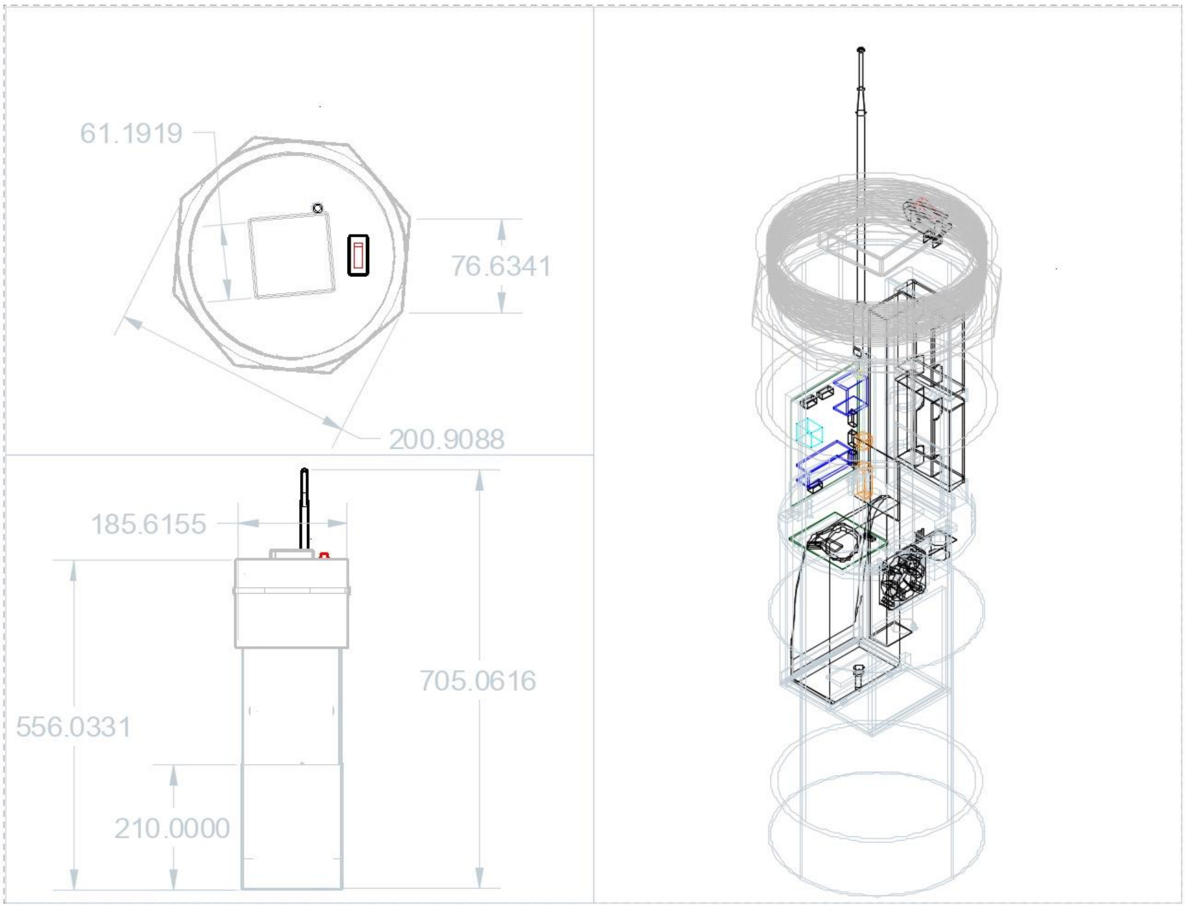


Figure A-1. Technical drawing of the device with dimensions (mm) and inner structure layout

