TerraProbe Soil Sampling Robot

Preliminary Design Review

ME463: Senior Design

6 Feb 2025

TERRA PROBE

A Down 2 Earth (D2E) Company

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Executive Summary

The agricultural industry is focused on increasing and optimizing productivity of crop growth through data and testing. Traditional soil testing methods remain expensive, labor-intensive, and slow, preventing farmers from making timely, data-driven decisions. At Down2Eath, the team aims to provide a solution designed to transform soil analysis by integrating real-time data collection with an innovative hybrid auger-core sampling mechanism accessing multiple depth profiles. TerraProbe directly targets market inefficiencies and market gap by offering an intermediate solution in the current market by offering an affordable, portable, and efficient system tailored for small to medium-sized farms, with the potential to scale globally.

The core innovation of TerraProbe lies in its automated depth control and sealed sample chambers, ensuring accurate multi-depth sampling while preventing contamination. By incorporating real-time sensors and data acquisition system for connectivity, the device enables instant analysis and transmission of soil health metrics such as temperature, moisture, and NPK (Nitrogen, Phosphorous, Potassium) to a centralized digital platform. This real-time capability bridges the gap between soil diagnostics and precision agriculture, allowing farmers and agronomists to optimize nutrient management, reduce input waste, and enhance crop yields.

Market analysis reveals a compelling opportunity. The global soil testing market is growing at a CAGR of 10.4%, while the smart agriculture market is valued at $22.65 billion and expanding rapidly with advances in AI, automation, and IoT. With an estimated 360,000 potential units annually in the U.S. alone, TerraProbe is positioned to capture a significant share of this demand by providing a cost-effective alternative to traditional soil sampling and laboratory-based testing.

Our competitive advantage lies in three key areas:

1. Cost & Accessibility – Unlike expensive lab-based solutions, TerraProbe reduces costs by integrating automated on-site sampling and analysis, making high-quality soil testing accessible to smaller farms.
2. Efficiency & Speed – Traditional soil testing requires days to weeks for results; TerraProbe provides instant insights, allowing farmers to adjust their strategies in real time.
3. Ease of Use & Portability – With a lightweight, user-friendly design, the device requires minimal training, making it ideal for widespread adoption.

Beyond technological advantages, the broader impact of TerraProbe aligns with sustainability and environmental responsibility. By enabling precise input application, it helps reduce fertilizer runoff, improve soil health, and minimize waste, directly supporting global efforts toward climate-smart agriculture.

Our project schedule is structured in three design phases from preliminary to critical to final design review. We have completed extensive research, initial CAD/Design & prototyping, and initial economic feasibility analysis. Figure 1 showcases a preliminary model of TerraProbe. The next phase involves finalizing the CAD models, creating a structured manufacturing and assembly plan, and ordering materials. This will allow the team to pilot and test with key agricultural stakeholders to refine performance and collect real-world feedback.

TerraProbe's vision is to revolutionize soil sampling and monitoring with an on-demand, portable, and labor/time efficient solution that delivers real-time analytics across different soil depths. TerraProbe should empower agricultural professionals and environmental researchers by providing accurate, data-driven insights to optimize crop yield, ensure soil stability, and enhance soil health management worldwide.

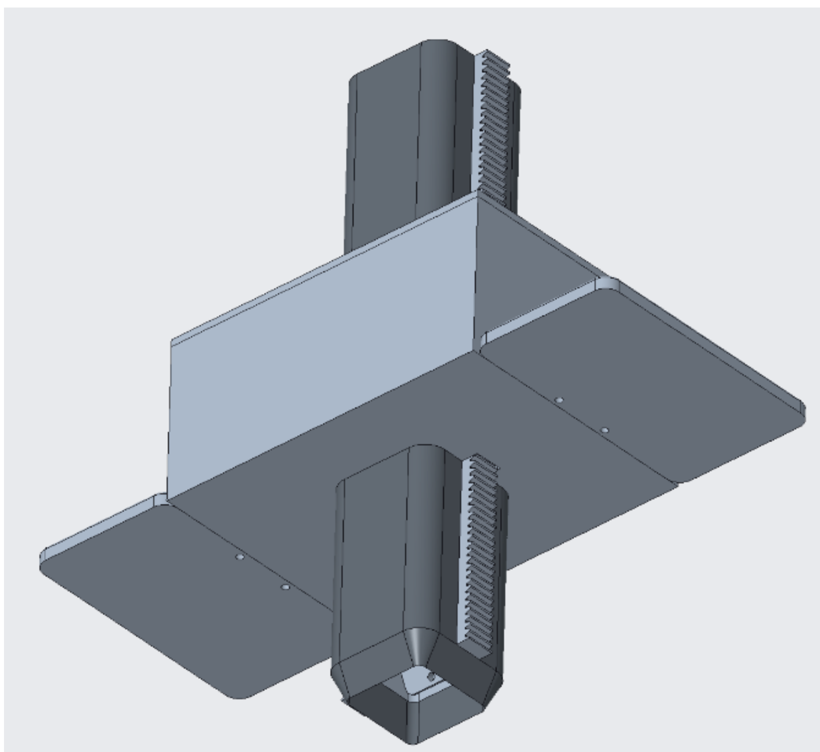

Figure 1: TerraProbe Concept Design

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Introduction

I. Identifying the Problem

The Down To Earth (D2E) team has identified a significant gap in the soil sampling market. Soil sampling plays a crucial role in agriculture, environmental monitoring, and geotechnical engineering. Reliable soil analysis provides insights into soil composition, fertility, contamination levels, and mechanical properties. However, traditional soil sampling and testing methods involve several challenges including inconsistencies in sample collection due to heavy bulky equipment, soil contamination between depth layers, and inefficiencies in manual operations. These limitations hinder the accuracy of soil assessments, leading to suboptimal decision-making in farming, land development, and environmental remediation. The market consists of either manually operated soil sampling equipment or complex, bulky machinery that require skilled access to greater soil depths. This presents an opportunity for an intermediate solution, a device that is portable, efficient, and capable of burrowing and collecting soil samples at multiple depths without compromising sample integrity (Refer to Appendix A.2)

To address this gap, we intend to build TerraProbe, a soil sampling robot designed for agricultural professionals, construction firms, and environmental researchers. The system will efficiently burrow into the soil, extract samples at various depths, and provide real-time data through an integrated dashboard, displaying critical soil properties such as NPK (Nitrogen, Phosphorus, Potassium Concentrations), moisture, and temperature. Our vision is to revolutionize soil sampling and monitoring by delivering an on-demand, portable, and labor-efficient solution that offers real-time analytics across different soil depths. The device will not only provide a method to accurately excavate and extract soil samples but also provide data on-site instead of requiring testing at the lab. TerraProbe is a tool not only for farmers and agronomists, but a daily household solution that will enable data-driven decision-making to optimize crop yield, improve construction planning, and promote sustainable land management practices globally.

II. Understanding the Stakeholders & Market

In the agricultural market, the need for more efficient, accurate, and accessible soil testing is becoming increasingly important. Our primary and target consumers are farmers and agronomists who require the collection of soil samples to analyze properties at various depths. The global soil testing market, valued at $5.5 billion in 2023, is experiencing significant growth, driven by the expanding adoption of precision agriculture technologies.

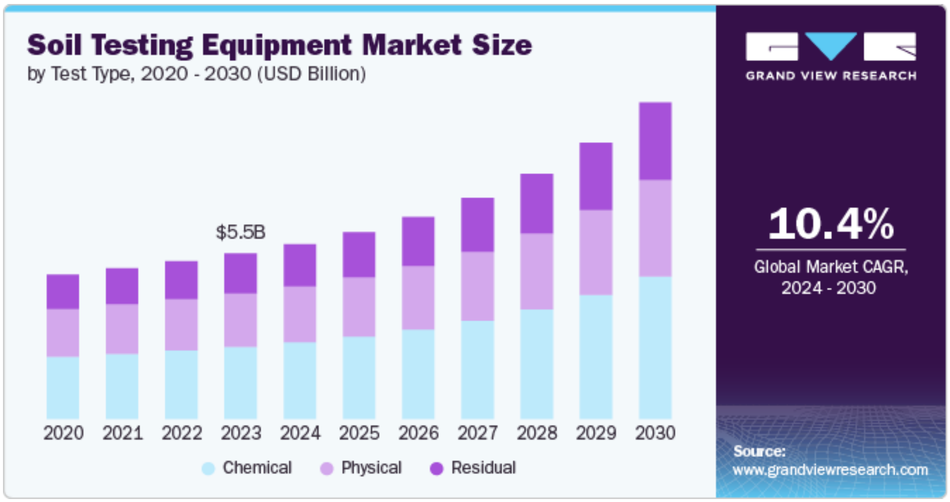


Figure 2: Market Growth

As shown in Figure 2, with an expected compound annual growth rate (CAGR) of 10.4%, there's a clear opportunity to capitalize on this market, especially considering the significant inefficiencies of existing solutions. In the U.S. alone, there are 1.8 million farmers, and with a conservative 20% adoption rate, TerraProbe could tap into a market of 360,000 units annually, providing a scalable opportunity for business. This indicates that there is a sufficient market and consumer base for TerraProbe especially given the significantly high costs and intense labor demanded by current benchmark solutions.

AMS Soil Probes	WintexAgro 1000 Automatic Soil Sampler	Amity Technology Soil Sampler
		

Figure 3: Benchmark Models

Figure 3 showcases a few examples of the benchmark solution. Currently, market alternatives range from low-cost, manual soil probes to high-end automated systems. For instance, AMS soil probes, which are simple and cost-effective, are manual and lack depth accessibility, automation, and data integration. On the other end of the spectrum, products like the Amity Technology Soil Sampler are highly automated, capable of sampling to depths of 48 inches, but they come at a high price range of $3000-$6000 and lack portability or real-time data analytics as they require mounting on vehicles and third-party data acquisition systems. While the WintexAgro 1000 provides some automation, its shallow depth capacity (up to 30 cm), bulky and heavy equipment, and lack of integrated data analysis further highlight the gaps in existing solutions.

A core feature and vision of our product, TerraProbe, is the real-time data collection and autonomous soil sampling, especially in challenging soil conditions like soft clay. This feature not only differentiates TerraProbe but also positions it as an asset for both precision agriculture and other industries such as construction and environmental research. Unlike AMS probes or the Wintex 1000, TerraProbe will combines portability (≤ 25 kg), autonomous operation, and multi-depth sampling (up to 18”) with integrated sensors for moisture, salinity, and temperature, offering real-time data analysis that none of the benchmark products can provide. While farmers are the core target, firms in the geotechnical investigation space, including companies like Fugro and AECOM, as well as environmental monitoring organizations like NASA and the USDA, also stand to benefit from TerraProbe’s capabilities.

In terms of product strategy, we aim to offer TerraProbe at an affordable price range of $1500-$1800, with additional revenue streams coming from the subscription for data analytics softwares. This strategy will ensure that the product reaches both individual farmers and larger organizations while capitalizing on the growing trend of smart agriculture, which is valued at $22.65 billion in 2023 and is expanding at a CAGR of 13.7%.

With its vision of portability, automation, depth accessibility, and real-time data analysis, TerraProbe stands apart from existing solutions. It fills a critical gap in the market by offering an affordable, autonomous, and data-driven solution to soil testing, positioning it as a transformative tool for agricultural professionals, environmental researchers, and construction firms looking to make data-driven decisions efficiently and sustainably (Refer to Appendix A.2 for more details).

III. Engineering & Customer Requirements

As we are developing the design of TerraProbe, we focused on addressing the core challenges that farmers, agronomists, and environmental researchers face with current benchmarks into engineering solutions that address their needs. The benchmark models had a common theme such as high cost, portability, operational complexity, and limited depth accuracy, which can be prohibitive for small to medium-sized farms or non-experienced users.

One major issue with benchmark models is their high cost, which often makes them inaccessible for small-scale farmers. TerraProbe addresses this by keeping the prototype development cost under $1000 which will allow us to price below high-end models yet keep it affordable. Another key challenge is portability. Many existing models are bulky and difficult to transport, but TerraProbe is designed to be lightweight (≤ 25 kg) and compact (≤

23” W x 20” D x 14” H), ensuring that it can be easily carried and stored. Additionally, the product needs to operate autonomously with minimal supervision, making it easy for users with little experience to collect soil samples. TerraProbe should enable accurate multi-depth sampling (up to 18”) and integrate real-time data analysis for moisture, salinity, and temperature, providing actionable insights. Durability is another key engineering requirement, with the device needing to function effectively in extreme temperatures and varying moisture conditions. Low maintenance is crucial, with removable, washable parts and minimal storage needs. Lastly, TerraProbe should have a dashboard or web app that displays real-time data, accessible on mobile or desktop devices. A few important customer requirements and engineering requirements are laid out in Table 1 below. (Refer to Appendix A.3 for more)

Table 1: Translating Customer Requirements to Engineering Requirements

Customer Requirement	Engineering Requirement	Importance Rating (1-5)
Safety	Automatic shut-off if the device malfunctions or detects an obstacle	5
Portability & Lightweight Design	Device must be < 25 kg and compact to ensure portability	5
Autonomous Operation	Must operate and collect soil without manual force for at least 2 hours of continuous operation	3
Accurate Multi-Depth Soil Sampling	Collect up to 18” of soil profile without mixing	5
Integrated Real-Time Data Analysis	Equipped with sensors for moisture (±5%), salinity (±5%), and temperature (±1°C), with data processed in under 30 seconds.	3
Cost-Effective and Affordable	Prototype development costs \$600-1000 per unit, Sell Price Under \$2000	4
Durable for Diverse Environments	Operable between 0°C and 50°C, Water-Resistant	4
Low Maintenance	Maintenance required every 100 hours of operation	3
Depth Accessibility	Can collect soil samples from at least four depths: 0-2 in, 2-4 in, 4-8 in, 8-18 in.	5

IV. Concept Generation & Ideation

Post generating the engineering specifications, the team had engineering constraints that had to be taken into account when generating concepts. The development of a soil sampling solution began with an extensive ideation phase. The team generated multiple concepts by evaluating existing techniques and identifying errors or pain points in the current designs. The process to develop the final design was done by firstly brainstorming and benchmarking current industry designs and standards. The objective of the project is to design a portable, cost-effective, and easy-to-use soil sampler with onsite detection and data provided to the user. Some requirements of the project are collecting 18" of soil in payload, ensuring no mixing of soil is done in the process, providing on-site data collection and analysis, and portable design.

Three main concepts were chosen based on the requirements of the project. (Refer to Appendix A.3 for more on each design) The first design highlighted in Figure. 4 is a soft robotics everting system. The design includes a soft skin that inverts itself to push the robot through the dirt. The design comprises a top chamber that houses all electronics such as batteries, sensors, and microcontrollers which allow for the design to provide onsite detection and collection. The core is surrounded by the everting skin, as seen in Figure 4. The soil will be collected in a chamber located in the core of the robot as it descends. It would collect a small column of soil. In addition, many sensors were to be installed on the robot's exterior to record data at various depths of soil. This data could then be processed to generate temperature, moisture, nitrogen, phosphorus, and potassium levels relative to depth. Lastly, a tow rope was going to be attached to the rear of the robot to aid in extracting the robot after it had burrowed a hole. This would safeguard against the device not being operable underground in the event of a mechanical failure. There were several noticeable benefits to this design. First, the robot was flexible, which enabled it to navigate around large boulders and obstacles underground. The robot would also be lightweight due to the use of soft robotics, which mitigates the implementation of heavy metals like aluminum and steel. However, there were some critical drawbacks to this design, the first of which was the fact that everting systems require pressurized gas to propel the system forward. This would have required pressurized tanks to either be installed onboard or airlines to be fed from the surface down into the hole. Furthermore, the everting system would have a low fatigue life if used in rocky environments. Lastly, the tow rope on the rear of the robot made the design too large and clunky.

