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Soil Sampling and Analysis Robot S.S.A.R.

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***Abstract*– This project aims to design and build an innovative, low-cost soil sampling and testing robot for increased efficiency in agriculture, environmental studies, and farming hobbyists. The goal of this project is to create an autonomous system that can sample and analyze soil in different environments on the spot to swiftly reduce testing time and allow rapid mitigation of soil to improve its quality. With the use of an auger drill, the robot will be able to extract five soil samples, gathering it all in one basket containing sensors that will test for the following soil properties: nitrogen, phosphorus, and potassium. These values will then be displayed on a Liquid-crystal display (LCD) screen mounted onto the frame of the mobile robot. This robot will create a direct impact on how farmers can improve fertilizer use by providing them with focused information on nutrient requirements, preventing excess application, and lowering input costs. Additionally, this robot will be powered by a rechargeable lithium battery and charged by a solar panel with its required specifications.**

Keywords—STM32, soil sampling, soil properties, auger drill, NPK sensor, linear actuator, LCD module, solar panel

I. Introduction

The project's objective is to design and implement a Soil Sampling and Analysis Robot (SSAR) that retrieves samples of soil from a field and efficiently analyzes the soil properties retained, evaluating and identifying soil nutrient deficiencies. Equipped with sensors, the SSAR analyses nutrient concentrations like phosphorus, nitrogen, and potassium. After the SSAR analyses the soil, it summarizes the results obtained on a Liquid-crystal display (LCD) screen. With this information, the user can determine the quantity and type of nutrients needed for optimal plant growth, how to minimize wastage, ensure even distribution of fertilizer so the least number of crops are lost, and allow farmers to maximize their crop production. The robot also includes a solar panel with a Pulse-Width Modulation (PWM) load controller to charge the battery when the robot is not being used, reducing pollution and the farmer's electricity consumption. Overall, the SARR helps agriculture by optimizing practices, reducing costs, and improving crop yields while minimizing the environmental impact.

II. Need Statement

Agriculture is one of the most important components of our and any society, as it produces the food needed to maintain human life. Soil analysis is a crucial part of the success of agriculture and farming for several reasons: it is the source of nutrients for the crops which optimizes crop production, it protects the environment from contamination by excess fertilizer or unhealthy substances, and it aids in the diagnosis of plant problems. To test the fertility of the soil, several factors are considered and are usually determined by the soil's biological, chemical, and physical properties.

Physical properties such as soil texture, structure, and color are easily analyzed by human eyes. However, the chemical properties are less noticeable and usually significantly more important in determining the crop's health. [1] Therefore, examining the nutrients in farm soil is the first step in planning a nutritious and healthy farm.

Over the past few years soil degradation has been spreading at an alarming rate endangering the fertility and productivity of the farmland, ultimately affecting the world's food supply, global food security, and ecosystem health [2]. Soil degradation refers to losing the soil's property quality due to natural and human-caused effects. Some examples that have caused soil degradation are the exhaustion of nutrients, acidification and erosion of the soil, and pollution, among others, etc. Preventing soil degradation could potentially help preserve farm-land quality and enhance productivity, and taking prompt actions to effectively do this will become the first step to success.

A soil sampling robot with analysis features of the soil included would be a valuable contribution to the industrialization of agriculture and farming. Some designs and research have been done in this area, with this objective previously; however, making it low-cost would benefit low-resource communities that also need efficient farming methods.

III. Background Survey

The discussion of similar robots includes soil sampling, agriculture, and farming robots. Some development designs for soil sampling robotic systems already exist, but the SSAR provides a solution for a low-cost agricultural system, to differ from the ones in the market.

Another soil-sampler robot is the *Agrobot Lala,* going a step ahead, analyzing nitrate. Its 2022 completed version only measured assured nitrate nitrogen content; however, they claim that with different probes it could measure electric conductivity, pH, nitrogen, potassium, sodium (NPK), and other similar elements important to the quality of the soil [3]. This robot was developed in Serbia, and it is estimated to cost around USD 55,000.