Appendix B: Additional Information for Additive Manufacturing

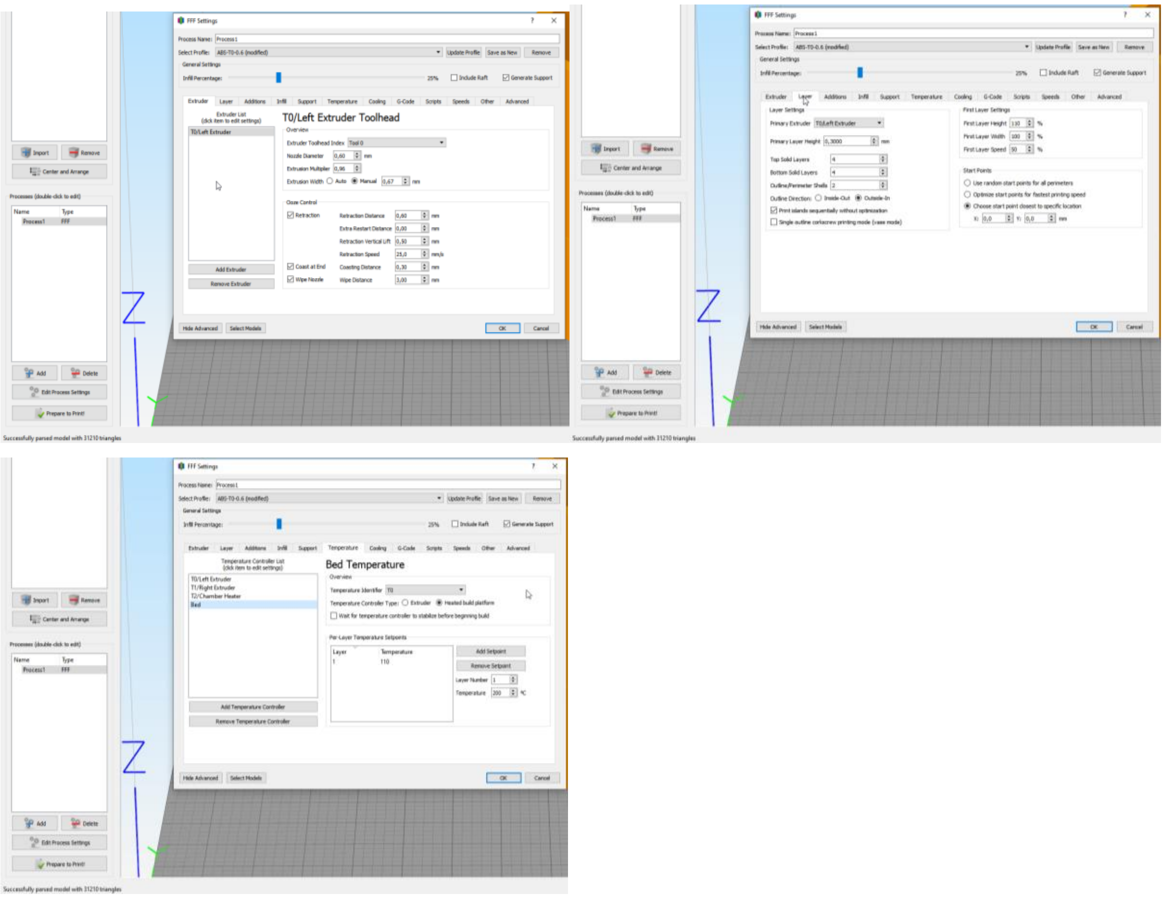


Figure B-1. 3D printing settings

Appendix C: Software codes

C.1 NG2-F-3 Sensor Library functions

```
/******************
  Ng2Lib.cpp
  Created by Jinxue Hao
******************/

//#include "Arduino.h"
#include "Ng2Lib.h"
#include "SoftwareSerial.h"  //Virtual Serial library
//SoftwareSerial* _Serial;

byte cmd_get_last_measure= 'A';
//A;[Model];[Temperature];[Ppm];[Correction];


Ng2Lib :: Ng2Lib(uint8_t Rx,uint8_t Tx)
{
  this->_Serial = new SoftwareSerial(Rx,Tx);
  this->_Serial->begin(9600);
}



void Ng2Lib :: getResponse(byte response[],int respSize)
{
  sendRequest();
  waitResponse(respSize);
  if(this->_Serial->available() >= respSize)
    for (int i=0; i < respSize; i++)
    {
      response[i] = this->_Serial->read();
    }
//  while(this->_Serial->available())
//
//    this->_Serial->println(this->_Serial->read());
}
```

```
void Ng2Lib :: sendRequest(){
  while(!this->_Serial->available())  //keep sending request until we start
to get a response
  {
    this->_Serial->write(cmd_get_last_measure);
    delay(100);
  }
}

void Ng2Lib :: waitResponse(int resSize){
  int timeout=0;  //set a timeout counter
  while(this->_Serial->available() < resSize ) //Wait to get a 5 byte
response
  {
    timeout++;
    if(timeout > 10)    //if it takes to long there was probably an error
    {
        while(this->_Serial->available() == 0)  //flush whatever we have
          this->_Serial->read();
          break;                        //exit and try again
    }
      delay(50);
  }
}


/******************
  Ng2Lib.h
  Ng2f3 library
  Created by Jinxue Hao
******************/

#include"Arduino.h"

#ifndef Ng2Lib_h
#define Ng2Lib_h

#include <SoftwareSerial.h>   //Virtual Serial library

class Ng2Lib
{
```

```
  public:
    Ng2Lib(uint8_t Rx, uint8_t Tx);
    void getResponse(byte response[],int respSize);
  private:
    SoftwareSerial* _Serial;
    void sendRequest();
    void waitResponse(int resSize);
};

#endif
```

C.2 NG2-F-3 Testing Codes on Computer

```
/*******************
  N2O sensor demo
  Created by Jinxue Hao
*******************/

#include "Ng2Lib.h" //include Ng2 Library
Ng2Lib Ng2(12,13); //Initialize a Novagas2 Sensor with pin 12 as Rx and 13
as Tx

void setup() {
  Serial.begin(9600); //start a serial port to communicate with the
computer