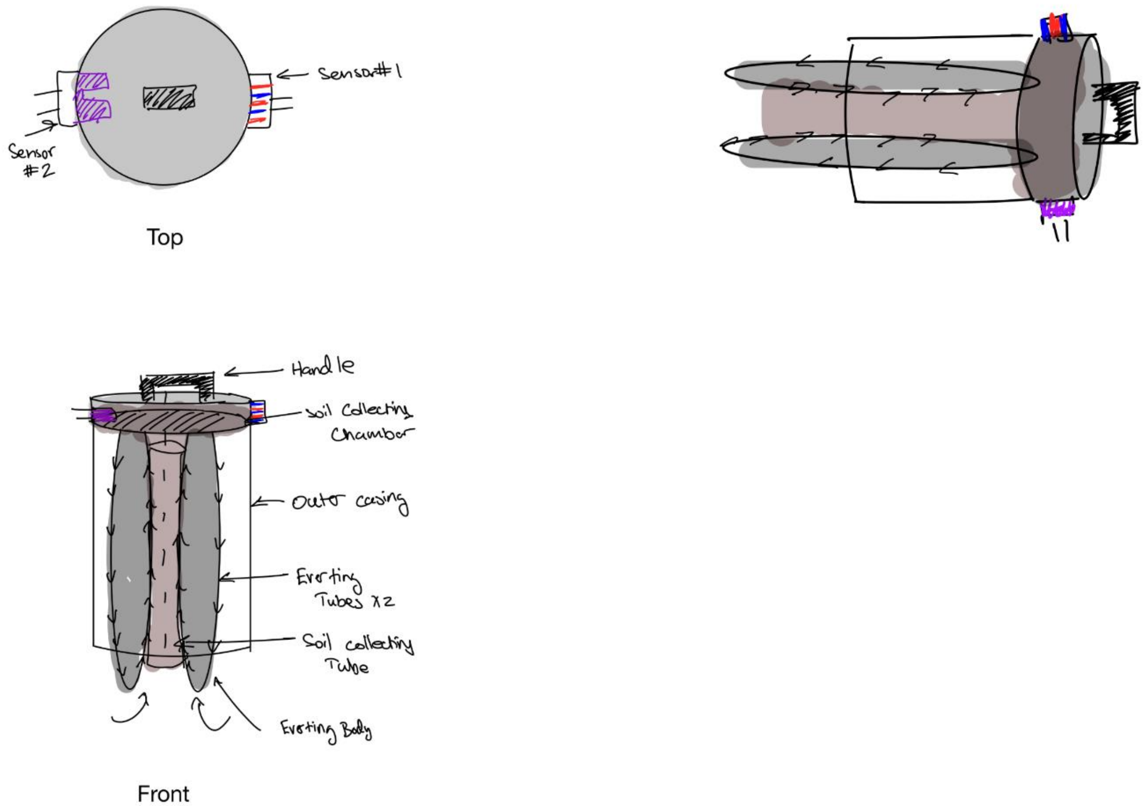


Figure 4: Design 1 Concept

The second concept design is a drilling robot, which utilizes a large drill head followed by an electronics and soil storage compartment which are encased above. Figure. 5 depicts the orientation and soil storage compartments of the device. This design requires the soil to be forced into holes in the drill bit. Payload is collected into a column chamber above and sensors are wall-mounted to provide quick data collection. Above the payload, there is storage for battery and electronics. Some aspects of the design are that it is more wear-resistant and easier and faster burrowing and ease of operation. Some cons of this design are that the drill collects samples and due to spinning the soil sample can be mixed. Additionally, using a using is relatively invasive and can disturb nearby soil arrangement.

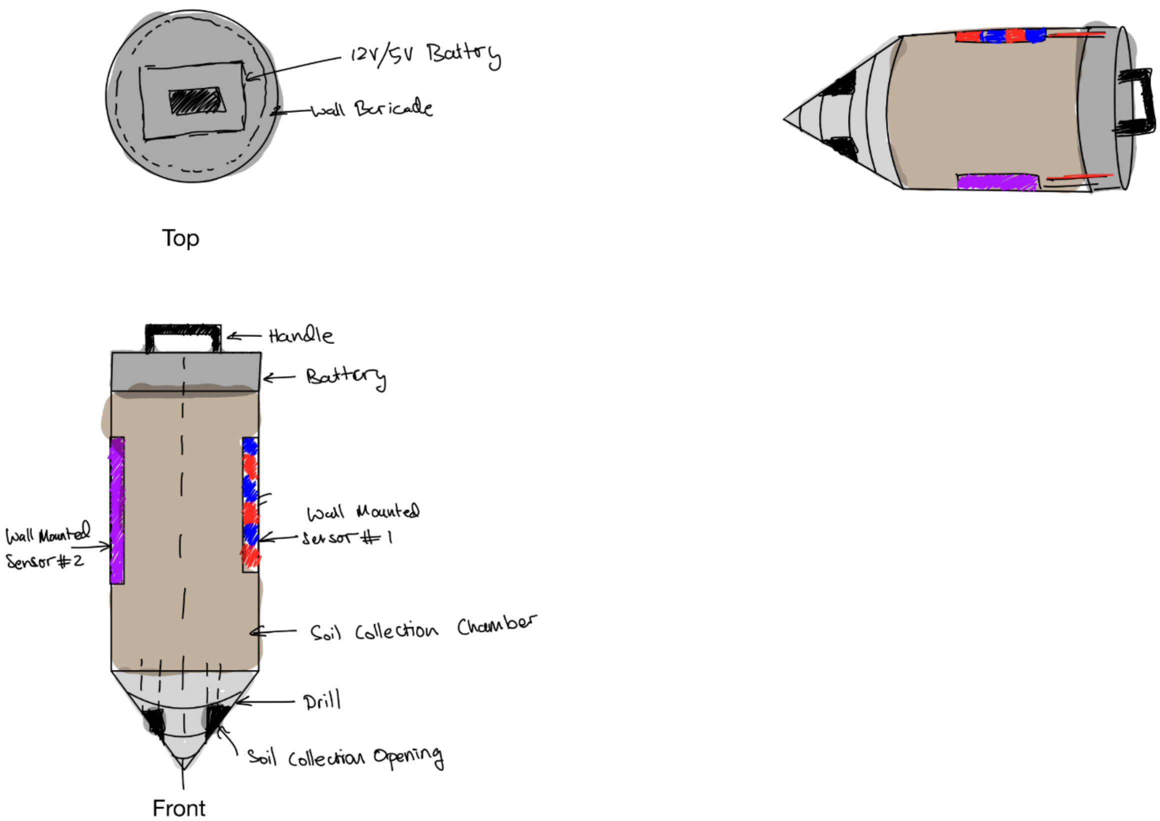


Figure 5: Concept Design 2

The third design uses a pinion and rack mechanism to dig precisely 18” into the soil ground. This operation is done through vertical force as described in later sections and provides an undisturbed and unmixed payload of soil for testing at different heights. The payload can be opened from the top as shown below in Figure 6. In this design, the payload does not contain any sensors, but an additional Data Acquisition System as seen in the design sketch. The purpose of this is to increase soil sample collection while maintaining the durability and portability aspects. The main ‘digging’ mechanism is done using a pinion and gear system. There are two 30 NM high torque motors selected to lower a payload that can be opened from the top chamber and additionally, a one-way valve on the bottom to allow one directional collection of the soil. The design also includes a foot placement to provide stability to the design, so the mechanism doesn't push up from the ground and a force is provided in the –y direction. Some advantages of this design are the ease of operation and the simplicity of the mechanism. Additionally, the parts utilized are commonly manufactured which helps in sourcing the material. Separating the sample and data collection also provides an easier assembly process. Some disadvantages of this design are that it requires high torque which requires higher power for the system, specifically 24V. The design will also need separate microcontrollers to separate the two systems. However, due to the simplicity and feasibility of the design, the pros outweigh the cons.

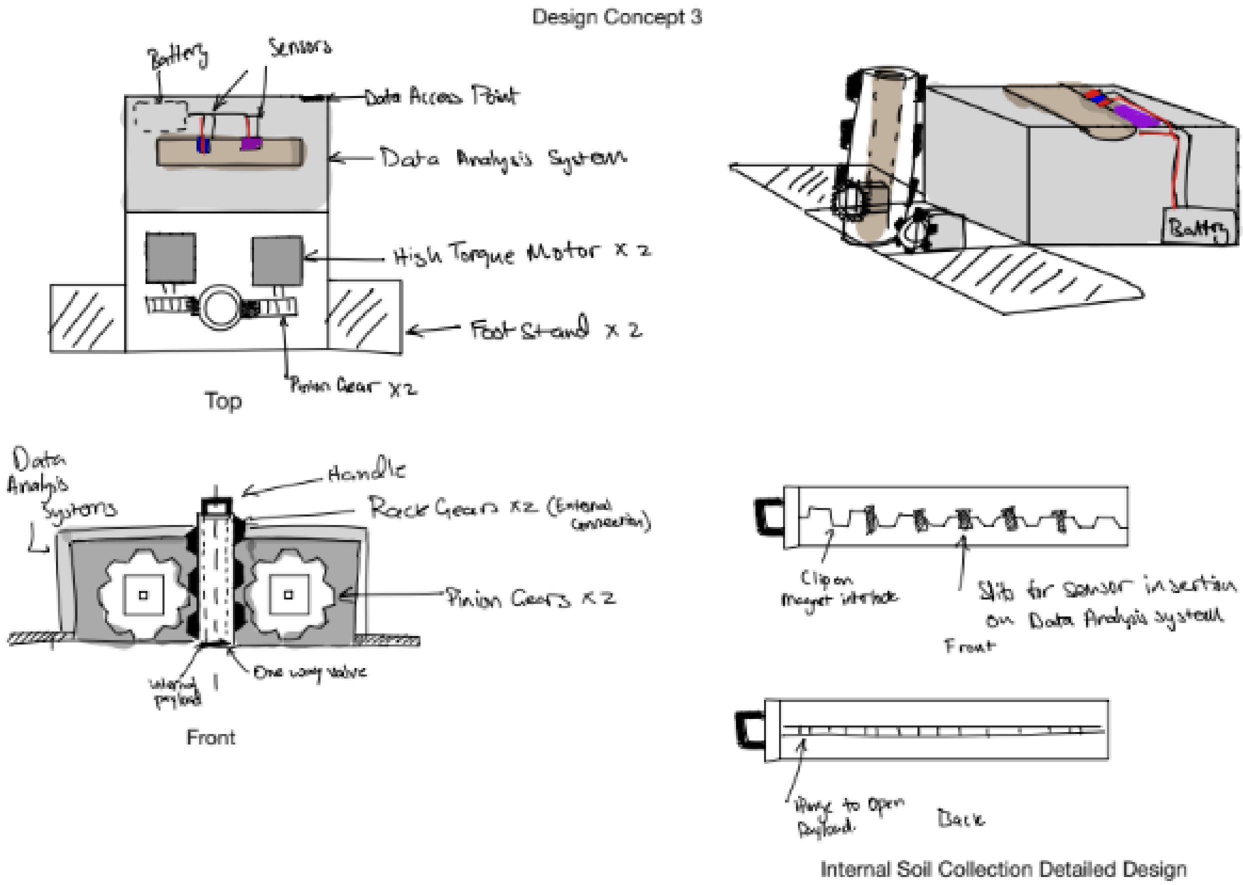


Figure 6: Concept Design 3

V. Patent Research

To demonstrate that our original design is distinct from existing patents, we conducted thorough patent research using Google Patents. We analyzed multiple patents related to soil extraction machines, identifying their key design elements, functionalities, and claims (Refer to Appendix A.2) While some existing patents feature automated soil sampling and lifting mechanisms, none incorporate our unique combination of a rack and pinion system specifically designed for stable vertical soil extraction, integrated with real-time multi-sensor analysis for material property assessment. Additionally, our design introduces a novel approach to electronic data collection that are absent in prior patents. By documenting these distinctions and ensuring that no single prior patent fully anticipates our design, we have confirmed that our invention offers a novel and non-obvious advancement in the field.

VI. Down-Selection & Rationale

The design process explored the three concepts outlined and sketched earlier. Based on the customer requirements and the importance of each requirement, the team settled on Concept 3 – a pinion-rack mechanism as the best approach. This design stood out from other concepts mainly due to its ability to excavate the soil without mixing which could potentially cause contamination between soil depths. The concept also maintained durability and was best suited to function in diverse soil conditions.

To make this decision, the team used a weighted decision matrix (Pugh's Method) to assess and compare each concept. The matrix considered key customer requirement metrics such as depth accessibility, accuracy, durability, cost, and ease of use, helping to narrow down the best option. Each customer metric also contained a weight based on the matrix provided which can be found in Table 1. The concepts were compared to a benchmark to determine whether they performed better or worse against each metric. To compare fairly against the benchmark, the intermediate product in the market, WintexAgro 1000 Soil Sampler, was selected. Since WintexAgro 1000 demonstrated an intermediate price, wasn't completely manual but also wasn't completely automated, and didn't have the data acquisition features, our team believed it provided a fair benchmark to evaluate. After comparing and analyzing the results, the hybrid auger-core (Pinion and Rack) mechanism scored highest across all categories.

While Concept 3 – Pinion & Rack System had scored the highest, each concept had its merits and flaws. Unlike traditional methods, which risk mixing soil layers, Concept 3 ensured that the samples remained undisturbed, offering more precise data. Additionally, Concept 3 proved to be more portable than Concept 2, which relied on a bulky drilling mechanism that made transport and operation more difficult. It also eliminated safety risks posed by the drilling process.

Concept 1, the Soil Robot, fell short in accuracy of soil sampling and required continuous operation, which limited its adaptability. Concept 2, the Drilling Robot, offered strong performance in real-time data and sampling accuracy but was hindered by its lack of portability and potential disruptions to soil layers caused by the drilling mechanism.

In the end, Concept 3's superior performance in sampling accuracy, portability, and ease of maintenance made it the ideal choice. It addressed the key challenges faced by current soil sampling methods while offering an innovative, cost-effective solution. The decision was clear: the hybrid auger-core sampling mechanism was the way forward for TerraProbe, promising a more efficient, safer, and affordable soil testing tool that would revolutionize soil analysis for agriculture and environmental research. Figure 6 above highlights the design. The respective weights and matrix values can be found in the Decision Matrix excel file attached to the Appendix.

VII. Preliminary Design Details & Analysis

After considering many designs for the prototype, a preliminary design was selected. The plan is based on a rack and pinion system, which drives a soil-collecting payload into the ground as seen in figures 7 and 8. The main base plate contains all the motors, gears, pinions, and electrical components to operate the device. The gear system increases the torque from the motor by 4x before driving the payload downward. Furthermore, ball bearings are implemented to support the axles that drive the rotational motion of the system. Attached to the sides of the base are two foldable foot pedals, which allow the user to apply their body weight as a downward force to help the machine burrow into the earth. On the top of the base compartment, there is a lid that can be removed to perform maintenance or clean the device. Ultimately, there will be a limit switch installed on the top of the base lid to stop the outer shell from driving too far downward.

The central penetration apparatus is comprised of two pieces: the inner payload and outer shell. The payload is a 20-inch-tall chamber with one-way doors at the bottom that allow soil to fill the space as the probe is pushed into the ground. This payload can be removed from the outer shell, which is the component that has the gear racks mounted to it. After the payload is removed from the shell, it can be probed for moisture, salinity, and temperature via the horizontal slots spaced intermittently along the vertical length of the chamber. In addition to the payload being tested in-field, it can be shipped off to a lab for further testing. The payload features a hinge that allows the structure to open in half, exposing the undisturbed soil sample. At the bottom of the outer shell, there is a 2:1 chamfer that allows the payload to slide into the dirt with ease. The data acquisition probe and test stand are not shown in the figures below, as their design is currently being investigated.