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Fig. 1 Agrobot Lala

A further example is an implemented design by Edulji et al. [4]. This system uses an Arduino board to collect the soil data of an area, and a GPS algorithm. From the related work discussed, this development is the one that implements the most economically accessible design. This design includes a vertical drill for soil collection and a rotational table with 12 containers to store the soil; therefore, SSAR proposes an improved design for more efficient soil recollection.

Finally, the most well-known robots, like the proposed SSAR, are those from *RoGo Ag LLC*, the *Smartcore Gen*X as shown in Fig. 2 below, which is a service in the market [5].

Fig. 2 - Rogo Ag Smartcore Robot

Another option is the manual soil sampling process, which is a time-consuming and exhausting job done by people. This is a less efficient way of soil testing with a large margin for human error; therefore, increasing the chances of inaccurate results. The company claims to be twice as fast as humans [6].

Rogo Ag LLC is a company start-up, valued at thousands of dollars. Some entities have invested $100,000 in this start-up. It can be concluded that these robots are very expensive for a farmer, and not worldwide accessible.

The distinction between SSAR and other similar robots is its economical accessibility since the robot is an intended low-cost system compared to those in the market and done in previous research. Also, the SSAR robot includes a rechargeable battery powered by a solar panel. Additionally, this accessible alternative robot could be accessible to countries with low Gross Domestic Product (GDP) and would be even more useful to those who have a high percentage in the agricultural sector of GDP.

IV. Impacts

Between 2010 and 2050, the projections for worldwide food consumption are anticipated to rise from 35% to 56%. On the other hand, the population at risk of famine will increase by -91% to +8% [7].

A. Social Impacts

Farmers can improve fertilizer use by getting focused information on nutrient requirements, preventing over-application, and lowering input costs.

Making economically accessible technology for farming benefits countries with low GDP per capita, especially those whose agricultural sector is a considerably high percentage of their total GDP. For instance, Fig. 3, retrieved from *Nature* [8], shows the world map of GDP per capita (in US dollars).

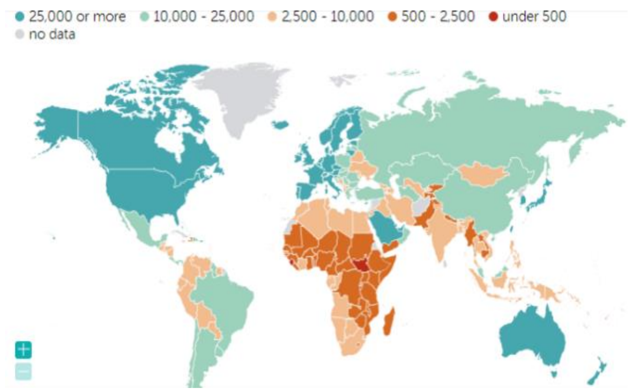

Fig. 3 2023 World Map GDP per capita

Countries in blue shades are most likely to have this technology, or they are close to it. However, those in orange/red could benefit from this kind of initiative. The usage of soil sampling robots may require training and instruction, hence, facilitating knowledge transmission among communities is needed, establishing a learning culture. Since this robot is low-cost, individuals and hobbyists who have their garden as a leisure activity or for healthier choices could take advantage of it.

B. Economic Impacts

The SSAR. robot not only aims to create a low-cost robot for soil sampling and testing but also attempts to make the entire process more efficient by providing better results in less time. The usual testing procedure for soil requires the collection of samples manually, bringing the samples to a laboratory center for analysis, and waiting for the results. Therefore, SSAR could help develop better and higher quality harvests, because crops will be planted at the most optimal state, and less time will be lost in the analysis portion.

The SSAR would also be helpful for the soil life span. Since crops, after a period of consecutive planting, erode the soil or harm it, with the SSAR, a longer life usage for the soil can be given, making the most of the land for production.