  Serial.println("   Ng2f3 N2O sensor demo :  uses the Ng2Lib.h library");

}

void loop() {
  byte response[5];
  Ng2.getResponse(response,5);

  Serial.print("  Ng2f3 N2O sensor:  ");
  Serial.println(response[]); //print value
  Serial.println();
  delay(2000); //wait 2 seconds
}
```

C.3 Integrated Codes with NG2-F-3 included

```
//Libraries

#include <SPI.h>
#include <RH_RF95.h>
#include <kSeries.h>
#include <Wire.h>
#include <Adafruit_Sensor.h>
#include <Ng2Lib.h>
//Define pins

#define RFM95_RST 9
#define RFM95_CS 10

#define RFM95_INT 2
#define K30_ARD_RX 6
#define K30_ARD_TX 7
#define ULTRASONIC_TRIGPIN 3
#define ULTRASONIC_ECHOPIN 4
#define FAN_PIN 5

#define NG2_RX 11
#define NG2_TX 12
//Define Parameter

#define RF95_FREQ 915.0
#define RF_NODE_ID 1
#define SENSOR_NODE_ID 13
#define DHTTYPE DHT11

//instantiation

RH_RF95 rf95(RFM95_CS, RFM95_INT);
kSeries K_30(K30_ARD_RX, K30_ARD_TX);

Ng2Lib Ng2(NG2_RX,NG2_TX);

//variables
```

```
int transTime = 0; // time it takes to transmit the data
int sampleTime;
long volume;
float CO2;

float temp;
float N2O;

int a;
int b;



void setup() {

pinMode(RFM95_RST,OUTPUT); // sets digital pin to output
digitalWrite(RFM95_RST,HIGH);

pinMode(ULTRASONIC_TRIGPIN, OUTPUT);
pinMode(ULTRASONIC_ECHOPIN, INPUT);

pinMode(FAN_PIN, OUTPUT);
digitalWrite(FAN_PIN, LOW);



Serial.begin(9600);

//manual reset
digitalWrite(RFM95_RST, LOW);
delay(10);
digitalWrite(RFM95_RST, HIGH);
delay(10);

//Initialize Radio
while(!rf95.init()){
  Serial.println("LoRa radio init failed");
  while(1);
  }
if(!rf95.setFrequency(RF95_FREQ)){
  Serial.println("setFrequency failed");
```

```
  while(1);
  }
rf95.setTxPower(23,false); // power from 5 to 23 dbm
rf95.setThisAddress(SENSOR_NODE_ID);
rf95.setHeaderFrom(SENSOR_NODE_ID);
rf95.setHeaderTo(RF_NODE_ID);
rf95.setPromiscuous(false);

// ready display
Serial.print("Sensor Node: ");
Serial.println(SENSOR_NODE_ID);
Serial.print("Set Frequency: ");
Serial.print(RF95_FREQ);
Serial.println("...Ready to transmit Data");
Serial.println("All systems are a go!");

delay(5000);
// initial sample values time = 0
  for (int k=0; k<2; k++){

  sampleTime= millis()/1000;
  volume = getVolume();
  CO2 = K_30.getCO2('p');

  byte response[5];
  Ng2.getResponse(response,5);
  N2O = response[3];
  temp = response[2];

  operationB();
  transTime = 0;

  }
}

void loop() {

operationA();
operationB();

}
```

