Development of an Autonomous Agricultural Vehicle to Measure Soil Respiration

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***Abstract* - Soil respiration (SR), the carbon dioxide flux produced by organisms in soil, is not well quantified and understood compared to other soil characteristics. Currently, environmental scientists collect SR data either by manually taking measurements in the field, which is time intensive, or by receiving information from permanently placed sensors, which limits the locations where data is collected. This project aims to provide an efficient means of collecting spatially diverse data for environmental research and agricultural monitoring by designing and constructing an autonomous ground vehicle that can navigate to specific points of interest, collect SR and other ambient atmospheric measurements, and transmit the data remotely to a base station. To do so, the robot relies on a variety of subsystems including the robot's frame, differential steering, a mechanical arm that deploys an array of ground sensors, a radio network, and on-board temperature, pressure, humidity, wind speed, and GPS ambient atmospheric sensors. The vehicle will use the Robot Operating System (ROS) along with GPS, motion planning, and LIDAR to navigate between user-specified sampling locations while avoiding obstacles, which will minimize the need for human labor and allow more areas to be visited for data collection as compared to permanently placed sensors. The proposed autonomous system will help environmental scientists and agricultural managers collect and analyze soil data in the field.**

Index Terms - Agricultural monitoring, Autonomous vehicle, Soil respiration, System design

Introduction

As the world's agricultural system faces the challenges of increasing population and decreasing farmland, new solutions will be essential to meet demand [1]-[2]. One way to improve the efficiency of current farming techniques is to effectively monitor growing conditions. Measuring and understanding SR has become of particular interest. SR is the measure of the flux of carbon dioxide over time produced by microscopic organisms in soil. This microbial activity is due to a combination of the decomposition of organic matter as well as plant respiration [3]. A higher flux of carbon dioxide is desired, as it indicates a healthier soil biome. Data on SR is useful to soil scientists as an agroecological metric, but is also of interest to agricultural managers.

Currently, SR measurements are taken using a handheld sensor or by employing an array of permanent sensors. Taking SR measurements by hand is time intensive and laborious. Relying on permanently placed SR sensors limits the locations for data collection. A new solution to take SR measurements that incorporates the flexibility of using a portable measuring device while requiring little direct human control would be a significant innovation. Trends toward greater precision in agriculture have led many companies and organizations to invest in unmanned ground vehicles (UGVs) research.

UGVs are used for a wide set of agricultural tasks including field management, harvesting, and weeding. The recent popularity of UGVs in farming applications can be attributed to advancements in imaging and detection technologies, improved control systems, and commercial technologies [4]. However, due to the variability of potential use cases, there are few commercial UGVs available for agricultural purposes. Custom-built robots are the most popular choice for agricultural UGVs [5].

Project Objective

The project objective is to create a remotely operated vehicle as an alternative method to collect SR and other ambient atmospheric sensor measurements. The custom vehicle is designed to be durable, cost-effective relative to the research-grade Clearpath Jackal that was used for intermediate testing [6]. The system provides a proof of concept for the chosen design and enables future researchers to build on this project. System and subsystem testing was conducted at Ramiiisol vineyards in Virginia.

System Requirements

Technical and operational requirements were determined based on interactions with environmental, agricultural, and robotics engineers and comparisons with current methods of taking SR.

Technical requirements are necessary to ensure the solution is technically feasible and scientifically accurate. The system must be able to provide the user with accurate SR

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flux and other contextual soil characteristic measurements without disturbing the soil. The system must be rechargeable and be used repeatedly. The system should be able to take measurements in the same terrain and at the same speed that SR can be measured using established methods of manually operated and permanently placed sensors.

Operational requirements are necessary to ensure that this system is functional for a user and easy to use. A user without a technical background must be able to operate this system without training. The system must navigate by remote control input from a supervisor and provide a user with environmental information that can be understood.

After evaluating the system requirements and objectives, the project was decomposed into the custom vehicle, soil measurement, ambient atmospheric, and data management subsystems.