C. Health Impact

Farmers' physical work may be reduced if soil sample duties are automated, contributing to improved health and safety conditions for soil laborers.

D. Environmental Impacts

By providing precise data on soil health, the use of fertilizers and other inputs can be optimized. This can lead to minimizing nutrient runoff and soil erosion. The robot also uses solar power as a source of energy to recharge the battery while testing if needed and expanding battery life.

V. Requirements and Constraints

A. Market Requirements

1) Accurate: The robot should be able to accurately analyze the soil composition and nutrient levels to predict the correct type and amount of nutrients required.

2) Efficient: The robot should be able to efficiently analyze large or small areas of land to minimize the time and effort done by farmers or hobbyists.

3) Cost-effective: The robot should offer cost-effective solutions compared to the robots that exist in the market.

4) Easy to use: The robot should be user-friendly and require minimal training to set up and operate.

6) Safe: The robot should have safety features to prevent accidents and protect both the robot and the environment.

B. Engineering Requirements

1) Robot Structure: The robot should weigh at least 20 kg to withstand the drilling mechanism. The dimensions were designed to be 0.67m x 0.46m x 0.5m. The drill is made of stainless steel. Aluminum was chosen for the chassis, gears, and gearbox after developing Pugh's decision matrix.

2) Motion control; The primary consideration is the torque required for the motors to support the robot's weight, ensuring it remains grounded during drilling. To achieve this, 12V DC geared and encoded motors with a maximum torque of 49 kg-cm, a no-load current of 0.2 A, a nominal speed of 20 rpm (up to 67 rpm), and 19.2W of power were chosen.

3) Microcontroller: For the complexity of this project a microcontroller with many I/O, and PWM is needed. The STM32 was selected, which has a total flash memory of 512KB, SRAM of 128KB, and a clock speed of 180 MHz, making it suitable for the complexity of the expected programming of the robot.

4) Power Supply: The robot is powered by a 12V lithium polymer battery with a 60Ah capacity. Additionally, it includes a solar panel to charge the battery. The panel chosen is a 12V with a maximum power of 30W. For the solar panel to charge the battery a charge or load controller is needed. For this application, a PWM controller was chosen, rated for 12V or 24V systems, with a maximum load current of 30A.

5) Soil Extraction: The soil extraction mechanism needs to go at least 15.24 cm deep into the ground. Therefore, an Auger bit was chosen, with a total length of 30.48cm, which is more than enough. For this, a linear actuator of 12V and at least 20cm is needed to push the auger bit to the appropriate depth.

6) Soil testing and display: Nitrogen, Potassium, and Phosphorus are primary macronutrients crucial for plant growth and crop production. Nitrogen is essential for protein synthesis, Phosphorus aids in energy use and photosynthesis, and Potassium enhances disease resistance, yield, and quality, while also protecting crops in varying weather conditions [9].

For this NPK probe sensor is needed to measure the levels of pH and of these nutrients found in the soil. The probe must have electrolytic resistance**,** rust resistance and alkali corrosion resistance. The information gathered by the NPK sensor will then be displayed on a screen display.

VI. Estimated Cost

The estimated cost for the SSAR robot is shown below in Table II. Summarizing, this robot ranges between $700-$800 for the prototype. This range considers the components and materials listed in Table II with the cost breakdown.

TABLE II
BUDGET

Component	Qty.	Subtotal USD
STM 32 Nucleo board	1	10.00
Inertial sensor: Adafruit 9- IMU BNO055	1	25.00
NPK and pH sensor for soil	1	45.00
RS485 adapter module	1	9.00
Single Motor Driver Shield	4	44.00
High Torque Geared and Encoded Motors	4	192 .00
Threaded wheels	4	40 .00
Drill	1	13 .00
High torque motor for the drill	1	47.79
Linear actuator	1	41.99
LCD display	1	11.00
ST-Link STM32 programmer & emulator	1	14.95
12V Rechargeable Battery	1	56.95
Voltage regulator LM2576	1	1.75
Solar panel 30W	1	45.00
Load controller	1	23.00
Frame	1	115.00
Total		757.43

VII. Standards

A. Design

1) All computer-aided design (CAD) done in SolidWorks adhered to the International Organization of Standards (ISO) criteria, using millimeter, gram and second (MMGS) units.