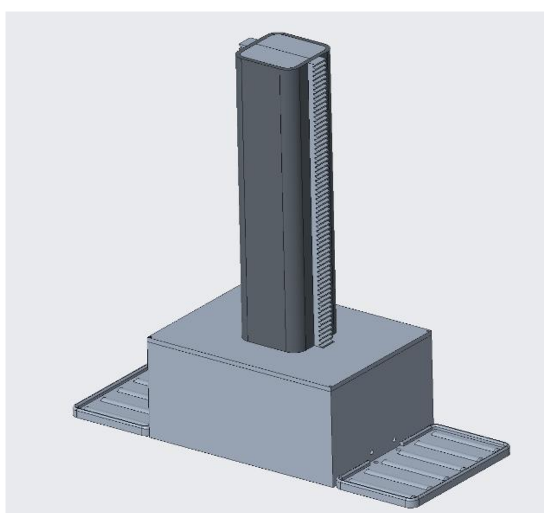


Figure 7: TerraProbe CAD Assembly

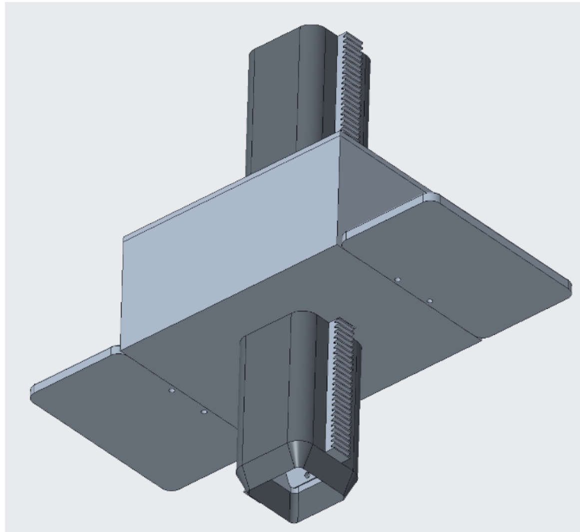


Figure 8: TerraProbe CAD Assembly Underside

Now that the team has a preliminary 3D design (Refer to Appendix A.3 for more details on the same), the mechanical work required to run the device to reach the required depth needs to be considered. First a free body diagram was drawn to determine all the forces that would act on the payload.

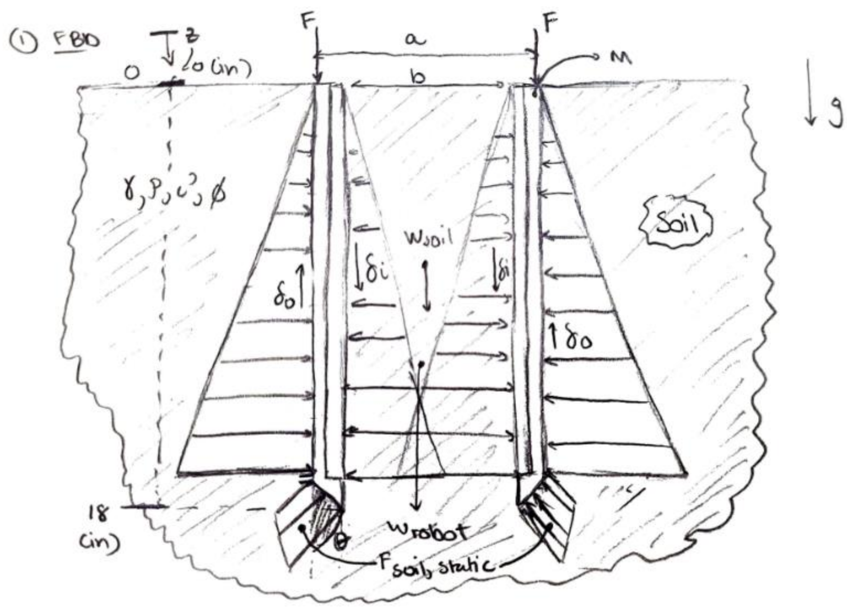


Figure 9: Free Body Diagram

Now the main forces are along the Z direction, and this will be the direction in which the rack will be provided force. The following Force balance equation can be used to determine the required force F.

$$\sum F_z = 2F + f_i + W_{robot} + W_{soil} - f_o \;\; - F_{soil_{static}} = (m + M)\ddot{z} \tag{1}$$

Where f_i is the internal frictional force, W_{robot} is the weight of the robot, W_{soil} is the weight of the soil collected, f_0 is the external frictional force, $F_{soil_{static}}$ force acting upwards modelled as a buoyancy force, m is the mass of the soil collected, M is the mass of the robot, and $\ddot{z}$ is the acceleration of the body

However, the frictional forces and desired motion profile are unknowns. To determine the frictional forces were calculated according to the Rankine Theory (Earth Pressure Theory and Application, Purdue University, n.d). Then a desired motion profile was created such that the robot would reach the required depth in 2 minutes The calculated required force ranges between 200-400 N for soft cohesive soils to medium stiff cohesive soils. (Refer to the Appendix A.3 to see the calculations).

To provide the same force, a 30 Nm which requires 24V can be used alongside a 1.17” outer diameter driver gear on each side. However, if the design need be implemented on more cohesive soil, a gear box can be used to increase the gear ratio and hence the torque provided to the system.

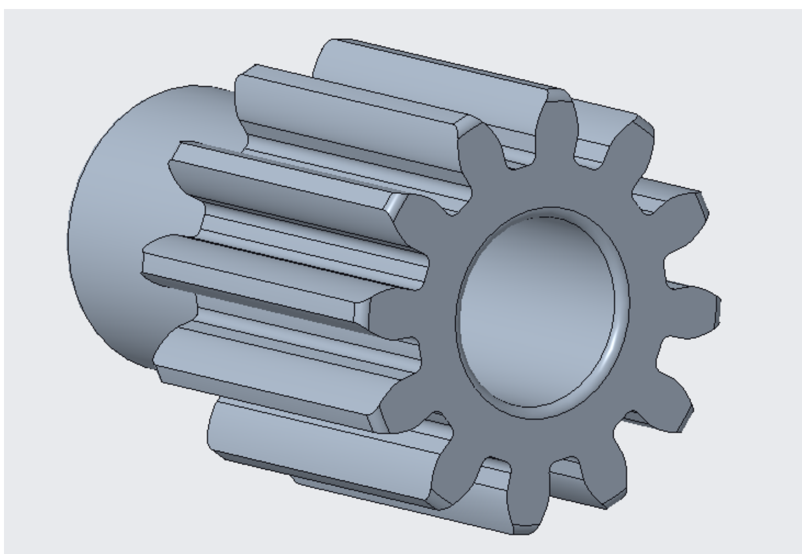


Figure 10: Driver Gear

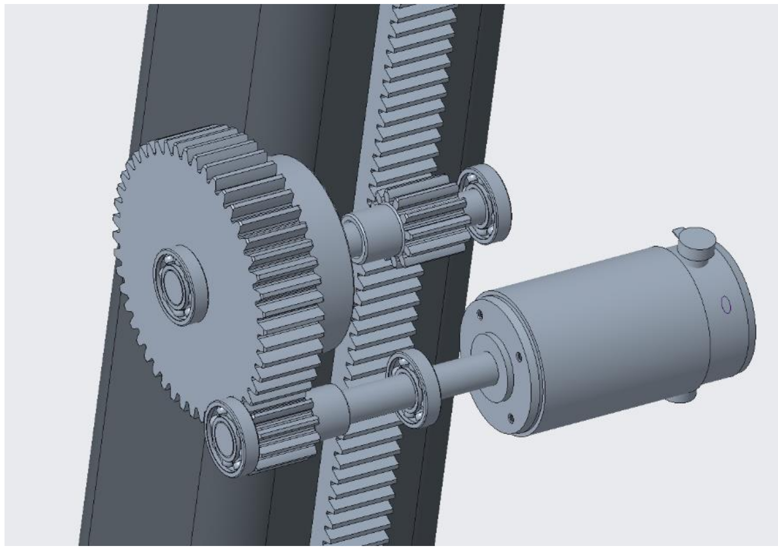


Figure 11: TerraProbe Gearbox Design

To gather data for analysis, the TerraProbe will come with a probe to stick into the extracted dirt column through the shaft slots. This probe is a combination of three common soil probes. The main base is the head of the Taidacent RS485 Soil Sensor. This sensor tests the nitrogen, phosphorus, and potassium content in the soil. On the top side of the Taidacent sensor, a HiLetgo temperature probe is attached via a collar. sensor. This sensor is made to be used with Arduino. This design is very preliminary and going forward will most likely change as we adjust our shaft design.

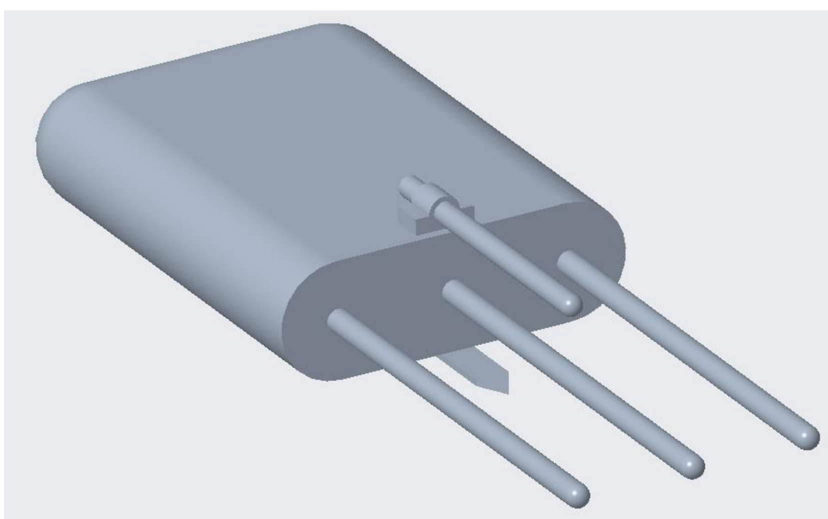


Figure 12: TerraProbe Sensor Probe Design

VIII. Project Feasibility & Risk Assessment

The TerraProbe presents several mechanical, electrical, operational, and environmental risks that must be addressed to ensure safe and efficient operation. Key risks include rack and pinion failure, system overloading, structural instability, machine tipping, and unexpected subsurface conditions, which could lead to mechanical breakdowns or safety hazards. Additionally, operator injuries, sensor malfunctions, electrical failures, and software errors pose medium to high risks that may compromise system performance and data accuracy. Environmental concerns such as soil contamination and noise pollution also require mitigation to comply with safety and regulatory standards.

To reduce these risks, several mitigation strategies should be implemented. Mechanically, reinforced materials, load monitoring systems, and stabilizing outriggers can improve structural integrity and prevent failures. The addition of automated safety interlocks, protective guards, and emergency stop mechanisms will help prevent operator injuries. Electrical and sensor-related risks can be mitigated by using redundant sensors, protective casings, and routine software updates to ensure operational reliability. Environmental risks can be controlled by implementing noise dampening materials, and proper disposal protocols for extracted soil.

Moving forward, a risk monitoring plan should be established, including regular maintenance checks, real-time system diagnostics, and user training on emergency response protocols. Conducting pre-operational safety audits, compliance reviews, and environmental impact assessments will further enhance reliability and legal adherence. By proactively managing these risks, the machine can operate safely, efficiently, and in compliance with industry standards. (Refer to Appendix A.1 for the Risk Register)

IX. Economic Analysis

As we are planning the engineering and design feasibility of TerraProbe, it is also important to identify the market size and assess the economics of TerraProbe. TerraProbe is strategically positioned as an intermediate-tier product, bridging the gap between low-cost, manual soil sampling tools and high-end, fully automated solutions that are often prohibitively expensive for small to mid-sized farms. With an estimated total production cost of $905.86 per unit, accounting for overheads, retail margin allocation, assembly, and manufacturing, we have set a competitive sale price of $1,500. This pricing strategy ensures a 65% gross margin while keeping TerraProbe accessible to a broad segment of the market that seeks advanced capabilities without the premium cost of high-end models.

The U.S. agricultural market consists of 1.8 million farmers, and based on a conservative 20% adoption rate, we estimate a potential market of 380,000 units. Our financial model assumes no sales in the first year, as this period will be dedicated to R&D and manufacturing setup, with an initial $10 million investment allocated to plant infrastructure and production readiness. Sales will commence in year 2, starting with 5,000 units, and scale rapidly doubling each year until reaching 380,000 units by year 8. Given our cost and revenue projections, we anticipate breaking even between year 3 and 4. The figure below shows the projected revenue and cost each year based on estimations on number of units sold.

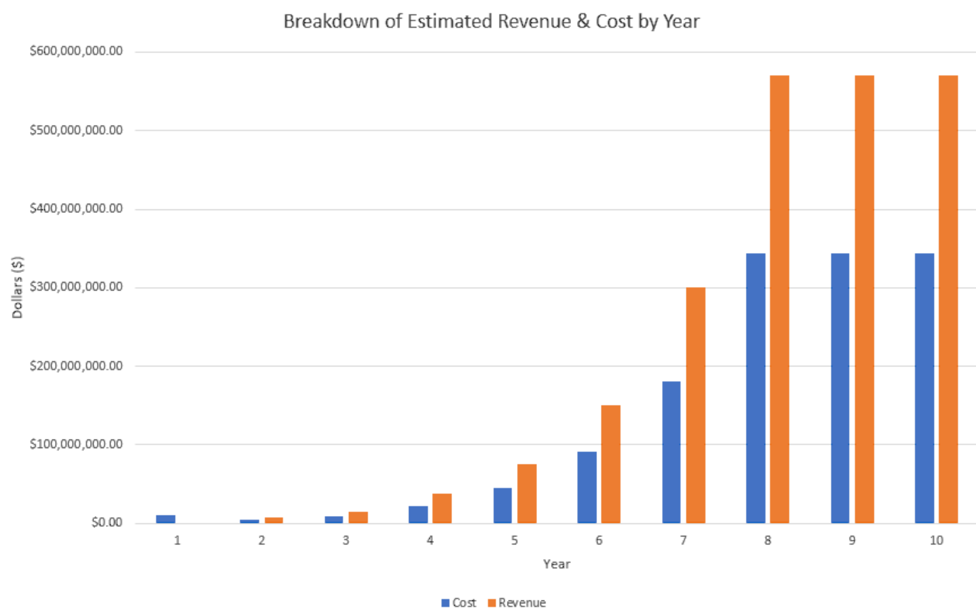


Figure 13: 10-Year Revenue & Cost Projections

At full market penetration, TerraProbe is projected to generate approximately $600 million in revenue, firmly establishing itself as a key player in the precision agriculture industry. This forecast is based solely on U.S. market potential, indicating substantial room for expansion into global markets and additional precision agriculture applications. By offering a cost-effective yet highly advanced solution, TerraProbe is well-positioned to redefine real-time soil sampling for farmers seeking affordability, efficiency, and data-driven insights. (Refer to Appendix A.1 for more)

X. Conclusion & Next Steps

The TerraProbe project addresses a significant gap in the soil sampling market by developing an innovative, portable solution for agricultural professionals, construction firms, and environmental researchers. By focusing on a pinion-rack mechanism design, the team has created a tool that offers accurate soil sample collection capabilities. The device stands out through its ability to collect samples up to 18 inches deep without soil layer contamination, real-time data analysis, and a competitive price point of $1500-$1800. Positioned within a global soil testing market valued at $5.5 billion and growing at a 10.4% CAGR, the design not only meets critical engineering requirements for portability, autonomous operation, and data integration but also provides a scalable solution that could potentially serve 360,000 units annually in the U.S. market alone. By delivering actionable insights on soil moisture, salinity, and temperature, TerraProbe is set to improve soil testing in agriculture, environmental monitoring, and land management.