CUSTOM UGV

In order to meet the system requirements, two solutions were considered: mounting the soil measurement system and ambient atmospheric sensors to a custom UGV or a trailer driven by a Jackal. Using a trailer introduced numerous challenges, namely accurately maneuvering and determining the exact position of the trailer relative to the Jackal. There were carrying load limits, which put strict weight constraints on the design of the trailer and soil sensor system. Creating a custom UGV introduced resource allocation problems, requiring more money and time. The custom vehicle was chosen because it could be manufactured for specific agricultural tasks and be designed to handle the weight requirements needed for the SR arm system. Navigation and sensor interfacing were tested using the Jackal in parallel with the manufacturing of the UGV.

TABLE I
UGV SUBSYSTEM REQUIREMENTS

#	Subsystem	Requirement
1	Drive/Internal	Must be able to reach 2 mph for at least 3 hours
2	Drive	Must be able to turn in an 8ft wide space
3	Drive	Must be able to navigate up 10% inclines
4	Drive	Must use the existing two 12 DC ⅕ HP Gearmotors
5	Chassis	Must be at least 8 inches off the ground
6	Chassis	Must be rigid enough to mount all components
7	Chassis	Must be weather resistant
8	Chassis	Must not tip or slip when measurements are taken

Several design objectives were defined for the development of the UGV: the UGV needed to be lightweight and compact for easy transportation, rugged to navigate different terrains, weather resistant to withstand light precipitation, high performance to climb inclines, and customizable to allow for future modifications. After an evaluation of system requirements and design objectives, a specific set of requirements for the vehicle was developed as shown in Table I.

The UGV was divided into three separate subsystems: chassis, drive train, and internal components. The general layout of components as shown in Figure I features a two-tier, rectangular chassis made of welded, low carbon steel tubing. Ample space was designed for on the chassis to optimize orientation and mounting locations for the SR measurement system. The internal components include the batteries, motors, microcontroller, and sensors. Two motors drive the UGV via a differential chain drive. The weights and locations of UGV components were evaluated to optimize center of gravity and increase the force required to lift the UGV off ground allowing for greater force to be applied into the ground by the soil measurement system.

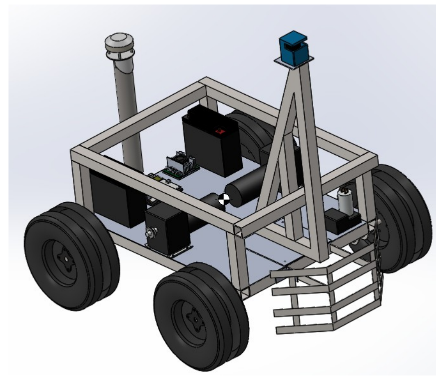

FIGURE I
CAD OF UGV WITHOUT EXTERIOR PANELS

I. Chassis

Low carbon steel and Aluminum 6061 were assessed as potential materials for the UGV's chassis. Although Aluminum 6061 is 2.8 times less dense, it is more difficult to weld and machine than low carbon steel. Additionally, Aluminum 6061 is less stiff than low carbon steel, and would flex more under similar loads. The ⅛" thick, 1.5" square low carbon steel tubing (SLCT) was primarily chosen for its rigidity to ensure the structural integrity of the UGV and weldability to permanently assemble. Additionally, acrylic panels were mounted on all four sides and the top of the chassis in order to enclose and protect the components that sit inside the chassis body. ⅛" Aluminum 6061 sheet was chosen as the chassis floor where internal components are mounted and protected from the debris.

The chassis, as shown in Figure I, is composed of ⅛" thick 1.5" SLCT welded together to form a 30"x 22"x 8" (l x w x h) rectangular body. Four 19" tubes were welded within the bottom frame to add structural support in high load areas where the batteries, motors, and soil sensor system are located. Additionally, four 8" SLCT welded to the chassis' bottom frame create an enclosure for the internal components.

II. Drive Train

A differential drive was chosen as the drive train because it was mechanically simpler and lighter weight compared to other steering mechanisms. In order to help reduce cost, two already-owned 12V IronHorse PM DC gearmotors were evaluated to determine if they met the needs of the system.