B. Programming

1) The Arduino IDE utilized ISO C++ language and was employed during the programming of the SSAR.

C. Soil Analysis

1) Guidance on the choice of evaluation of bioassays for ecotoxicological characterization of soil and soil materials adhered to ISO 17616:2019.

2) The structure of sampling described for any kind of soil investigation adhered to the ISO 18400-100-2017

3) The standard used to test methods for the pH of soils adhered to the American Society for Testing and Materials (ASTM) D4972-19.

D. Safety

1) The Electrostatic Discharge Association (ESD), (ANSI-accredited) has the ANSI/ESD S20.20-2021, which defines electrostatic discharge (ESD) as "the rapid, spontaneous transfer of electrostatic charge induced by a high electrostatic field.".

E. Solar Panel Implementation

1) IEC 62509 Ed. 1.0: Battery Charge or load Controllers for Solar Systems oversees the efficiency and operation.

2) IEC 61730-2:2016: Photovoltaic (PV) Module Safety Qualification specifies testing standards.

VIII. Design Concept

A. Mechanical Design

The mobile-wheeled robot comprises a frame built from manufactured parts and off-the-shelf components. It is a four-wheeled differential drive system with four DC-geared motors with built-in encoders for mobility. The frame is constructed from 6061 aluminum extrusions/rectangular tubing. Additionally, the robot features four 10-inch pneumatic tires with zinc hubs.

To appropriately select the motors for the differential drive system, we determined the required torque using (1).

$$\tau = \mathrm{F} \cdot \mathrm{r} \qquad (1)$$

Where τ represents torque, F is the total Force, and r is the wheel radius.

To calculate the total force exerted by the robot, we considered both the force of friction and the force of acceleration.

$$\mathrm{F_{total}} = \mathrm{F_{friction}} + \mathrm{F_{acceleration}} \qquad (2)$$

To determine the force of friction, (3) was used to first calculate the force caused by the robot's weight.

$$\mathrm{F} = \mathrm{ma} \qquad (3)$$

$$\mathrm{F} = 20\ \mathrm{kg} \cdot 9.81\ \mathrm{m/s^2} = 196\ N$$

Consequently, the friction force can be then calculated using (4) and with the values for our specific case as in (4.1) after having a mass of 20 kg which translated to a force of 196 N as shown in (3.1) and having identified through a literary review the coefficient of static friction, μ_{soil}, between the rubber wheel and the soil to be approximately 0.6.

$$\mathrm{F_{friction}} = \mathrm{F} \cdot \mu_{\mathrm{soil}} \qquad (4)$$

$$\mathrm{F_{friction}} = 0.6 \cdot 196\ \mathrm{N} = 117.6\ \mathrm{N}$$

Additionally, the acceleration force is determined using (5) where m is the mass of the robot, and a is its acceleration where it is assumed to be $0.15\ \mathrm{m/s^2}$.

$$\mathrm{F} = 20\ \mathrm{kg} \cdot 0.15\mathrm{m/s^2} = 3\ \mathrm{N} \qquad (5)$$

Now, the total force can be calculated as in (6).

$$\mathrm{F_{total}} = 117.6\ \mathrm{N} + 3\ \mathrm{N} = 120.6\mathrm{N} \qquad (6)$$

Subsequently, the torque was calculated as shown in (7)

$$\mathrm{T} = 120.6\ \mathrm{N} \cdot 0.127\ \mathrm{m} = 15.31\ \mathrm{N} \cdot \mathrm{m} \qquad (7)$$

However, since the robot has four motors, the torque per motor is 4.45 Nm. Converting this from N·m to kg·cm, a commonly used unit for motor torque, yields to 39.01 kg·cm as calculated in (8).

$$\mathrm{T} = 3.8275\ \mathrm{N} \cdot \mathrm{m}\ \times \frac{1\mathrm{kg}}{9.81\ \mathrm{N}} \times \frac{100\ \mathrm{cm}}{1\ \mathrm{m}} = 39.01\ \mathrm{kg} \cdot \mathrm{cm}\ (8)$$

The drilling mechanism of our soil sampling system comprises three main components: A DC-geared motor with a 64 CPR encoder, an auger drill bit, and a linear actuator as illustrated in Fig. 4 below.