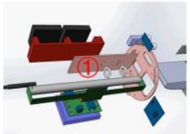
```
long getVolume(){
  long distance;
  long duration;
  long volume;
  digitalWrite(ULTRASONIC_TRIGPIN, LOW);
  delayMicroseconds(2);
  digitalWrite(ULTRASONIC_TRIGPIN,HIGH);
  delayMicroseconds(10);
  digitalWrite(ULTRASONIC_TRIGPIN,LOW);
  duration = pulseIn(ULTRASONIC_ECHOPIN,HIGH);
  distance = duration/58;
  volume = ((3.14*(4^2))/4)* distance;
  return volume;
  }



void operationA(){
  Serial.print("wait time: "); Serial.println((30000-transTime)/1000);
  delay(30000 - transTime);
  digitalWrite(FAN_PIN, HIGH); Serial.println("Fan ON");
  delay(30000);
  digitalWrite(FAN_PIN,LOW); Serial.println("Fan OFF");

  sampleTime= millis()/1000;
  volume = getVolume();
  CO2 = K_30.getCO2('p');

  byte response[5];
  Ng2.getResponse(response,5);
  N2O = response[3];
  temp = response[2];


  }

void operationB(){
  a = millis();

   rf95.setModeTx();
     Serial.println("set to transmit...");
```

```
  // Send a message to server
  String sampleTimeString = String(sampleTime);
  String volumeString = String(volume);
  String CO2String = String(CO2,2);
  String tempString = String(temp,2);
  String N2OString = String(N2O,2);

  String dataString = sampleTimeString + "," + volumeString + "," +
CO2String+","+tempString+","+N2OString;
  int size_Data = dataString.length();
  char data[size_Data];
  dataString.toCharArray(data,size_Data);

  //Serial.println(size_Data);
  //Serial.println(dataString);


for (int i= 0; i < 3; i++){


  Serial.print("Sending: "); Serial.println(data);




  delay(10);

  rf95.send((uint8_t *)data, sizeof(data));
  rf95.waitPacketSent();

  // Receive confirmation from the server
   uint8_t buf[RH_RF95_MAX_MESSAGE_LEN];
   uint8_t len = sizeof(buf);
   rf95.setModeRx();

  Serial.println("Waiting for reply..."); delay(10);
  if(rf95.waitAvailableTimeout(10000)){
    if(rf95.recv(buf, &len)){
      Serial.print("Confirmation Received: "); Serial.println((char*)buf);
      Serial.print(" Signal Strength(RSSI): ");
Serial.println(rf95.lastRssi(),DEC);
```