Therefore, a comprehensive mathematical analysis utilizing the expected weight of the system, given motor characteristics, and wheel radius, was done to ensure the motors would be powerful enough to navigate both flat and inclined terrain while remaining under maximum current draw. The torque needed to maintain a constant speed up an incline is given by (1) where T is torque, W is the weight, θ is the slope in radians, and r is wheel radius.

$$T = W \sin(\theta)\, r \tag{1}$$

The velocity and estimated current draw were approximated using the given rated motor characteristics. The analysis determined that the speed of the 190 pound vehicle will vary between 1.0 - 2.4 mph with a current draw between 4 - 11 Amps for inclines less than 10°. Table II below shows an overview of the key characteristics of the vehicle from 0-10°.

TABLE II
TECHNICAL SPECIFICATIONS OF UGV

Incline (degrees)	Torque (in-lbs)	Max Speed (mph)	Run Time (hrs)	Current Draw (A)
0	21.6	2.4	4.3	4.2
5	53.8	1.9	2.6	6.8
10	107.2	1.0	0.6	11.1

Transmission of power from the motors to the wheels was achieved with a single sprocket-roller chain system. To ensure the chain remains taut over time, a chain tensioner was designed with pulleys and shoulder bolts to tension the chain appropriately. Integrating suspension was considered, weighing the added stability on rugged terrain against the associated increased cost and complexity to the design. Ultimately, suspension was determined unnecessary for the needs of the project due to the even terrain and the UGV's large wheel size.

III. Internal Components

The locations of all UGV components were carefully assessed to minimize the potential of tipping when the soil probe system is inserted into the ground. Therefore, the heavier items such as the motors and batteries were distributed to the front of the UGV, where the soil system is located. In order to test and manually drive UGV, an already owned JPK 21v3 motor driver was used. Encoders were integrated to determine velocity and assist in motor control.

SOIL MEASUREMENT SYSTEM

The primary goal of the soil measurement system is to design a mechanism arm that would take accurate SR readings along with the soil moisture, ground and skin temperature. Table III details the requirements that guided the overall design of the mechanism. The soil probe subsystem consists of a SR chamber to measure respiration, additional sensors to measure soil characteristics, and the mechanical structure itself.

TABLE III
SOIL RESPIRATION SUBSYSTEM REQUIREMENTS

#	Subsystem	Requirement
1	Sensors	Must be able to measure within a 5% margin of error
2	Sensors	Must be able to touch the ground 90% of deployments
3	Chamber	Must be able to maintain a vacuum seal with the ground
4	Chamber	Must be able to take measurement under 2 minutes
5	Chamber	Must be rigid enough for 10 cycles without assistance
6	Mechanism	Must require less than 80 lbs to deploy
7	Mechanism	Must be mountable to UGV
8	Mechanism	Must be rigid enough to survive deployment

The final design of the SR subsystem, shown in Figure II, features a 20" stroke linear actuator, mounted onto a 32" tall triangular structure. The linear actuator can produce up to 200 pounds of force and will deploy until the ultrasonic distance sensor reaches the right height. On the end of the linear actuator, the SR chamber, soil skin temperature sensor, and soil moisture sensor are mounted to a shared mounting plate, which will be pushed into the ground simultaneously by the linear actuator. The bottom of triangle bracket is bolted to a plate, which in turn is bolted into the steel tubing of the UGV chassis.

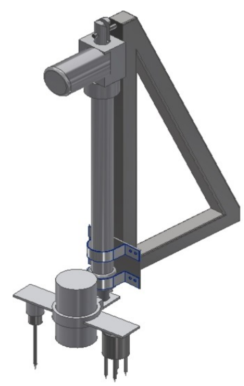

FIGURE II
SR SYSTEM CAD

I. Soil Sensors

An ATmega328 microcontroller was used to control the soil measurement system, which would then send a signal back to the UGV after all the measurements were finished at that location. The soil skin temperature and the soil moisture will be measured with a Stevens Hydra-probe and the Accurate Ground Temperature Sensor measures the ground temperature. After testing multiple CO_2 sensors, the SenseAir S8 Miniature CO_2 sensor was chosen because of its accuracy. Both the soil skin and moisture sensors were mounted to the linear actuator plate to ensure that they touch and plunge into the soil, respectively.