Fig. 4 CAD vs Real Life model of drilling mechanism

These three worked together to create a drilling mechanism in which the linear actuator was connected to the geared motor to lower the arm into the ground, and the motor which was attached to the auger drill bit created a rotary motion to allow the drill bit to penetrate the soil. These items were adapted to each other with designed couplers. Once the actuator and the motor penetrated the soil to its required standards, the soil sample was extracted by reversing the direction of the motor and placing the soil samples into a container that holds the different sensors to test for the soil properties.

The provided design in Fig. 5 represents the latest design of our mobile wheel robot frame.

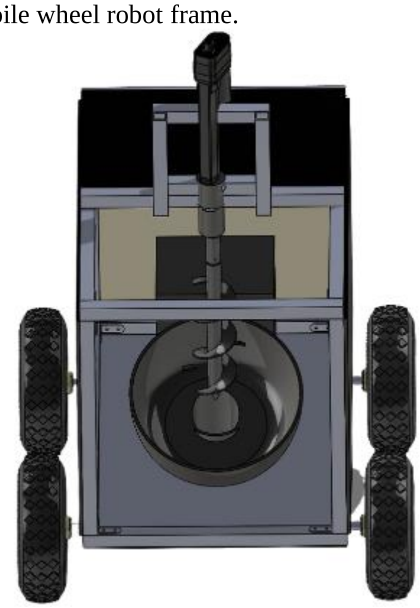

Fig. 5 Soil Sampling Robot Design

Within this frame, critical components are enclosed to safeguard them from the operational environment.

B. Electrical Design

An STM32 nucleo development board is used to control the system. The schematic described is shown in Fig.6 below.

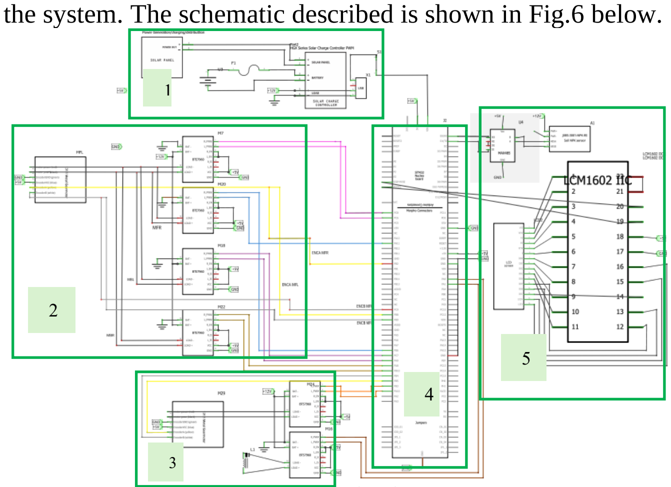

Fig. 6 Schematic Diagram

From this, the electrical design is divided into:

1) Power: The load controller connects all components and stores the extra energy in the battery. It ensures controlled output, independent of panel fluctuations by managing power storage and supply. The battery line uses a 40 A fuse as a protection from overvoltage.

The motor drivers are connected directly to the load controller. The chosen PWM controller includes a USB port, allowing a USB to USB-C cable to link to the STM32 board, simplifying wiring and voltage control.

2) Drive train system: The system includes motors, motor drivers, and encoders. Single-channel drivers were chosen and placed close to the motors to reduce the current draw. Each H-bridge motor driver has two PWM and two enable pins. From (9) we know torque is proportional to current.

$$\tau = NIAB\sin\theta \qquad (9)$$

Therefore, since high torque motors are needed, they draw high current as well.