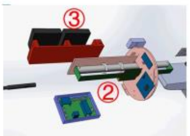
```
      i = 3;

      }
      else{Serial.println("bad message sending again");}
    }
    else{Serial.println("no reply sending again");}
}
  b = millis();

  // Time to send send data calculation
    transTime = b-a;

    if (transTime > 30000){transTime = 30000;}
    Serial.print("Transmission time: "); Serial.println(transTime/1000);

  }
```

Appendix D: Assembly Protocol

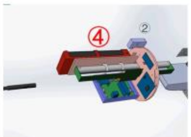
The Interior Structure Installation - Part I



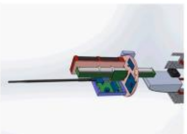
1. Fix the clips to the main support.



2. Place the N2O gas sensor in the clips.

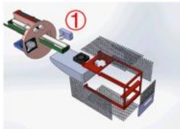


3. Fix the battery holders onto the battery holder support and insert on the main support.

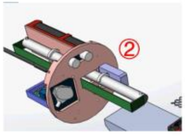


4.Install the CO2 sensor, ultrasonic sensor and the configuration unit on the main support.

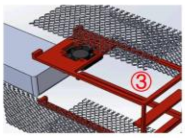
The Interior Structure Installation - Part II



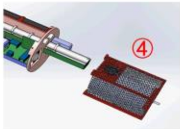
1. Fix the clips to the bottom NG2-F-3 support block.



2. Fix the bottom NG2-F-3 support block to the main support.



3. Install the filter wire screen to the lower support.



4. Fix the entire lower support to the main support.

5. The demonstration of the interior structure.

The Final Installation

1. Fix the pipe and the soil blade together

2.Add the adapter to the pipe.

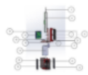
3. Place the interior structure in the pipe and fix it.

4. Install the switch on the cap and cover the pipe with the cap.

Appendix E: Manufacturing Costs

Components	Quantity	Costs/Chamber
pipeware		
6in female thread adapter	1	
6in pipe plug	1	$45.44
6in PVC pipe (length: 1 foot)	1	$53.36
sensors		
K-30 CO2 sensor	1	$85.00
Navasis N2O sensor	1	$970.00
Ultrasonic sensor	1	$5.59
circuitry		
Arduino Nano	1	$5.67
RF M95W LoRa Transciever	1	$13.95
Rasbeery pi 3B+ project borad	1	$57.96
3D printing manufacturing costs		
Material and printing services (including studnent discount)		$229.71
Other		
Ended alligator clips jumper wires	1	$14.94
Portable battery-operated air pump	1	$20.36
Lithium ion battery 3.7V	6	$83.86
Lithium ion battery 1.5V	2	$4.19
Micro coolingfan DC 5V 0.08A	1	$5.45
Keyboard USB wire	1	$26.17
Wave-11750, 10.1in HDMI LCD	1	$139.99
PVC glue	1	$21.70
Fan tubeaxial 3VDC square-Vapo bearing	1	$68.48
Woven wire mesh Filter 304 stainlesss steel (5.9in x 8.2in)	1	$11.49
Screw (112unit/box)	1	$15.40
Nuts (100unit/box)	1	$14.13
Total(excluding Labour and delivery)		$1,932.89

Appendix F: Pugh Chart

Description	Weight	Previous Design	First Design	Second Design	Third Design	Current Design
Sketch	/					
Criteria	/	/	/	/	/	/
Potability and Easy to use	1	+	-	0	+	+
Durability	3	+	-	0	0	+
Safety	3	+	0	0	+	+
Cost	2	0	+	0	0	0
Soil-chamber interaction/Functionality	2	-	0	0	+	+
Ergonomy	3	+	-	0	0	+
Aesthetics	1	+	-	0	0	+
+	/	+11	+2	/	+8	+13
0	/	2	5	15	/	2
-	/	-2	-8	/	/	/
Net Score	/	9	-6	0	8	13