The team is entering the refinement phase of the project, focusing on the specificity of all the choices made. The team will fine-tune the material selection and dimensions of the production prototype, ensuring they align with the performance requirements and manufacturing constraints. The existing technical analysis will be revisited and models updated to consider any recent changes or insights (such as considering the trade-offs between running at a constant speed or constant torque). The current Bill of Materials (BOM) will undergo a thorough review, with a focus on cost optimization and component availability. Refining the sourcing plan to ensure reliable and efficient procurement is crucial. The manufacturing process and design for assembly will be considered, incorporating any new information about production capabilities. The CAD model, will be improved to its final stages, incorporating all recent design decisions and tolerancing information where needed. Finally, the team will conduct a comprehensive re-evaluation of project risks and adjust our schedule as needed, ensuring the team remain on track.

APPENDIX

A.1 - Project Management

A. Charter (Attached as Project_Charter.xlsx)

PURDUE UNIVERSITY Mechanical Engineering

ME 463 Senior Design

Project Title: TerraProbe

Team Name: Down to Earth (D2E)

Team Members: Sankaran Iyer, Lokesh Sriram, Chris Meyers, Jacob McKenrick, Avie Ghatge

Vision Statement: Our vision is to revolutionize soil sampling and monitoring with an on-demand, portable, and labor/time efficient solution that delivers real-time analytics across different soil depths. TerraProbe should empower agricultural professionals and environmental researchers by providing accurate, data-driven insights to optimize crop yield, ensure soil stability, and enhance soil health management worldwide.

Problem Statement (Current State)

Soil sampling for agriculture, construction, and environmental research is labor-intensive, requires bulky equipment, and prone to contamination. Existing solutions are either manual, require significant time and effort, or are automated but bulky, expensive, and dependent on trained operators. Additionally, no current solution provides real-time soil analysis, as samples must be transported to laboratories for testing, delaying decision-making and increasing costs. There is a need for a portable, autonomous, and cost-effective soil sampling system that ensures accurate collection across multiple depth profiles and real-time analysis on salinity, mositure, NPK to improve efficiency and precision in soil assessment.

Key Stakeholders (Role, Influence, Interest)

External stakeholders in the TerraProbe project include agricultural professionals and environmental researchers. Agricultural professionals (e.g., farmers and agronomists) will use TerraProbe for unmixed precise and multi-depth soil sampling. This can help them identify soil properties through device's real-time data on moisture, salinity, and temperature that determine/optimize crop yield, manage resources efficiently, and implement precision agriculture practices. The size and portability of TerraProbe are key advantages for farmers. Given that the device is compact and lightweight (under 25 kg), it is easy to carry, transport, and deploy across diverse agricultural fields, including small to medium-sized farms, making it ideal for conducting multiple soil samples without the need for heavy machinery or complicated setup.

Business / Society Benefit (Future State)

We envision the TerraProbe Soil Sampling Robot to be a portable and small-sized solution designed to dig soil without mixing and separate soil at different depths. Using a pinion and rack system, we ensure accurate sampling up to 18 inches deep with three distinct intervals. Unlike traditional methods that are labor-intensive, expensive, and lack real-time insights, TerraProbe offers a compact (≤ 25 kg) and cost-effective (<$600 prototype) solution.The robot also integrates real-time data sensors for moisture (±5% accuracy), salinity (±5%), and temperature (±1°C), delivering instant analytics via a user-friendly dashboard or web app. TerraProbe should surpass manual tools by eliminating human effort/labor and reducing sample contamination. It outperforms existing automated solutions by combining portability, real-time data collection, and affordability in a single device. Users gain instant soil condition reports, enabling informed decisions in precision agriculture and environmental monitoring.

Project Scope

IN Scope	OUT of Scope
1) Designing, Prototyping and Testing of Portable Soil Sampling Robot capable of Autonomous Operation. 2) Integration of sensor and Data Aquisition System measuring real-time data for soil properties (mositure, salinity, temperature, NPK). 3) Development of a user-friendly dashboard or WebApp for data visualization. 4) Cost effective design and production prototype (under $600/unit)	1) Soil analysis beyond moisture, salinity, NPK, and temperature (ex. pH, nurtient levels) and advanced predictive analytics. 2) Diverse or extremely hard soil conditions (such as those suitable for construction land) 3) Mounting or attachment on vehicles

Key Milestones

Key milestones for the TerraProbe project include procuring essential materials, such as sensors, steel, and rack and pinion gears, followed by the manufacturing of the keyhole and casing. The next phase involves designing the DAQ system and dashboard to enable real-time data collection and visualization. Once completed, the assembly of the inner and outer casing, along with the integration of rack and pinion gears, will take place. Finally, the product will undergo rigorous testing across various soil types, including potting soil, soft clay, and hard dry soil, to ensure performance and reliability.

Key Assumptions & Risks

Key assumptions include that the pinion and rack system will generate sufficient force to navigate through soil types, particularly clay-like conditions, without compromising performance. Additionally, the stainless steel casing is expected to support the weight requirement while maintaining a lightweight design, crucial for portability. The system will also incorporate a separate handheld device for sensors, designed to be inserted into the soil, with the assumption that the soil conditions will generally be soft or clay-like for optimal sensor function. Risks associated with the project include potential issues with sensor accuracy, especially in varying soil types, and the possibility of sensor tip failure during use. Another risk is the challenge of competing with established market leaders who offer solutions for a wider range of soil conditions. Additionally, soil accumulation could impair the operation of the device over time, requiring frequent maintenance or design adjustments to ensure long-term reliability.

Team Members & Roles

Sankaran Iyer: Project Manager & Software Lead
Avie Ghatge: Electronics & Components Lead
Loki: Chief Engineer
Chris: CAD & Modeling Lead
Jacob: Sourcing, Materials & Design Lead

Key Resources Required

Machine Shop, E-Shop, Rack & Gear Assembly, Soil for Testing

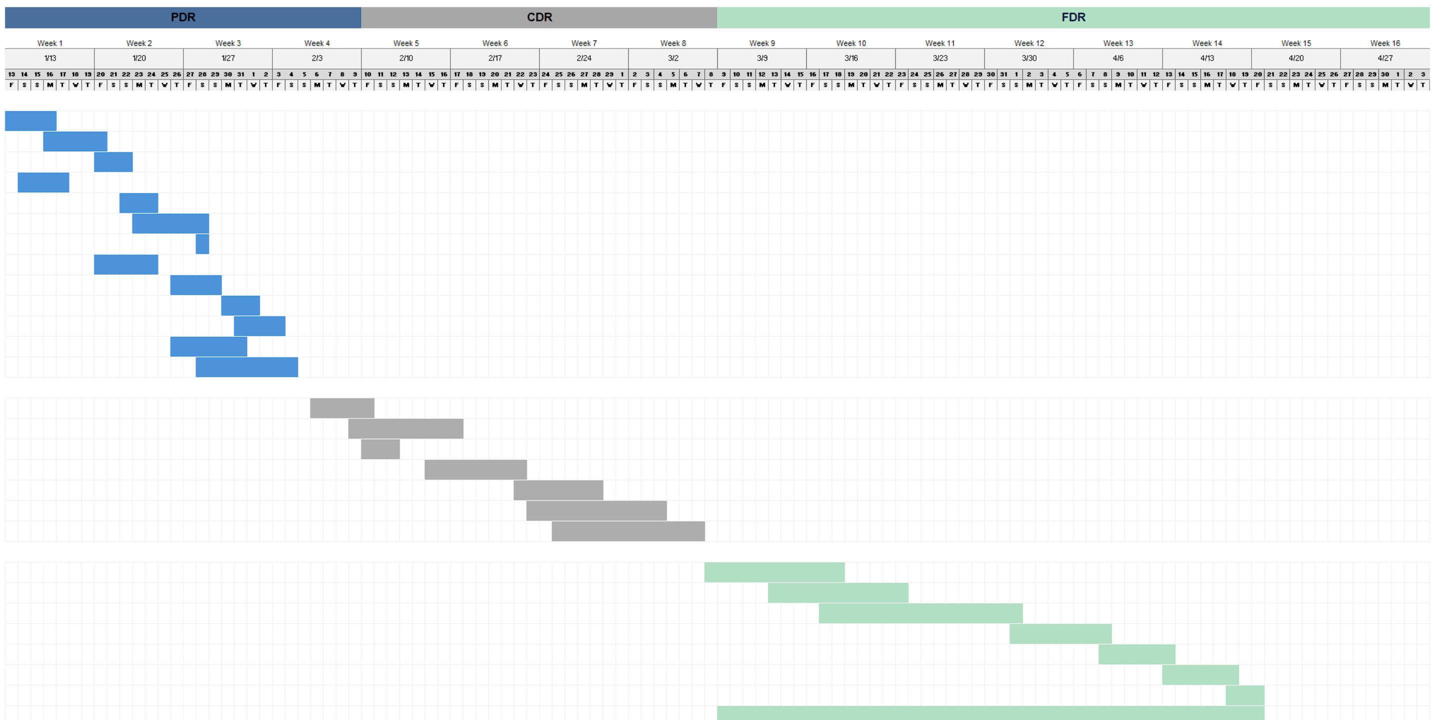
B. Schedule (Attached as Project_Schedule.xlsx)

A Down To Earth (D2E) Company

Project start: 01/13/25

Display week: 1

TASK	START	END
Preliminary Design Review - Initation		
Problem Definition	1/13	1/16
Market Analysis & Benchmark Research	1/16	1/20
Customer Requirements & Vision/Mission Statement	1/20	1/22
Member Roles & Resposibilities	1/14	1/17
Business/Engineering Specifications & Requirements	1/22	1/24
Concept Generation & Sketches	1/23	1/28
Down-Selection (Decision Matrix & HOQ)	1/28	1/28
Project Charter	1/20	1/24
Preliminary Materials List (BOM) & Budget	1/26	1/29
Economic Analysis	1/30	2/1
Initial Risk Register & FMEA	1/31	2/3
Assumptions & Free-Body Diagram	1/26	1/31
Preliminary CAD Model	1/28	2/4
Critical Design Review - Design		
Finalized Material & Dimensions of Production Prototype	2/6	2/10
Technical Analysis Inputs & Modeling	2/9	2/17
Finalized BOM & Sourcing Plan	2/10	2/12
Manufacturing Capabilities & Process Outline	2/15	2/22
Finalized Design & CAD Model	2/22	2/28
Re-evaluation of Risk & Schedule	2/23	3/4
Finalized Design & CAD Model	2/25	3/8
Final Design Review		
Purchase & Shipping of Parts	3/8	3/18
Detailed Manufacturing & Assembly Plans	3/13	3/23
Final Production Prototype Manufacturing	3/17	4/1
Final Production Prototype Assembly	4/1	4/8
Testing & Validation	4/8	4/13
Refine Prototype	4/13	4/18
Quality Check	4/18	4/20
Budget Management	3/8	4/20



C. Preliminary Budget

The preliminary budget can be found on Economic_Analysis.xlsx file attached.

Component #1 - ESP 32 Module/Arduino Uno	
Descripton	Main Controller Module
Vendor	Amazon
Retail Cost	$15.99
Units / yr	5000
Volumized % of Retail	80.00%
Part Cost	$12.79
Overhead	8.50%
Component Cost	$13.88

Component #2 - NPK Soil Sensor	
Descripton	Nitrogen, Phosphorous, Pottasium Sensor
Vendor	Amazon
Retail Cost	$20.29
Units / yr	5000
Volumized % of Retail	80.00%
Part Cost	$16.23
Overhead	8.50%
Component Cost	$17.61

Component #3 - Soil Moisture Sensor	
Descripton	Nitrogen, Phosphorous, Pottasium Sensor
Vendor	Amazon
Retail Cost	$8.68
Units / yr	5000
Volumized % of Retail	80.00%
Part Cost	$6.94
Overhead	8.50%
Component Cost	$7.53

Component #4 - Motors	
Descripton	DC 24V Electric Gear Motor 45W, Qty 2
Vendor	Walmart
Retail Cost	$98.00
Units / yr	5000
Volumized % of Retail	80.00%
Part Cost	$78.40
Overhead	8.50%
Component Cost	$85.06

Component #5 - Batteries	
Descripton	1 20V Dual Battery 1 12V Battery
Vendor	Amazon
Retail Cost	$61.97
Units / yr	5000
Volumized % of Retail	80.00%
Part Cost	$49.58
Overhead	8.50%
Component Cost	$53.79

Component #6 - Electrical Hardware	
Descripton	Buttons, Display Module, Wires
Vendor	Amazon
Retail Cost	$23.23
Units / yr	5000
Volumized % of Retail	80.00%
Part Cost	$18.58
Overhead	8.50%
Component Cost	$20.16

Component #7 - Temperature Sensor	
Descripton	Temperature Sensor Chip
Vendor	Amazon
Retail Cost	$9.99
Units / yr	5000
Volumized % of Retail	80.00%
Part Cost	$7.99
Overhead	8.50%
Component Cost	$8.67

Component #8 - Rack	
Descripton	Gear Racks, 1.125" Gear Pitch, Qty 2
Vendor	McMasterCarr
Retail Cost	$127.34
Units / yr	5000
Volumized % of Retail	80.00%
Part Cost	$101.87
Overhead	8.50%
Component Cost	$110.53

Assembly Time [hrs]		
Sub-Assembly 1 - Inner Tube	0.25	hr
Sub-Assembly 2 - Guidance System	0.75	hr
Sub-Assembly 3 - Sensor Probe	0.25	hr
Final Assembly	0.125	hr
Total Assembly Time	1.375	hr
Labor Rate	$60.00	/hr
Overhead	35.00%	
Component Cost	$111.38	

Component #9 - Waterproofing Plastics	
Dimensions	12" x 100' (30 Mil Thickness)
Vendor	Mainline Materials
Material	$202.26
Area Per Part [Feet]	2
Cost Per Feet	$2.02
Material Cost	$4.05
Machining/Cutting Hours	1
Labor Rate	$60.00
Labor Cost	$60.00
Material + Labor Cost	$64.05
Overhead	35.00%
Component Cost	$86.46

Component #10 - Steel	
Dimensions	
Volume	140
Material	Alloy Steel
Density [kg/in^3]	0.13
Weight [kg]	25.00
Cost / kg	$4.41
Material Cost	$110.25
Machining/Cutting Hours	0.25
Labor Rate	$60.00
Labor Cost	$15.00
Material + Labor Cost	$125.25
Overhead	35.00%
Component Cost	$169.09

Component #11 - Driver Gear	
Descripton	12 Teeth, 1.17" Carbon Steel Gear, Qty 4
Vendor	McMasterCarr
Retail Cost	$123.32
Units / yr	1000
Volumized % of Retail	90.00%
Part Cost	$110.99
Overhead	8.50%
Component Cost	$120.42

Component #12 - Pinion	
Descripton	Metal Gear - 20 Degree Pressure Angle, Round Bore with Set Screw, 24 Pitch, 48
Vendor	Amazon
Retail Cost	$79.86
Units / yr	1000
Volumized % of Retail	90.00%
Part Cost	$71.87
Overhead	8.50%
Component Cost	$77.98

Total Product Cost	Margin	Sell Price	Revenue
$852.6	65%	~$1400	$570M

D. Risk Register

The file Risk_Register.xlsx is attached to the document.