3) Drilling system: This is composed of a linear actuator and a high-torque DC motor. To drive and control these, the same single-channel motor drivers are used to control how far the linear actuator goes and the speed of the motor that is set to be turning the auger bit to drill into the soil. Both components were selected according to the power specifications available from the load controller and battery.

4) Microcontroller: The microcontroller selected has different interface pins such as PWM, SPI, I2C, Serial (USART/UART), Analog, ADC/DAC, and CAN which allow for simple communication with the components.

5) Soil Monitoring: The NPK sensor for soil analysis uses RS485 UART communication, which the microcontroller doesn't support. A Modbus RS485/MAX485 is needed to convert RS485 to Transistor-Transistor-Logic (TTL) readings for the STM32. The sensor readings are displayed on an LCD with I2C communication, saving microcontroller pins by only requiring two instead of the usual eight.

After reviewing the electrical design, some power constraints were considered to ensure proper functioning. The selected battery is rated at 12V and 60Ah.of capacity. Table II below shows the power budget to consider where stall currents of the motors were taken into consideration.

TABLE II
POWER BUDGET

Power	Qty	Stall current	Total	Rated current	Total
Motor	5	5.5 A	27.5 A	0.75	3.75
Linear actuator	1	3 A	3 A	3A	3A
STM32	1	~500mA	500mA	500mA	500ma
Total	31A		7.25		

Table II above considers the load-current for each component. Therefore, the maximum current drawn from the major components is approximately 31 Amps, approximately. However, this is only if the five motors ever reach a stalling point at the same time. The nominal current drawn should be within 7.25 A. With this data, the total runtime of the robot can be calculated as in (10), as well as the charging time with the solar panel. The runtime of the robot considers the total load-current of the components and the battery selected. Minimum operating time considers the stall current.

$$\text{Operating time} = \frac{\text{battery capacity (Ah)}}{\text{nominal current of components}} \qquad (10)$$

$$\text{Nominal operating time} = \frac{60\text{Ah}}{7.25\text{A}} \approx 8.28\ \text{h} \qquad (10.1)$$

$$\text{Minimum operating time} = \frac{60\text{Ah}}{31\text{A}} \approx 1.9\ \text{h} \qquad (10.2)$$

What this means is that the robot would normally be able to go at approximately 8 hours from full charge as shown in (10.1). Technically it could go one hour and 54 minutes running at stall current as shown in (10.2); however, this is not possible since the motors can only endure less than five minutes under these conditions.

Now for the charging time, the nominal power of the solar panel and the energy of the battery in Watt-hour is needed. The solar panel selected is of 30W and the battery's energy was calculated from the following equation where Q is capacity.

$$E = Q \cdot V \qquad (11)$$

$$E = 60\text{Ah} \cdot 12\text{V} = 720\text{Wh} \qquad (11.1)$$

Now with this information, the total charging time was calculated as shown in (12), where E is in Watt-hour and P is in Watts, and with the information of our components as shown in (12.1)

$$\text{Charging time} = \frac{E}{P} \qquad (12)$$

$$\text{Charging time} = \frac{720\text{Wh}}{30\text{W}} = 24\text{h} \qquad (12.1)$$

C. Programming

The programming for the robot is developed using an Arduino IDE programmed in ISO C++. The STM32 F446RE microcontroller was chosen due to the number of sensors and components the robots require, and its greater capability of both storage and Static Random Access-Memory (SRAM). The

SSAR soil sampling process starts off initializing the components, such as NPK sensors, motors, and encoders. The flowchart diagram is illustrated in Fig. 7.