II. Soil Respiration Chamber

The SR chamber consists of a PVC body to act as a testing chamber, CO_2 sensor to measure the CO_2 flux over time, and pump to create a vacuum which isolates the testing area. In order to create the seal needed to contain the respiratory area, the SR chamber would require roughly 80 lbs of force to plunge into the ground. Other mechanisms of deploying the chamber into the ground, beyond a linear force, were investigated, including applying a torque to the cylindrical body or increasing the chamber's momentum by swinging the chamber into the ground. However, these ideas were too complicated for the resources allotted and instead, the redistribution of the weight to better accommodate plunge force was prioritized.

III. Mechanism

The tips of each sensor needed to be at least 8" off the ground to ensure they had enough clearance above obstacles in the vineyard. Since the longest sensor is around 5" long, the sensor holding plate had to be at least 13" of the ground. Therefore, the stroke length of the linear actuator needed to be at least 13". The 20" stroke linear actuator was chosen so the sensors will be fully inserted into the soil. A truss structure was designed to withstand the lateral force required to plunge the sensors into the ground.

Navigation and Site Selection

To fulfill the aforementioned system requirements, the UGV must be able to take in a series of sampling locations to visit, navigate to each sampling location, and avoid obstacles. While fully autonomous navigation has not yet been implemented, work has been done to explore navigation algorithms and develop the foundation needed to complete this functionality in next year's project. To date, exploration of this problem has been done using the Jackal.

Site selection will be directed by user input. By entering a series of GPS locations, the user will be able to give the UGV a 'roadmap' of what stops it needs to make. Using an onboard GPS module, the UGV can track its location in the field relative to sampling locations and uses this information to update its route. To accomplish this task, the Robot Operating System (ROS) has been used, which is an open-source framework specifically designed for multiple sensor-stream systems. ROS allows for code reuse via its selection of highly modular packages. To accomplish site selection, the gps_goal package is being used, which takes a user-specified GPS coordinate pair and converts it into a format the UGV can recognize and navigate to.

Once a list of sites has been provided, the UGV must then decide how to get from point to point, called global path planning. The most common way of implementing this in ROS uses the move_base package, which automatically takes in goals from an outside source-in this project, the gps_goal package-and constructs a global path.

Finally, while the UGV traverses the path from point to point, it must avoid obstacles by updating its planned path, which is called local path planning. This project has explored solutions through the use of odometry and LIDAR data to 'see' obstacles. Odometry, information about the position and speed of the UGV, is measured by motor encoders and fed into the local path planner. LIDAR is a technology where a pulsed laser is used to estimate distances from nearby obstacles. Based on the time it takes for a beam to return to the LIDAR module, a picture of the local physical geometry can be inferred. There exist many ROS packages that accomplish this. Exploration of the local planning problem has centered around the Berkeley Simultaneous Mapping and Localization (BLAM) algorithm, which creates 3D maps. Another alternative, HDL Graph SLAM, was initially explored but abandoned because of incompatibilities with the Jackal.

Ambient Atmospheric Sensors

Consultation with environmental scientists and agricultural managers drove the decision to have temperature, humidity, pressure, light, wind speed, and wind direction ambient atmospheric sensors onboard the robot. By exploring the difference between traditional sensors and Phidgets, which are proprietary plug-and-play sensors designed to easily interface with ROS, the final decision was to maximize Phidget usage because it would be fastest to integrate with the Jackal, which was running ROS [7]. This decision was reached by comparing part availability and specifications including price, error, resolution, and range. The air temperature had to be within 0.5 ℃ and the humidity within 5%RH. The Phidget Humidity/Temperature Sensor and Absolute Air Pressure Sensor were selected over the SparkX Humidity Sensor Breakout and MPL3115A2 pressure and temperature sensor because the Phidgets had the same ranges, less maximum error, and higher resolution. There were no anemometer Phidgets and no Phidgets that measured light over the required 300 to 1100 nm wavelengths, so the DS-2 Sonic Anemometer and APDS-9301 light sensor were chosen and interfaced with an ATmega328 microcontroller. This microcontroller was able to subscribe to the Phidgets ROS node that published the temperature, pressure, and humidity information, and could communicate the selected information to a SAMD21 Pro RF radio over a UART connection which in turn transmitted the data to a server over the 915 MHz ISM band. The Jackal had a built-in GPS that provided location and timing information.