	1. IDENTIFICATION					2. CURRENT ASSESSMENT			3. TREATMENT		4. RESIDUAL ASSESSMENT		
	RAISE BY	DAT RAISI	CAUSE (IF_)	EFFECT (THEN_)	RISK OWNE	I		Current F Score	STRATE	TREATMENT DESCRIPTION			Residual Score
	The originator of the risk	*When the risk was first identified*	*If* ***uncertain event*** *occurs due to (or because of) specified* ***root cause(s).*** *Tip: ask "why, why, why..." to drill down to root cause*	*then the* ***ultimate impact*** *to our objectives are. Tip: ask "so what, so what, ..."*	*Single named owner*	*Probability of the event occurring*	*'Worst' impact*	*Calculated risk score*	*Select overall approach to treatment (Mitigate or Accept)*	*Summary of the treatment responses (actions, controls, fallbacks) that treat the risk.*	*Probability of the event occurring*	*'Worst' impact*	*Calculated risk score*
1	Jacob McKenrick	2-Feb-25	Machine tries to extract too much soil	Overloading lifting system		M	H	15	Mitigate	Factor of safety of 3.0 used in design for the rack and pinion system	L	H	11
2	Jacob McKenrick	2-Feb-25	Gear is improperly lubricated	Rack and pinion failure		M	H	15	Mitigate	Provide guide on how often, and how to lubricate gears in rack and pinion system	L	H	11
3	Jacob McKenrick	2-Feb-25	Soil gets lodged between teeth in the rack and pinion system	Rack and pinion jamming		H	M	14	Mitigate	Cover rack and pinion as much as possible with machine frame to prevent liklehood of soil jamming	L	M	6
4	Jacob McKenrick	2-Feb-25	Vibrations jeopardize structural integrity	Machine frame could damage or break		L	H	11	Mitigate	Could use stronger material resistant to vibrations	L	H	11
5	Jacob McKenrick	2-Feb-25	Wear on bearings	Bearing failure		M	M	10	Mitigate	Design bearings for a large factor of safety	L	M	6
6	Jacob McKenrick	2-Feb-25	Dirt, moisture, or calibration issues	Sensor malfunction		H	L	9	Accept	Operator can always test samples several times to reduce error	H	L	9
7	Jacob McKenrick	2-Feb-25	Short circuits or loose connections	Electrical Malfunction		M	M	10	Mitigate	Ensure connections are strong and stable. Prevent wires from being exposed.	L	M	6
8	Jacob McKenrick	2-Feb-25	Electomagnetic interference could influence data collection	Electrical Malfunction		L	M	6	Accept	Operator can always test samples several times to reduce error	L	M	6
9	Jacob McKenrick	2-Feb-25	Software errors	Incorrect Data Collection		L	L	1	Accept	Double check software during testing	L	L	1
10	Jacob McKenrick	2-Feb-25	Pinch points in rack and pinion system during extraction	Operator Injury		M	H	15	Mitigate	Added limit switches as an Estop for rack and pinion system. Added safety covers over pinch points	L	M	6
11	Jacob McKenrick	2-Feb-25	Instability of machine in soft soil	Machine could fall over		L	M	6	Mitigate	Foot pedals added for operator to stand on to add stability to design	L	M	6
12	Jacob McKenrick	2-Feb-25	Expelling of machine lubricant	Soil Contamination		L	M	6	Accept	Look for more environmentally safe lubricant, use proper amount of lubricant	L	M	6
13	Jacob McKenrick	2-Feb-25	Machine is loud	Noise Pollution		M	L	5	Accept	Look into noise reduction or lubricant	M	L	5

A.2 – Business / Marketing

E. Market Analysis

The global soil testing market is experiencing significant growth, driven by increasing demand for precision agriculture and environmental monitoring. Valued at $5.5 billion in 2023, the market is projected expand with a compound annual growth rate (CAGR) of 10.4% from 2023 to 2030 (Grand View Research, 2023). This growth is supported by various factors, including the rising need for sustainable agriculture practices, increasing environmental concerns, and the adoption of advanced testing technologies. The market can be segmented into three primary target areas: agriculture, construction, and environmental research.

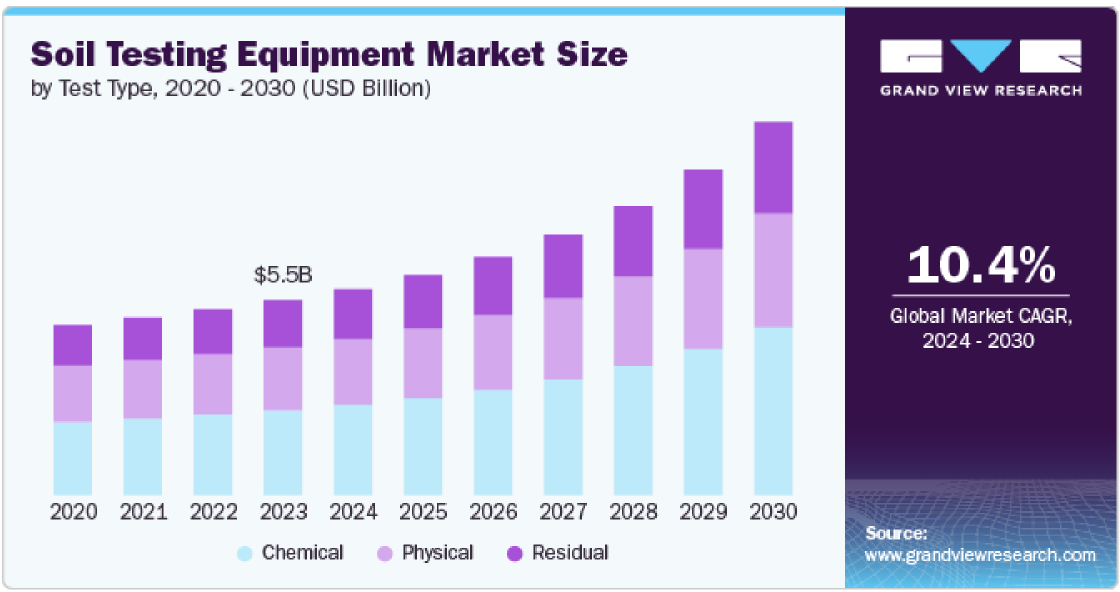


Figure 14: Soil Testing Market Projection

The agriculture sector shows promising growth potential, with the global smart agriculture market valued at USD 22.65 billion in 2023 and expected to grow at a compound annual growth rate (CAGR) of 13.7% from 2024 to 2030 (Grand View Research, 2023). This growth is driven by increasing automation in commercial greenhouses, implementation of controlled environment agriculture (CEA), and the adoption of advanced technologies such as IoT and AI in farming practices. Key players in this segment include AGCO Corporation, Deere & Company, and Trimble Inc., focusing on precision farming applications such as yield monitoring, field mapping, and irrigation management. The market is also seeing innovations in livestock monitoring, smart greenhouses, and the integration of technologies like drones, sensors, and data analytics to optimize agricultural processes and improve productivity.

In the construction sector, the geotechnical investigation market is valued at $5.22 billion annually in 2025 and expected to reach $8.65 by 2030 with a CAGR of 10.62% (Mordor Intelligence, 2023). Companies like Fugro, Geocisa, and AECOM are prominent in this space, addressing critical requirements such as foundation stability assessment, environmental impact evaluation, and site suitability analysis.

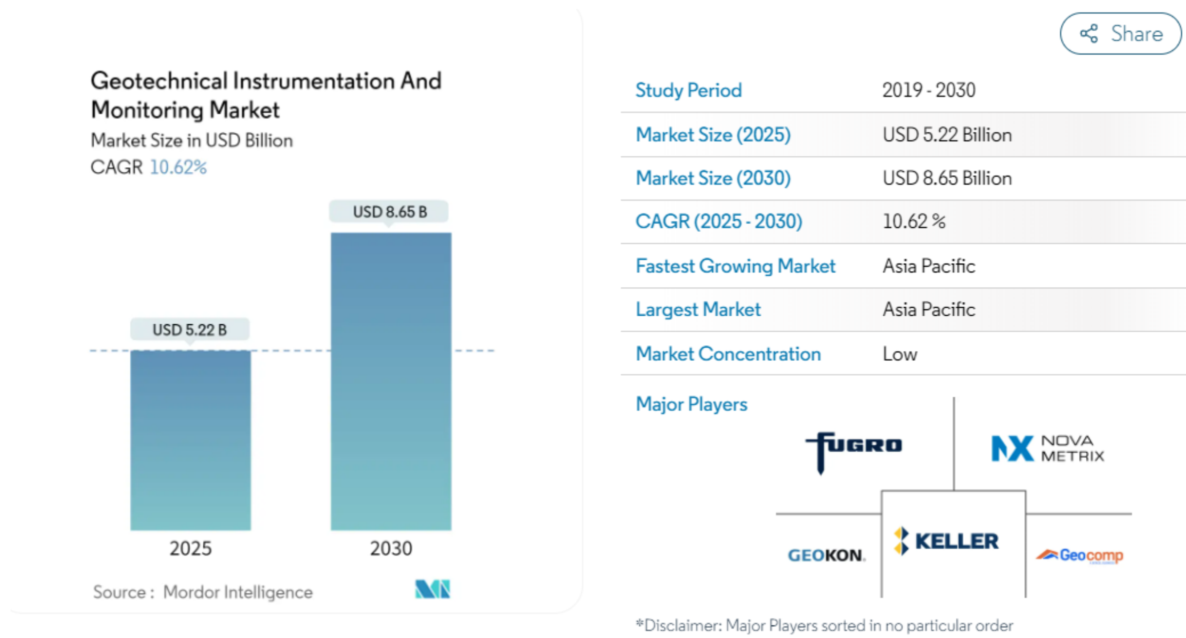


Figure 15: Geotechnical Instrumentation and Monitoring Market

The environmental research segment is driven by increasing climate change research and growing environmental monitoring programs, with organizations like NASA Earth Science Division, USGS, and the European Environment Agency leading efforts in soil carbon sequestration, contamination tracking, and ecosystem health monitoring (IPCC, 2022).

Despite the market's growth potential, there are several technological limitations and customer pain points to address in soil testing. Current soil testing methods often have limited accuracy due to sampling procedures, lack real-time data integration, and involve high operational complexities. Soil sampling can be time-consuming and requires careful consideration of factors such as sampling depth, pattern, and timing (University of Massachusetts Extension ,n.d.)

To enter this market effectively, a focus on the precision agriculture segment, particularly targeting small to medium-sized farms (50-500 acres), could be a strategic approach. Pricing strategies could include an initial unit price of $1500-$1800, complemented by sales of additional soil collection tubes. Distribution channels may include agricultural equipment dealers, online direct sales, and presence at agricultural technology conferences. Potential revenue streams for new entrants in this market include product sales, additional parts services, maintenance contracts, and custom research and development partnerships. To stand out in this competitive landscape, we plan to focus on developing a solution that offer real-time data collection, autonomous operation, compact and portable design, and lower costs compared to existing solutions.

However, potential challenges in market entry include technology adoption barriers, initial high development costs, regulatory compliance in different markets, and competition from established players. Stakeholders in this market ecosystem include internal entities like D2E, our team, and Purdue University professors, as well as external parties such as farmers, soil scientists, chemists, construction workers, land surveyors, and geotechnical engineers. Government agencies like the Department of Natural Resources, USDA, EPA, and Global Soil Partnership also play crucial roles in shaping the industry landscape (USDA Economic Research Service, 2023).

In conclusion, the soil testing market presents significant opportunities for growth and innovation, particularly in addressing current technological limitations and customer pain points. Companies that can develop cost-effective, efficient, and user-friendly soil testing solutions stand to capture a significant share of this expanding market.

Customer Analysis and Market Strategy

Current technological limitations in the field present several significant challenges, including a restricted depth range for sampling, inadequate real-time data integration capabilities, and high operational complexity that requires specialized training and expertise. These technical constraints have created substantial barriers to widespread adoption and efficient implementation.

Customer experience has been particularly impacted by the time-intensive nature of manual sampling, which requires 2-4 hours per acre to complete. This is further complicated by the high margin of error in traditional methods, with sampling errors ranging from 30-40%. Additionally, the substantial equipment costs have made it difficult for smaller operations to adopt these technologies, while the limited capacity for real-time data analysis prevents users from making timely, data-driven decisions in the field.

The initial target market focuses on the precision agriculture sector, specifically targeting small to medium-sized farms ranging from 50 to 500 acres. The pricing strategy has been structured to be competitive and accessible, with initial unit prices set between $600-1000, complemented by subscription-based data services for ongoing support and analysis.

The distribution strategy will utilize multiple channels to reach potential customers, including established agricultural equipment dealers, direct online sales platforms, and presence at agricultural technology conferences. This multi-channel approach ensures maximum market penetration and accessibility for customers.

Revenue generation will be diversified across several streams, including direct product sales, data subscription services priced between $50-200 per month, maintenance contracts for ongoing support, and custom research and development partnerships with agricultural institutions and technology companies. This diverse revenue model ensures sustainable growth while providing value at multiple customer touchpoints.

Benchmark Research

Table 2: Customer Requirement Comparisons of Benchmark Products

Customer Requirements	AMS Soil Probes 	WintexAgro 1000 Automatic Soil Sampler 	Amity Technology Soil Sampler 
Portability & Lightweight Design	Weight: ~1 to 3 lbs Length: ~33 inches Portable	Weight: ~48 kg, 105 lbs Length:	Weight: ~210 lbs Length: 36”
Autonomous Operation	No, Manual Operation	Designed for vehicle mounting, portable with vehicle. Semi-automated sampling when mounted on vehicle	Designed for vehicle mounting, portable with vehicle. Semi-automated sampling when mounted on vehicle
Accurate Multi-Depth Soil Sampling	Up to 24” in 3” increments	Up to 30 cm or 11.8”	24” to 48”
Integrated Real-Time Data Analysis	No	No	Yes, but might not be real-time
Cost-Effectiveness & Affordability	$100-150	Price not publicly listed, reports mentioned $8000	$3000-$6000
Durability for Diverse environments	Yes, Stainless Steel construction	Yes Designed for different soil types and conditions.	Yes
Low Maintenance	Yes, Simple design with minimal maintenance needs	No, requires heavy maintenance, such as components that might need to	Maybe, requires standard maintenance, such as components that might need to be

		be replaced and repaired rom time to time	replaced from time to time
Depth Accessibility	Yes	Yes, adjustable depth	Yes
Dashboard or WebApp for Analytics	No digital integration	No	Yes, partners with FARMQOA controller for cloud-based data and testing systems.
Differentiated Soil Depth Sampling	No, manual operation limits precise depth differentiation	No, multiple operations must be performed at the same location	Yes, higher level models available with multiple depth settings

Comparison of Benchmark Products to Terra Probe

1) **Alignment with Problem Definition**:
   - Existing products partially address the need for efficient soil sampling and collection but fall short of delivering real-time analytics, multi-depth sampling, and soil mixing.
   - **AMS Soil Probes**: Simple manual tools, effective for basic sampling but lack depth accessibility, automation, and data integration capabilities.
   - **Wintex 1000**: Provides automation for shallow soil sampling but is limited to 30 cm depth and does not include real-time data analysis or visualization.
   - **Amity Technology Soil Sampler**: High-end automated sampling equipment capable of reaching greater depths (up to 48 inches) but lacks portability, affordability for small-scale users, and integrated real-time data analysis.

2) Key Differentiators of Terra Probe**:**
   a. **Portability**: While AMS soil probes are portable, the advanced automation of Terra Probe combined with portability (≤ 25 kg, compact design) makes it unique.
   b. **Automation**: Terra Probe integrates fully autonomous operations, bridging the gap between manual tools like AMS probes and semi-autonomous systems like Wintex 1000.
   c. **Depth Accessibility**: Unlike Wintex 1000's shallow sampling limit, Terra Probe will achieve multi-depth sampling (up to 1 meter) with precise depth differentiation.
   d. **Real-Time Data Analysis**: None of the benchmark products feature integrated sensors for moisture, salinity, and temperature or real-time data visualization, a key strength of Terra Probe.
   e. **Cost-Effectiveness**: Terra Probe targets an affordable unit cost (prototype < $600) with low operational costs, making it accessible to small-scale users compared to Amity Technology and Wintex 1000.

f. **User-Centric Design**: Terra Probe incorporates a dashboard/WebApp for advanced analytics, providing actionable insights to users in real time, an area entirely unaddressed by existing products.