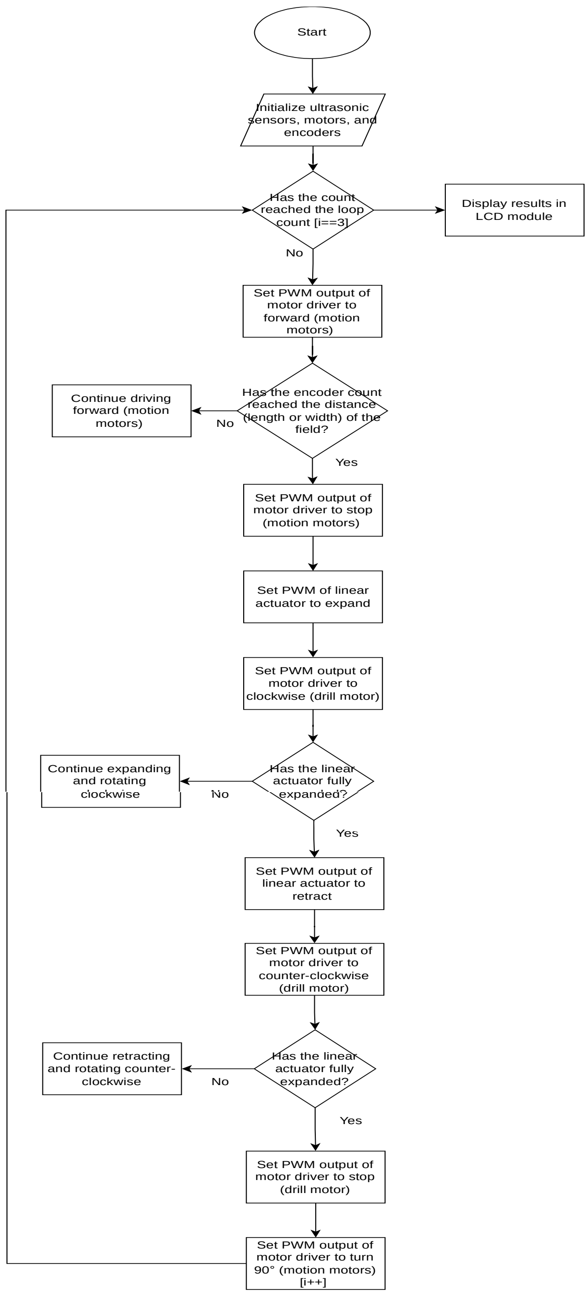

Fig. 7 Flowchart

A for loop simplifies the process of collecting soil samples at the corners of fields with square or rectangle-like shapes. Subsequently, The robot moves and reads the encoder to determine when it has reached a corner of the field. When it reaches the target, the linear actuator expands and sends a PWM output signal to the drill motor to rotate clockwise and drill into the soil. Once it has drilled, the linear actuator retracts and sends a PWM output signal to the drilling motor to rotate counterclockwise and retract the soil sample. When five samples have been taken, the NPK sensor reads the soil composition. The values read are displayed on the LCD module, and users can scroll to read the information.

IX. Functionality Tests And Evaluation

Different tests were performed to ensure proper functionality. The testing procedures were divided into:

A. *Drive Train and Load Test*

For the differential drivetrain system with four geared motors, the robot went through mobility testing with varying weights up to 41 kg. The robot was able to withstand the weight and drill into the ground without any lift off the ground.

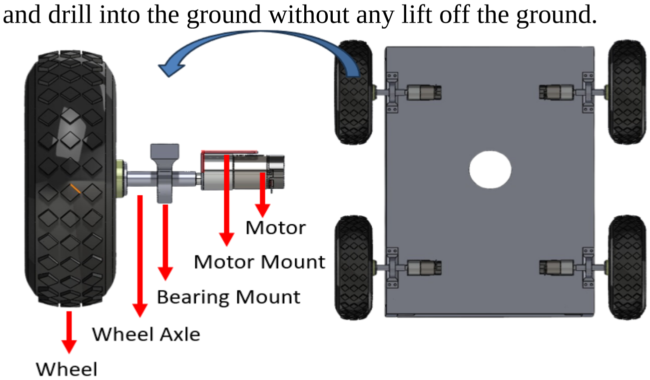

Fig 8. Drivetrain of SSAR

B. *Sampling Mechanism*

With the final assembly put together and the designed drilling mechanism mounted, the soil samples were retrieved following the desired standards. With the auger bit the soil samples were placed into a soil sampling bowl for analysis.