Data Management

To operate without direct human input, the UGV must communicate its measurements reliably while in the field. A viable solution must be able to aggregate sensor data on the UGV, then transmit that data to a base station where it can be uploaded to the Internet or processed by a human operator. Testing took place at Ramiiisol vineyards, where the distance from the field to the main office was roughly 0.6 mi. In addition, the Jackal was used to test data connectivity.

Sensor data aggregation on the UGV uses the ROS framework of Messages and Topics, which allows data to be communicated between system components easily. Data is sent in real time from the sensor arrays to a NVIDIA Jetson TX2, the onboard CPU running ROS. The communication microcontroller functions as a subscriber to each data Topic in ROS, aggregating the measurements and sending them to the base station. These connections are represented by solid lines in Figure IV.

The complete package of data gathered by the UGV must be sent to the base station, roughly 1 km away. Traditional wired connections, WiFi, and Bluetooth are all too short-range to be used, so additional options were explored. The 915 MHz Industrial, Scientific and Medical (ISM) band was chosen for its widespread compatibility with cyber-physical systems, relatively low cost, low power usage, and appropriate range for this project. The 915 MHz ISM band also requires no licenses or special agreements.

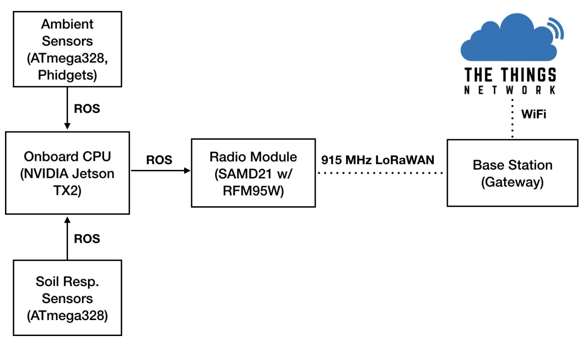

FIGURE IV
COMMUNICATION PROCESS

Use of the 915 MHz frequency range in cyber-physical systems has led to the development of a special network protocol, called Long Range Wide Area Network (LoRaWAN). It was developed as a standardized way for Internet-connected sensor devices to share data efficiently and quickly. Companies like Sigfox and The Things Network have created platforms that make the development and deployment of Internet-connected sensor systems easier. For this project, The Things Network platform is being used to provide a streamlined way to upload data from the 915 MHz radio to the Internet, where it can be processed and visualized, represented in Figure IV by dotted lines. The LoRaWAN protocol requires two components: a 915 MHz radio that can implement the network protocol, and a LoRaWAN-compliant Gateway that can receive radio transmissions and upload them to The Things Network's web platform. A SAMD21 Pro RF module from Sparkfun was used as the LoRaWAN sender. This module contains a 32-bit, 48 MHz SAMD21 microcontroller and a RFM95W radio, which operates at 915 MHz and is LoRaWAN-compliant. The most attractive Gateway choice is The Things Network's proprietary Things Gateway, which interfaces with the web platform relatively seamlessly.

SMART SAMPLING

Incorporating a system of smart sampling is another way in which an autonomous vehicle can be valuable by dividing a vineyard into regions of similar soil characteristics to efficiently collect data in a large area. A preliminary scoring system is still in the process of being modified, but it will be created to enable the vehicle prioritize sampling in regions where SR information is more valuable. Sampling SR takes multiple minutes and it is important for the robot to focus on sampling areas that are most important.

This scoring system requires a means of dynamically creating and adjusting regions with similar soil characteristics. To do this, an algorithm was created and tested using MATLAB that created Voronoi regions within distinct rows of a model vineyard that possessed similar soil characteristics as shown by two iterations in Figure V. These regions can be modified to handle changing soil conditions and be resilient to errors and outliers through iteration.