3) **Summary**: The Terra Probe addresses critical gaps in existing soil sampling solutions by combining portability, affordability, autonomous multi-depth sampling, and real-time data analytics in a single, compact design. This positions Terra Probe as a transformative tool for agricultural professionals, environmental researchers, and construction firms to make data-driven decisions efficiently and sustainably.

Patent Research

Below are four patents researched, each different than our original idea:

The first patent, US7827873B2, is a soil sampling apparatus that also uses a punching method like the TerraProbe, however, this patent is a device that is attached to a tractor. While this patent can collect several samples, it involves owning heavy machinery already.

The second patent, CN110470507B, is like the WintexAgro mentioned in the previous section, as a cart that collects soil. This patent aims to be able to collect soil samples while being mobile. This device uses wheels on a cart as a method of mobility, whereas our design uses its lightweight design to ensure mobility.

The third patent, EP1895090B1, is a patent for a method for creating a hole in the ground. This patent uses a bore similar to an augur to drill, whereas our method used a rack and pinion system.

Finally, patent US11076525B2 is a self-propelled seed planter. This seed planter penetrates the ground using a spring. This seed planter also uses wheels for mobility like the second patent researched. The TerraProbe is different than this design in both ways by using a rack and pinion system and lightweight materials.

F. Value Propositions & Economic Analysis

The product's unique selling points center on several key innovations that address current market gaps. Its ability to collect data in real-time represents a significant advancement over traditional methods, while its autonomous operation capability reduces labor requirements and human error. The design emphasizes compactness and portability, making it easily transportable between locations and suitable for various field conditions. These features are offered at a lower price point than existing solutions, making advanced soil analysis more accessible to a broader range of users.

However, several potential challenges need to be carefully considered and addressed. The agricultural sector traditionally faces technology adoption barriers, particularly among established farming operations with existing methodologies. The development phase requires substantial initial investment to ensure product reliability and effectiveness. Additionally, navigating regulatory compliance across different markets presents complexity, particularly regarding autonomous operation and data collection standards. The presence of established players in the market with strong brand recognition and existing customer relationships poses another significant challenge to market entry and adoption.

An economic analysis excel document is attached which provides a detailed economic analysis of TerraProbe, including cost breakdown, revenue projections, and return on investment (ROI). The findings highlight the financial feasibility and long-term benefits of implementing TerraProbe in real-time environmental data collection.

1) Cost Breakdown
    a. The total development and operational costs for TerraProbe were estimated and distributed as follows (Detailed breakdown and description of each part can be found on the attached file Economic_Analysis.xlsx):
        i. Hardware Costs: Approximately $538.93 per unit, covering sensors, microcontrollers, and communication modules.
        ii. Manufacturing & Assembly: Production costs amount to $366.92 per unit.
        iii. Operational Expenses: Recurring costs, including data storage, maintenance, and software updates were factored into the hardware, manufacturing, and assembly costs as overheads.

2) Revenue Model & Market Viability
    a. Based on market analysis and projected demand, TerraProbe is expected to generate revenue through the following models:
    b. Sales Model: Selling units at $1500 per device, with an estimated market penetration of 20% in the first 10 years. Given a total production product cost of $905.86 and a desired gross margin of 65%, this helps us at $1500.
    c. We estimate no production during the first year and will start with 5000 units in the second year, doubling each year until we capture 20% of the farmers market which is roughly 380,000 units. The figure below shows the projection for the number of units we expect to sell for each year.

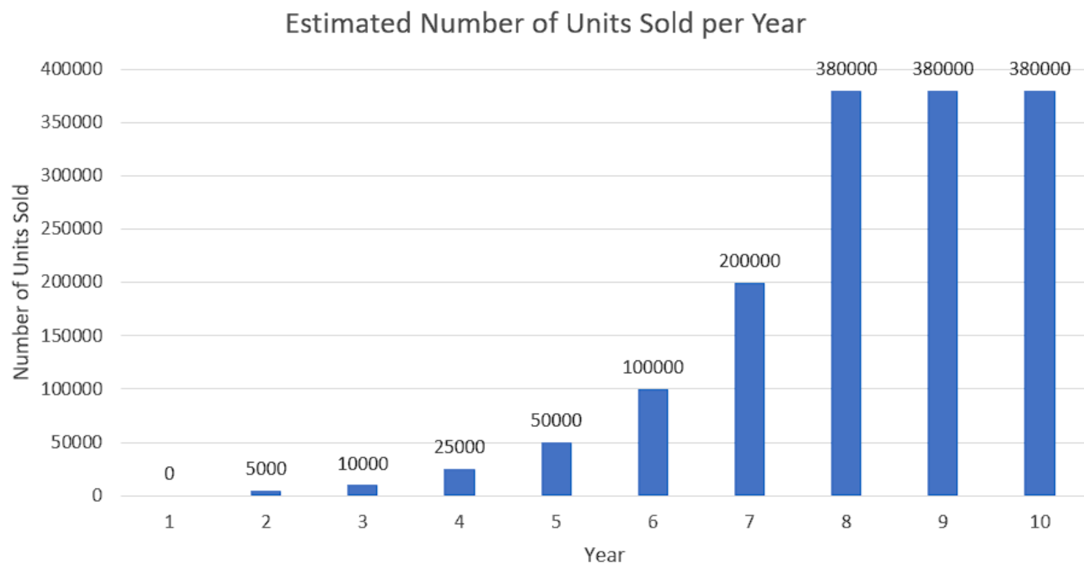


Figure 16: 10-Year Projection Number of Units Sold

- Cost Savings & Efficiency Gains: Given production at bulk, many parts can be bought at volumized quantity and prices, providing around a 10% advantage on cost savings. With the number of estimated units sold and the production cost at $905.86, the figures below shows the projected cost and revenue each year along with the respective profit.

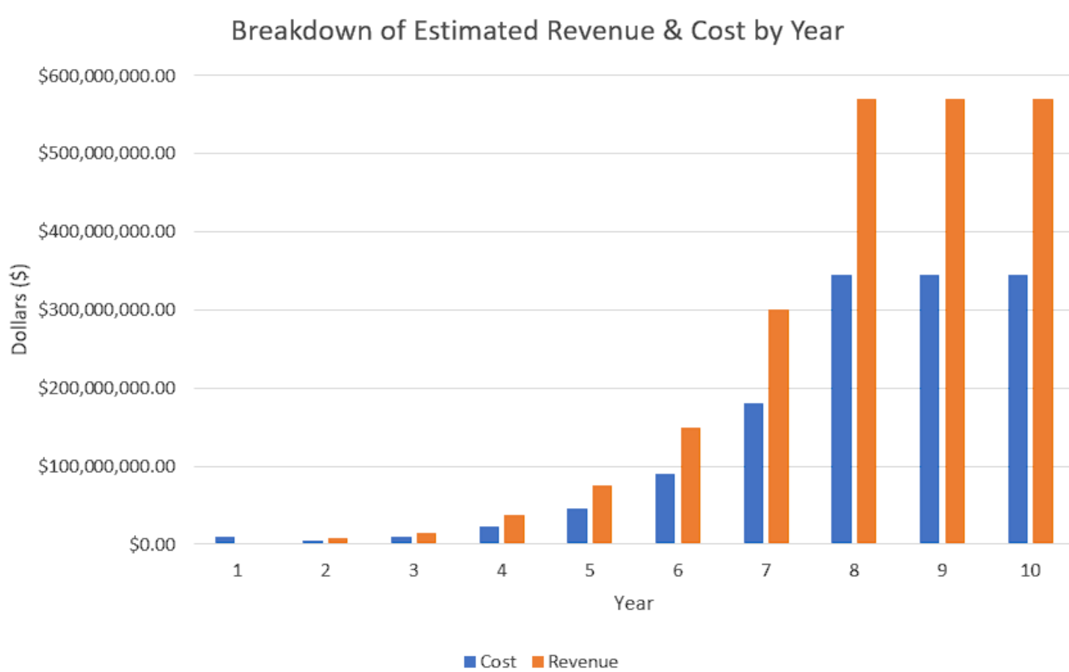


Figure 17: 10-Year Projection of Revenue and Cost

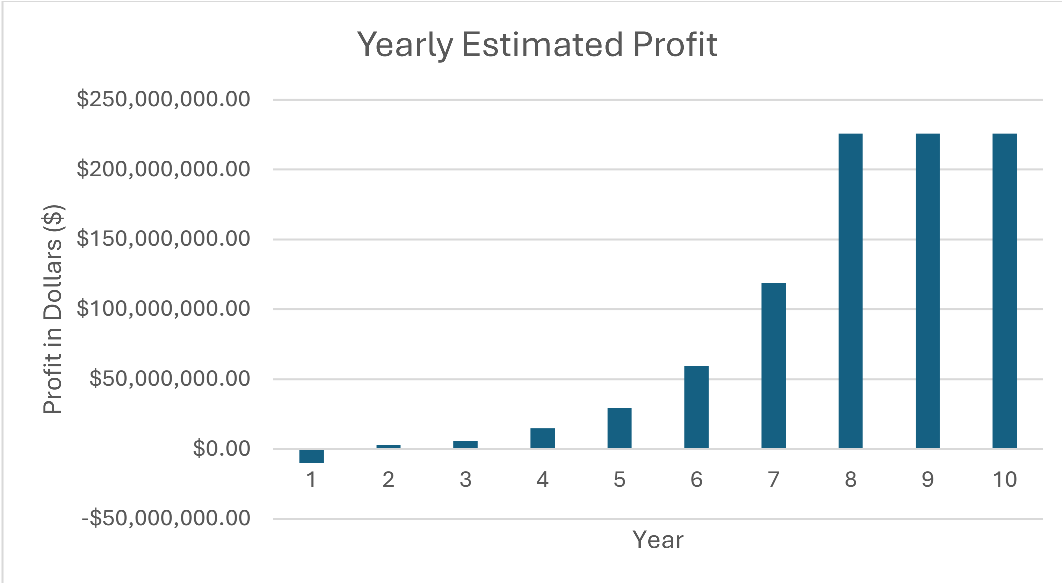


Figure 18: 10-Year Projection of Profit

3) Return on Investment (ROI) & Payback Period
    a. Breakeven Time: Based on initial investment and revenue projections, the breakeven point is estimated at ~3.5 years.
    b. Projected ROI: Over a 10-year period, the return on investment is expected to reach 64%, assuming steady market growth and adoption rates. The figure below shows the year-by-year ROI. As the number of units sold increases, the ROI increases as well.

Figure 19: 10-Year Projection of Return On Investment (ROI

A.3 – Design Process

G. Engineering Requirements & Constrains

Product Goals:

- Deployment: Carried and placed at the desired location.
- Operation: Burrows autonomously to target depths, collects samples, and analyzes properties in real time.
- Output: Provides instant soil condition reports via an integrated app or display.

Customer Requirements (CRs):

- Portable and lightweight design
- Operates autonomously with minimal supervision.
- Accurate multi-depth soil sampling.
- Integrated real-time data analysis: Moisture, Salinity, Temperature sensors
- Cost-effective and affordable
- Durable for diverse environments (terrestrial and extraterrestrial).
- Low Maintenance (cleaning and storage features)
- Access 1 meter in depth
- Differentiate between multiple soil depths (at least 3 intervals)
- Dashboard or WebApp for Advanced Analytics
- Autonomous operation

Engineering Requirements (ERs):

1) Portability and Lightweight Design:
   - Total weight ≤ 25 kg to ensure portability and ease of handling.
   - Dimensions not exceeding 23” W x 20” D x 14” H for easy transport and storage.
2) Autonomous Operation:
   - Capable of operating autonomously with minimal human intervention for at least 2 hours of continuous operation.
3) Accurate Multi-Depth Soil Sampling:
   - Ability to burrow and collect soil samples up to a depth of 0.5 meter ± 0.05 m.
   - Sampling accuracy of ≥ 85% for soil retrieval across different depths.
4) Integrated Real-Time Data Analysis:
   - Sensors capable of measuring:
     1) Moisture: Accuracy of ±5%.
     2) Salinity: Accuracy of ±5%.
     3) Temperature: Accuracy of ±1°C.
   - Data processing and visualization in under 30 seconds via integrated software.

5) Cost-Effectiveness and Affordability:

- Prototype development cost not exceeding $600 per unit.
- Operational cost of <$1 per sample collected.

6) Durability for Diverse Environments:

- Operable in temperatures ranging from 0°C to 50°C.
- Water-resistant and capable of functioning in soils with varying moisture levels (0-100% saturation).

7) Low Maintenance:

- Designed for easy cleaning, with removable and washable parts.
- Minimal storage requirements, with maintenance intervals >100 hours of operation.

8) Depth Accessibility:

- Ability to distinguish between and collect samples from at least three distinct depths (e.g., 0-30 cm, 30-70 cm, 70-100 cm).

9) Dashboard or WebApp for Advanced Analytics:

- Provides a user-friendly interface for viewing real-time and historical data.
- Compatibility with mobile and desktop devices using industry-standard software protocols.

10) Differentiated Soil Depth Sampling:

- Mechanism to analyze and record soil properties (moisture, salinity, temperature) for individual depth intervals with ≤10% error in differentiation.

11) Autonomous Operation:

- Fully automated navigation, sampling, and data transmission, requiring no more than 5 minutes of setup time.