Fig. 9 Sampling of soil into analysis bowl

D. *Soil Analysis System Evaluation*

The NPK sensor is a real-time monitoring component of its respective nutrients. Their working principle can be based on different technologies. One way uses ion-selective electrodes of the elements of interest. When these electrodes contact the soil, they produce electrical impulses proportional to the concentration of the specific ion present. Another way is since the NPK sensor detects the electric conductivity of soil, the manufacturer adjusts the calculated conductivity level by an equivalent factor that matches the levels for nitrogen, phosphorus, and potassium [10].

The NPK sensor was successfully programmed to read soil nutrient concentration in the soil samples for the units of mg/kg to then display this information read by the sensor to an LCD module that is attached to the frame of the robot so the farmer can read these real-time values. While trying to code a program for the NPK sensor a problem was found, the register hexadecimal values to send an inquiry for the sensor to know it needs to read a certain component were slightly off so through research the program was corrected to the right values for the inquiry. Using the appropriate register values for the NPK is crucial for the correct performance of the sensor. After fixing this issue the system proved successful and was able to capture the data desired and display it, as shown in Fig.10.

Fig. 10 - NPK sensor and LCD module before and after right register values

X. RESULTS

The initial robotic proposal proved the working concept. The robot was designed, assembled, and tested, providing a working prototype. After different functionality tests, the robot was able to run on its full load of around 41kg, with a 12V battery and a working solar panel system. The robot successfully executed the intended program, being able to stop and dill into the ground to extract the soil and deposit it into a bucket, and after collecting three samples it ran the nutrients test, displaying it on an LCD screen. As seen in Fig. 11, the robot is shown on its final result after running some tests.

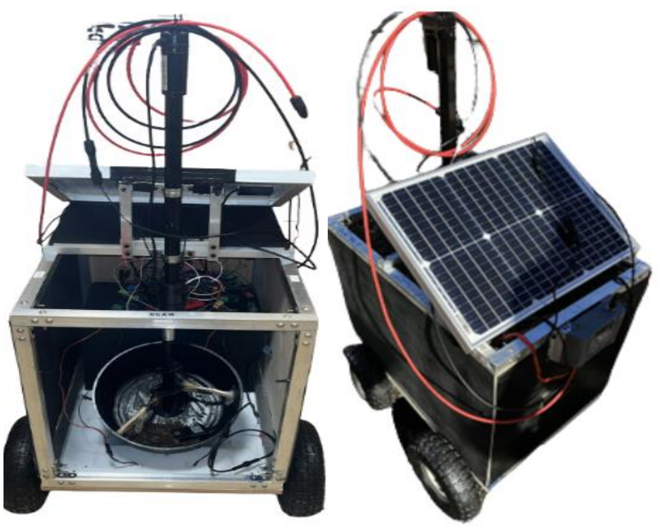

Fig. 11 Final Result – Front and Back View

X1. CONCLUSION

The Soil Sampling and Analysis Robot (SSAR) is a robotic device that collects soil samples from a field and thoroughly investigates the qualities required by crops. SSAR assesses soil conditions and determines nutrient shortages. This robot is designed for individual farmers in low-resource settings with high agricultural demand to accelerate crop planting. This is accomplished by automating the soil sampling and analysis process with a robot that has internal capabilities. SSAR uses sensors to measure soil pH, moisture content, and nutrient concentrations such as phosphate, nitrogen, and potassium. The robot also has a solar panel system that uses monocrystalline cells and a PWM load controller to charge a battery. Ultimately, SSAR attempts to benefit agriculture by optimizing methods, lowering costs, and increasing crop yields while minimizing environmental effects.

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