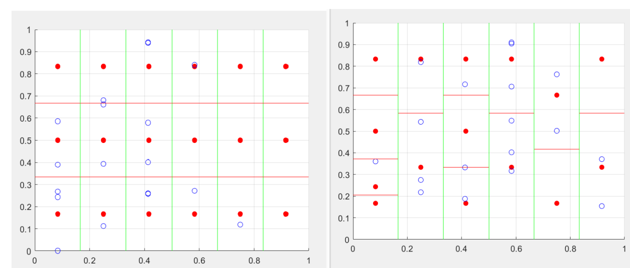

FIGURE V
SIMULATION: CREATION OF REGIONS IN VINEYARD

Each anchor point, in red, defines a unique Voronoi region such that any part of that anchor point's region's closest anchor point is the anchor point that defines the region. Within a given row shown in green, during each iteration of the algorithm, adjacent anchor points are compared and combined if their SR values are similar. In the same iteration, potential points, in blue, are created within each row and compared to the anchor point in their region. If the potential point is significantly different than its region's anchor point, than the potential point becomes another anchor point. The simulation was designed to make one dimensional comparisons within rows to simplify the process and showcase proof of concept.

DISCUSSION

This project has attempted to create a UGV that can help environmental scientists and agricultural managers gain SR data more easily. An autonomous vehicle is a feasible alternative to manually taking measurements or permanently placing soil sensors in specific areas. This initial phase of the project focused on designing a comprehensive system to benefit its target audience and creating a roadmap towards full integration of the aforementioned subsystems on a UGV. Parallel paths were simultaneously followed to test and design navigation, sensor interfacing, data communication, and smart sampling as proof of concept while the custom vehicle was constructed. The mechanical arm system with SR sensors demonstrated the possibility of automating the process of collecting CO_2 flux and other soil data. Interfacing sensors with the Clearpath Jackal allowed sensor data to be published as a topic on ROS and later synthesized. Testing navigation on the Jackal was delayed because of software problems. Preliminary simulations of smart sampling showcase the potential benefit of creating a smart vehicle; however, full implementation will create significant challenges that need to be addressed by future researchers. Limited manpower and delayed production of the custom vehicle and provided significant barriers to developing this system further in the allotted time. Because of this, integration of the custom robot with other components of the system will likely be delayed for future researchers.

Future Work

The SR monitoring system accomplished several project goals. A custom UGV was designed and fabricated according to requirements that interfaces with a custom SR probe as seen in Figure VI. Collection, aggregation, and transmission to the internet of ambient sensor data was accomplished. Autonomous navigation, while not implemented this year, was sufficiently explored so that future iterations of this project will know which algorithms and packages to use. The concept of smart sampling was explored and simulated in a way that advances towards implementation.

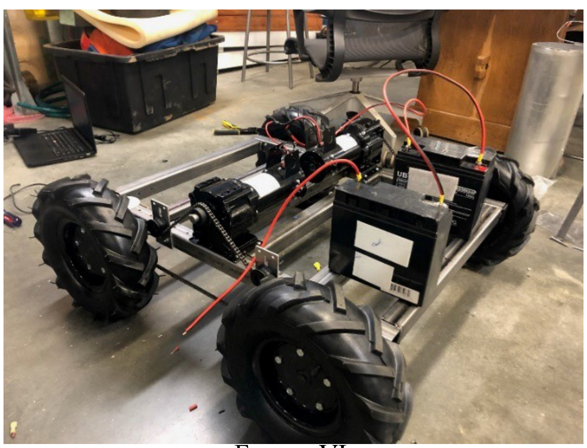

FIGURE VI
PROGRESS OF UGV, MARCH 2019

This project lays the groundwork to build a fully autonomous vehicle that performs smart sampling and samples locations with particularly interesting SR characteristics. The mechanical arm design can be improved so it requires less force to drive into the ground or so it has a smaller, more modular design to attach to various kinds of ground vehicles. The collected data could then be sent in to a dynamically updating web page that displays the sensor information graphically so an interested party could see how the SR and related values change with time. Additionally, a person could update navigation goals at the base station that would be wirelessly transmitted to the robot so it could adjust its path accordingly. Lastly, introducing another subsystem that would monitor weather or cloud cover would provide additional context for the SR measurements.

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