H. Concept Sketches

Design 1:

- Soft robot
- Everting system with pressurized tubes
- Central payload to carry the soil back up
- Sensors on the walls of the payload to conduct live data acquisition
- Tow rope on the tail to retrieve the robot from underground
- Pros:
  - More flexible design
  - More novel design
  - Relatively lightweight due to soft robotics materials
  - Could be improved in the future to shift directions other than just up or down
- Cons:
  - Requires pressurized gas to operate
  - Low fatigue like compared to steel/gear systems due to fiber materials used
  - Complex operation – may need extensive training to properly operate and fix
  - Everting system can get jammed with dirt/gravel
  - Current everting systems are used in different applications than this
  - Tow rope is unnecessary and bulky

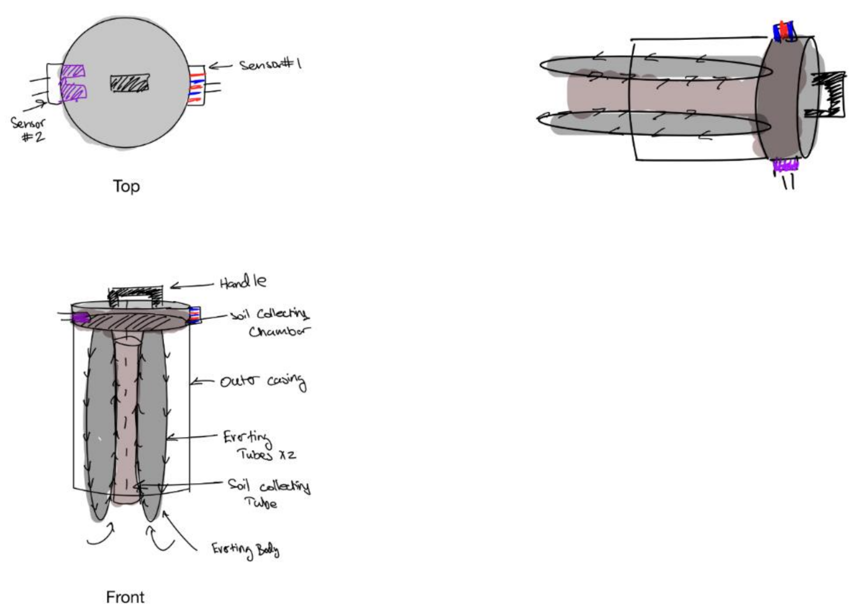


Figure 20: Design 1 Sketches

Design 2:

- Drilling robot
- Robot that shoves payload into soil but in this case main driving force is the drill
- The drill bit would have holes to allow the soil to collect in the payload
- Payload is collected as one continuous column
- Similarly, the payload would have the sensors inside It
- Pros:
    - More wear resistant
    - Easier and faster burrowing
    - Easy operation
- Cons:
    - Drill spoils collected samples particle organization
    - Drill ruins is relatively invasive, could disturb nearby soil arrangement too
    - Drill bit would require large motor and battery to be used
    - If the drill bit is damaged, the machine is inoperable

The second design considered was a drilling robot, which had a large drill head followed by the electronics and soil storage compartments which trailed behind. Figure 21 illustrates the orientation of the mechanical and electronic components. To gather soil, the robot would protrude hollow cylindircal cores from the soil collecting chamber to get

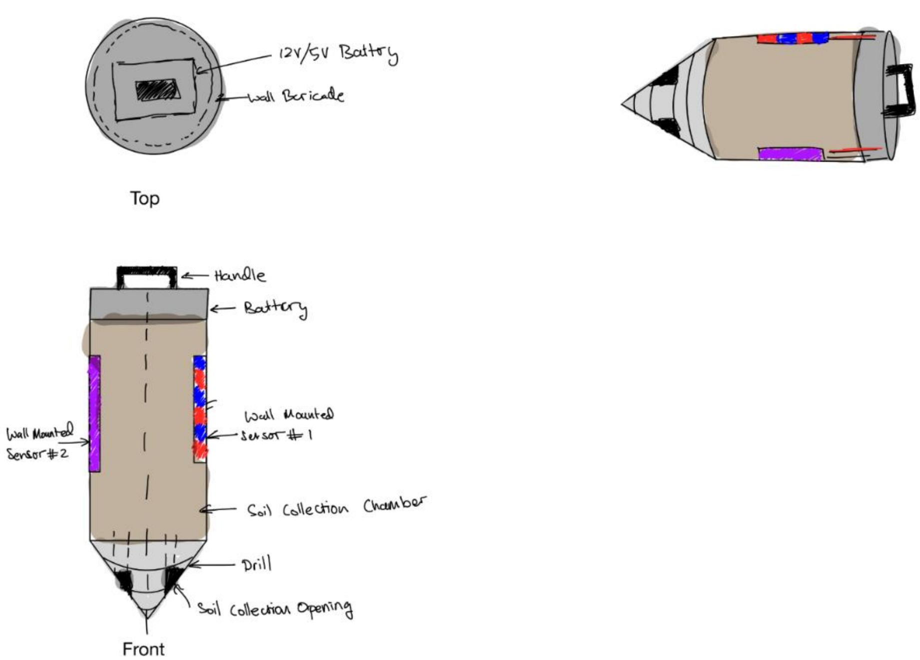


Figure 21: Design 2 Sketches

Design 3:

- Anchor and Simultaneous collection robot
- Uses a pinion and rack mechanism to collect undisturbed soil core
- Motors will be the main driving force
- Lowers a payload which can be opened
- Payload does not contain any sensors but contains slits to insert sensor probe
- Sensor probe is a holdable device which has sensors at fixed intervals along its length
- It would have foot holds to counteract the normal force
- Pros:
    - Easy operation
    - Simple mechanism
    - Commonly manufactured parts is the main driving force
    - Separates sample and data collection – simplifying design and assembly process
- **Cons:**
    - Requires high torque
    - Requires large amount of power
    - Would require 2+ microcontrollers as data and soil acquisition are now separate

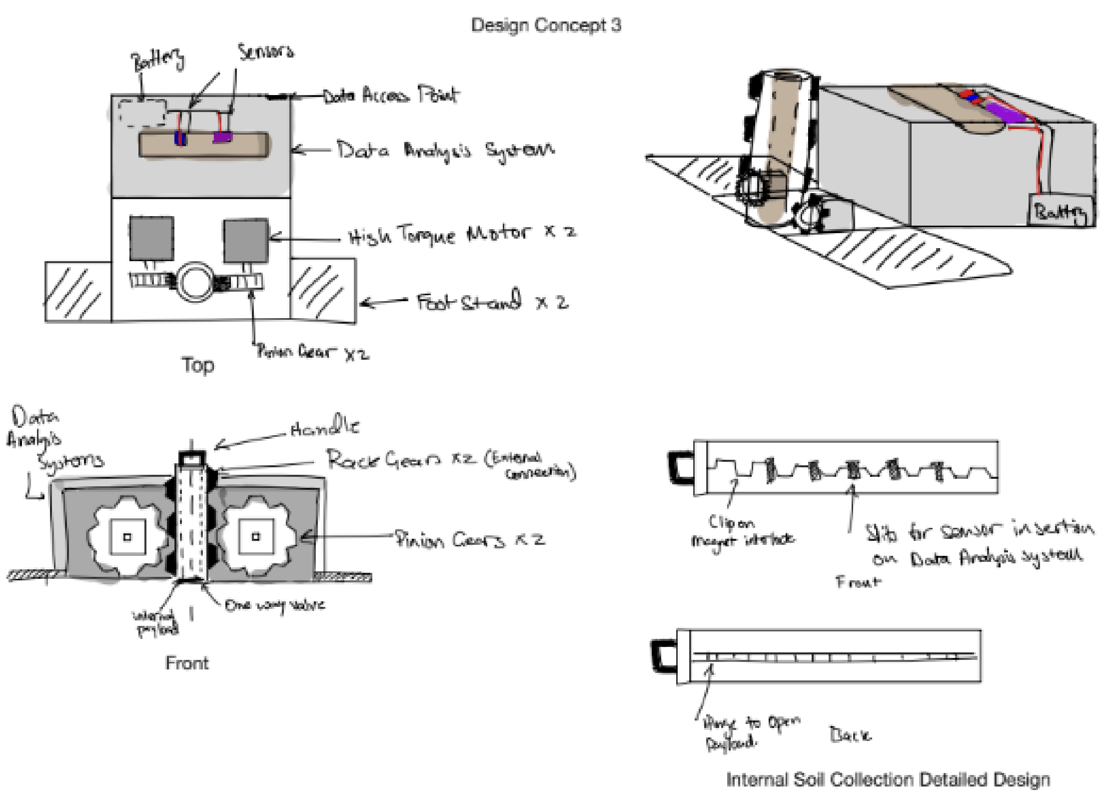


Figure 22: Design 3 Sketches

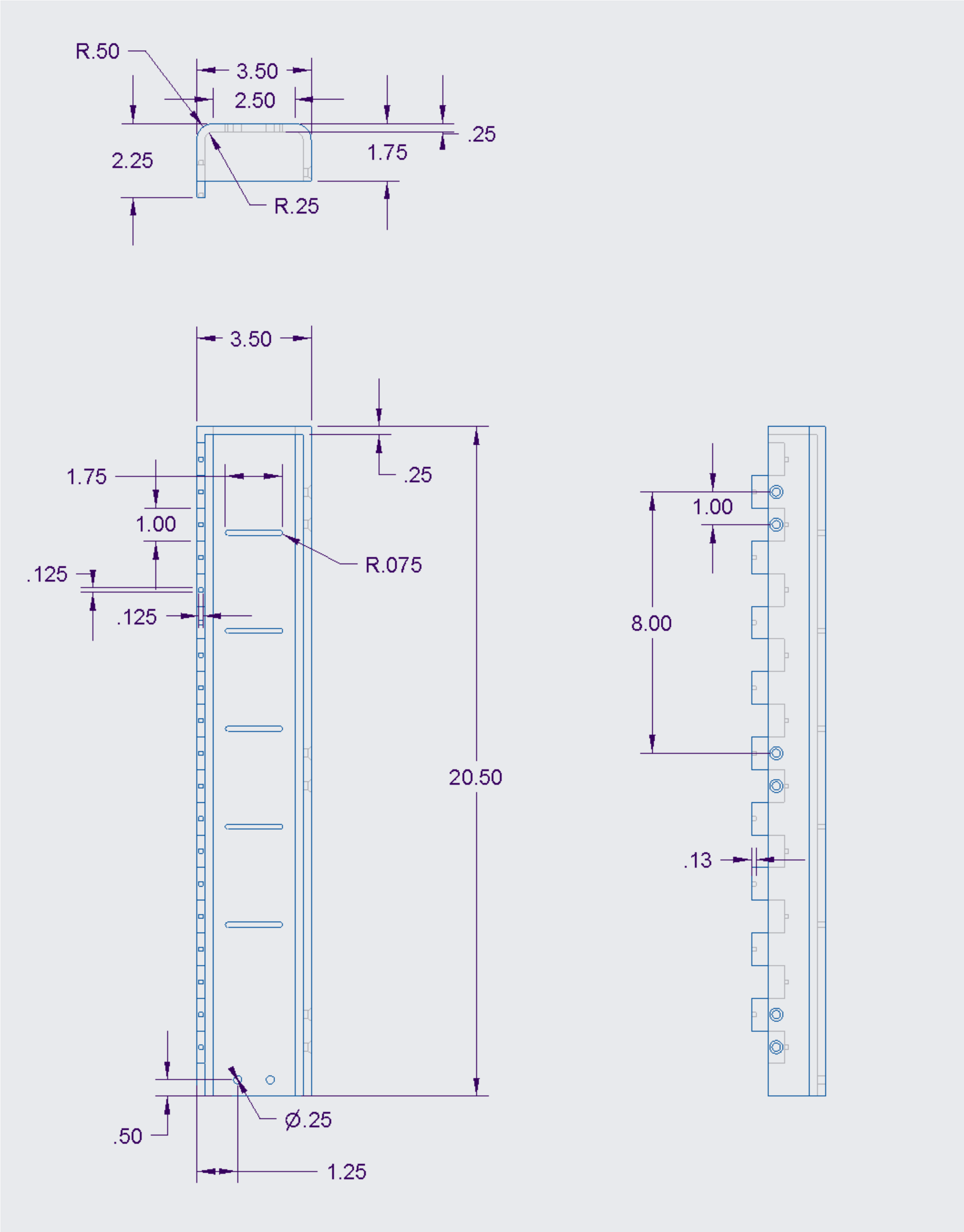


Figure 23: Left Payload Preliminary Engineering Drawing

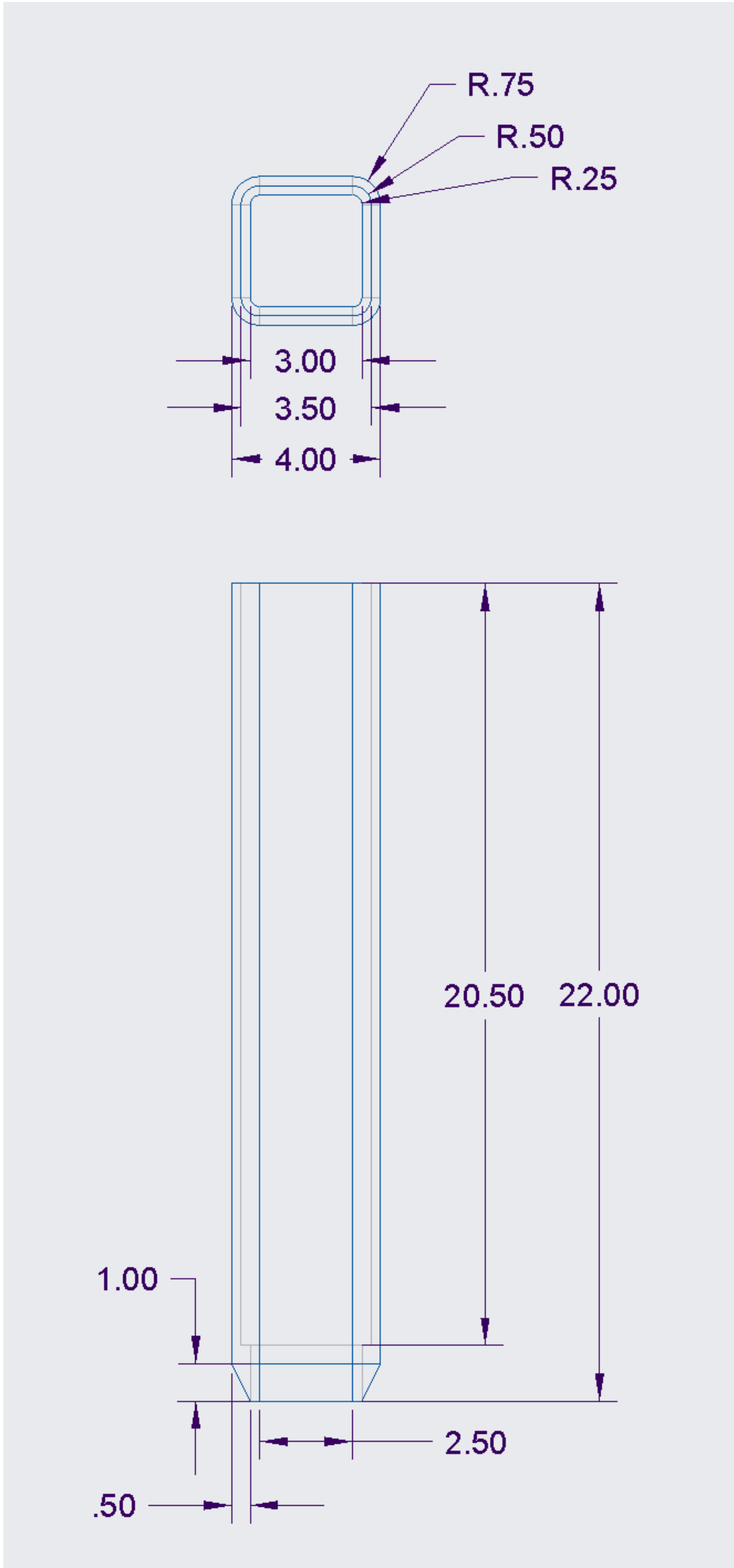


Figure 24: Shell Preliminary Engineering Drawing

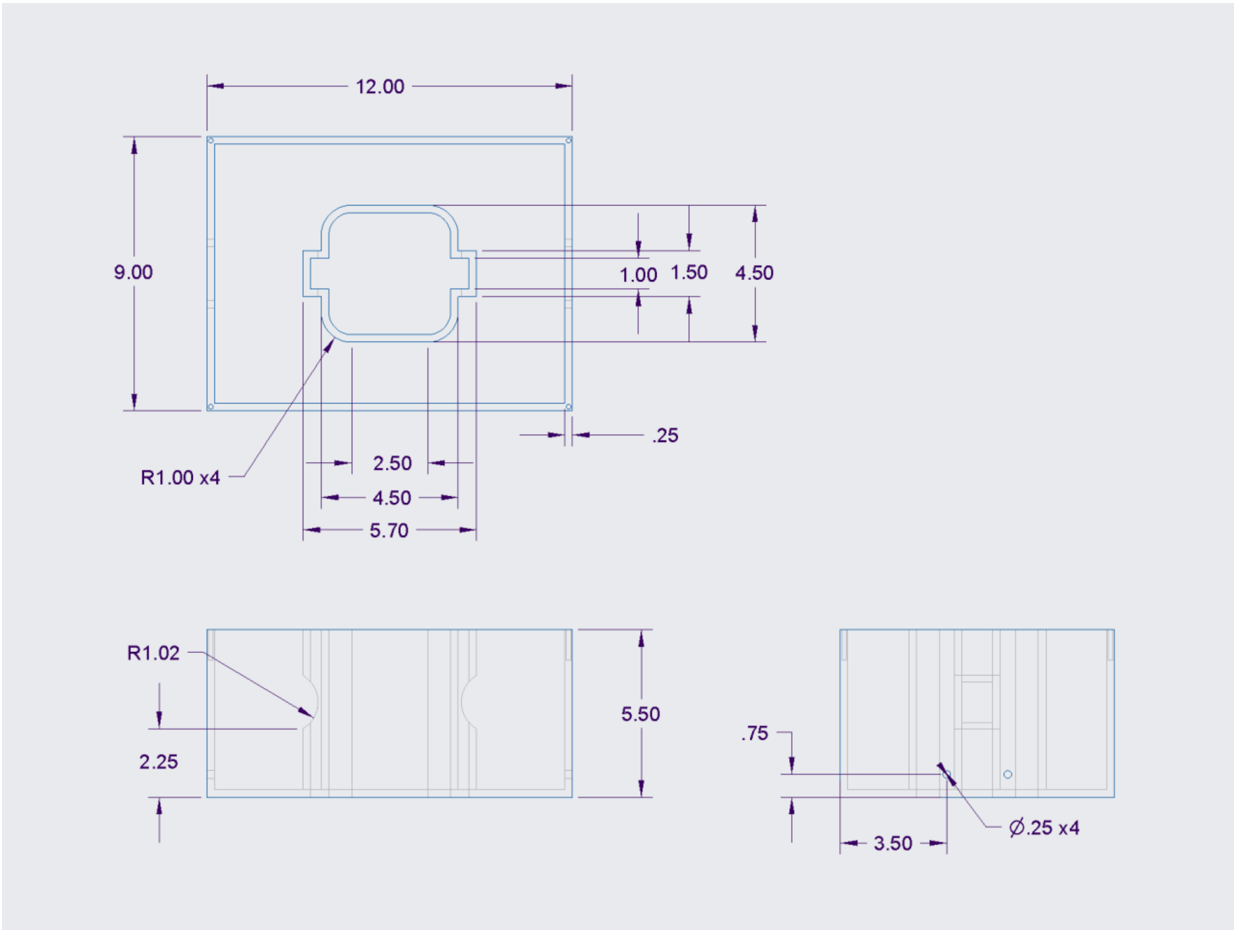


Figure 25: Base Preliminary Engineering Drawing

I. Down-Selection

Decision Matrix (Pugh's Method) – File Attached as Decision_Matrix.xlsx

Metrics/Features	Weights	WintexAgro 1000 Automatic Soil Sampler (Benchmark)	Concept 1: Soil Robot	Concept 1: Soil Robot Weighted Score	Concept 2: Drilling Robot	Concept 2: Driling Robot Weighted Score	Concept 3: Anchor & Simultaneous Collection	Concept 3: Anchor & Simultaneous Weighted Robot
Portability	5	0	2	10	-1	-5	1	5
Depth Accessibility	5	0	1	5	2	10	1	5
Sampling Accuracy	5	0	1	5	-1	-5	2	10
Real-Time Data Integration	3	0	2	6	2	6	2	6
Autonomous Operation	3	0	1	3	1	3	0	0
Durability	4	0	-1	-4	0	0	1	4
Ease of Maintenance	3	0	-1	-3	-1	-3	1	3
Cost	4	0	1	4	1	4	1	4
Data Visualization & Analytics	3	0	2	6	2	6	2	6
Time Efficiency	5	0	1	5	1	5	1	5
Soil Type Compatibility	3	0	-2	-6	-1	-3	-2	-6
Precision in Depth Segmentation	5	0	1	5	1	5	2	10
Sum				36		23		52

Legend
2 - Significantly better than baseline
1 - Slightly better than the baseline
Baseline = 0
-1 - Slightly worse than the baseline
-2 - Significantly worse than the baseline

The decision matrix illustrates that all three concepts (Concept 1 - Soil Robot, Concept 2 Drilling Robot, and Concept 3 - Anchor & Simultaneous Collection) outperformed the benchmark, showing that each design addresses key challenges faced by traditional soil sampling methods. Concept 3, the Anchor & Simultaneous Collection system, achieved the highest score due to its accuracy in soil sampling. Unlike traditional methods, Concept 3 ensures that the soil layers are not mixed, which is crucial for obtaining precise and undisturbed samples, thus improving the quality of the data collected. Additionally, the design improves portability over Concept 2 by eliminating the need for a bulky drilling mechanism, which also reduces safety risks associated with such equipment. This concept scored highly in precision in depth segmentation, ensuring that the samples are taken at the desired depth without interference.

Concept 1, the Soil Robot, demonstrated strong performance in areas such as real-time data integration, autonomous operation, and time efficiency. However, it fell short compared to Concept 3 in terms of sampling accuracy and ease of maintenance. While it offers a practical solution, the lack of precision in depth control and its heavier reliance on continuous operation limits its adaptability to different environments. Concept 2, the Drilling Robot, scored similarly to Concept 1, excelling in real-time data integration and sampling accuracy but struggling with portability and depth accuracy, as the drilling mechanism could potentially disrupt soil layers.

All concepts outperformed the benchmark in terms of key metrics, including real-time data integration, autonomous operation, and time efficiency, showcasing that each new design effectively solves the limitations of the current methods. Concept 3's overall superior performance in depth segmentation, portability, and sampling accuracy positions it as the most promising solution, addressing the existing problems of the benchmark system while offering improvements in several critical areas, including cost-effectiveness and maintenance. These results demonstrate the value of innovation in soil sampling technologies, providing more efficient, safer, and accurate alternatives to traditional systems.

As we move onto the Critical Design Review Phase, preliminary technical analysis is important. The frictional forces on the inner and outer edges will play a large role in determining the pinion and rack sizes along with the desired motor input to be provided. The technical analysis is provided below to show the planned engineering analysis for the CDR phase.

J. Technical Analysis

This section lays out one model that could be used to analyze the required Torque/Force to push the robot the required height into the soil. To determine all the forces that acted on the robot body, a free body diagram was used

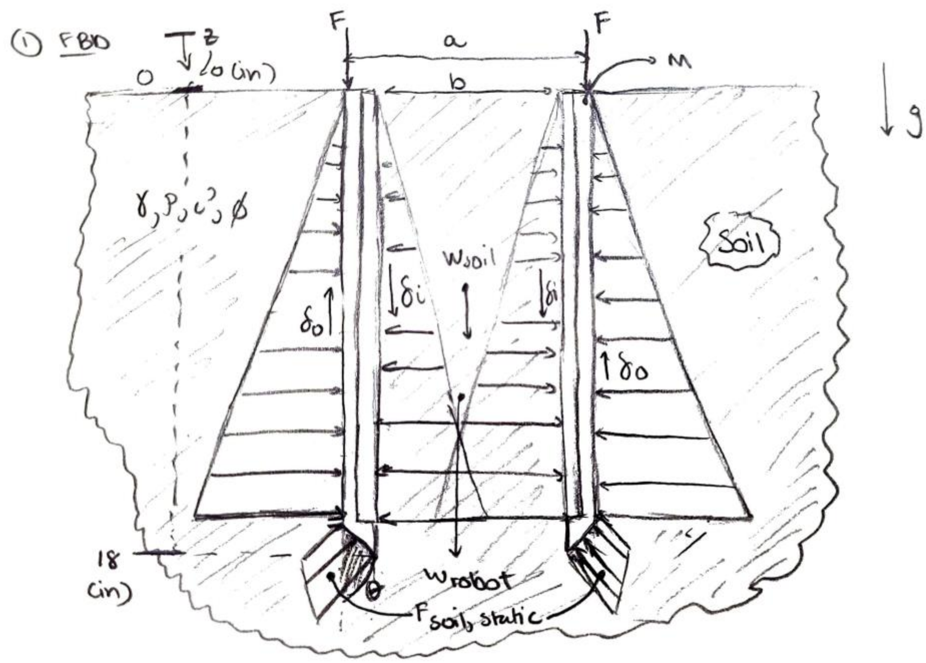


Figure 26: Free Body Diagram

- $g = 9.81\ ms^{-2}$ is the gravitational acceleration
- a is the internal side length of the internal payload
- b is the external side length of the external guidance system
- $A_o = a^2$ is the external cross-sectional area
- $A_i = b^2$ is the internal cross-sectional area
- z is the depth into the soil
- $A_{s,o} = 4az$ external surface area exposed to soil
- $A_{s,i} = 4bz$ internal surface area exposed to soil
- M is the mass of the robot unit
- $W_{robot} = Mg$ is the weight of the robot unit
- θ is the angle of the chamfer at the bottom
- Δz is the height of the chamfer
- A_{slant} is the surface area of the chamfer
- γ is the unit weight of the soil
- ρ is the density of the soil
- c' is the effective cohesion coefficient of the soil

- Φ is the friction angle of the soil
- $m = \rho A_i z$ is the mass of the collected soil
- $W_{soil} = mg$ is the weight of the collected soil
- F is the required input force (we are solving for this)
- f_o is the external friction
- f_i is the internal friction
- $F_{soil,static}$ is the "soil-static" pressure on the chamfer

Using the free body diagram, we can find the equation of motion in the z direction and that would be our governing equation

$$\sum F_z = 2F + f_i + W_{robot} + W_{soil} - f_o \; - F_{soil_{static}} = (m + M)\ddot{z} \tag{1}$$

We need to ensure that $\ddot{z}$ (the acceleration) is always greater than or equal to zero until the desired height is reached. Once that is solved, the robot can be run at reverse at the same Force/Torque. However, there remain many unknowns: $f_i, f_o, and\ F_{soil_{static}}$. According to Purdue University, the following equations can be used to determine the unknowns

$$f_i = N_i \tan(\Phi) \tag{2}$$

$$f_o = N_o \tan(\Phi) \tag{3}$$

Where N_i and N_o are the normal forces acting on the internal and external walls respectively (the hydrostatic equivalent force on each of the 4 sides of the walls)

$$N_i = \frac{1}{2}(P_i A_{s,i}) \tag{2.1}$$

$$N_O = \frac{1}{2}(P_o A_{s,o}) \tag{3.1}$$

Where P_i and P_o are the maximum lateral pressure acting on the internal and external surface respectively. The pressure can be calculated from the Active and Passive earth theory (Purdue et.al). Since the robot is moving through the soil on the external surface, it would experience passive pressure. On the other hand, since the soil is moving through the internal surface, it would experience active pressure. The equations can be seen below

$$P_i = K_a \gamma z - 2c'(K_a)^{\frac{1}{2}} \tag{2.2}$$

$$P_o = K_p \gamma z + 2c'\left(K_p\right)^{\frac{1}{2}} \tag{3.2}$$

The active and passive pressure coefficients (K_a, K_p) can be calculated using the friction angle

$$K_a = \frac{1-\sin(\Phi)}{1+\sin(\Phi)} \tag{2.3}$$

$$K_p = \frac{1+\sin(\Phi)}{1-\sin(\Phi)} \tag{3.3}$$

There remains one unknown which is the $F_{soil,static}$. This can be treated as a simple pressure distribution case and the equation below can be used to solve the same

$$F_{soil,static} = \frac{1}{2}\left(K_p\gamma(2z + \Delta z) + 4c'^{(K_p)^{\frac{1}{2}}}\right)A_{slant} \tag{3}$$

Using these equations, we can determine the minimum required force by pre-determining the desired motion profile. However, it is important to make note of the assumptions we made to derive the equation

- The soil is a homogenous substance (soft cohesive soil)
- Soil has negligible water content
- Soil has constant properties
- Gear rack surface area << than surface area of payload
- Assume cohesion > 0 (otherwise In sand the robot would sink)
- Friction on cone tip is << friction on the entire surface
- A_{slant}<< $A_{s,o}\ or\ A_{s,i}$

So, from preliminary estimates (can be seen in appendix), we estimate that the force required from each motor will be around **200-400 N**; Its this varied as the cohesion value greatly changes our results.

Technical Analysis Results

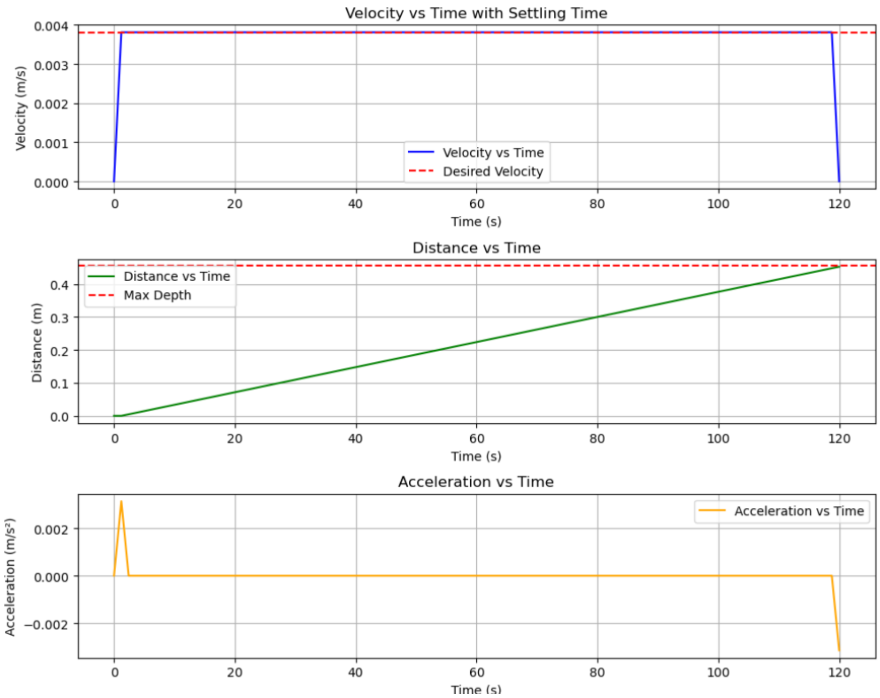
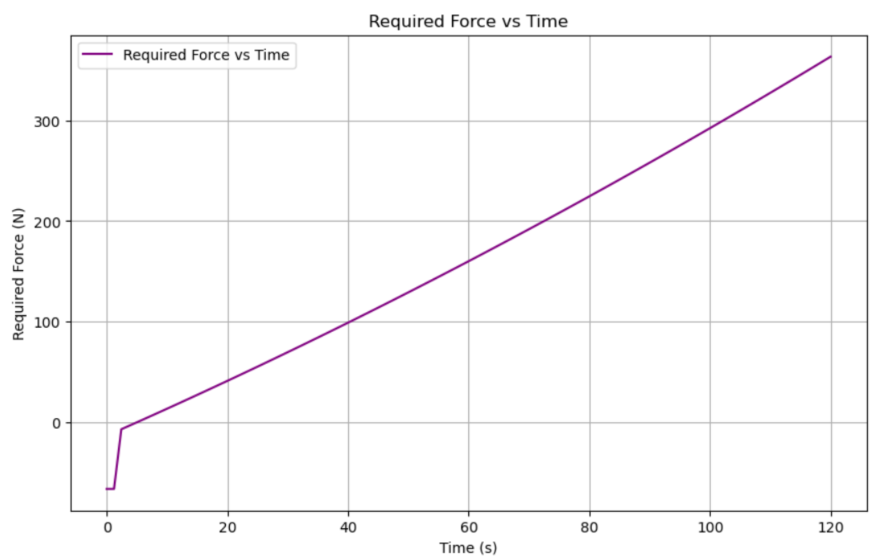


Figure 27: Desired Motion Profile with constant velocity



Maximum force required :363.7007865948643

Figure 28: Resulting Required Force over time to reach the desired depth

K. BOM & Sourcing Plan

Budget_BOM.xlsx is attached to this document

Item Description	How will the item be used for the project?	Vendor	Item Cost	Shipping Cost	Estimated Purchase date
ESP 32 Module/Arduino Uno	Main Controller Module (x 3)	Amazon	*$15.99*	*$-*	*15-Feb-2025*
NPK Soil Sensor	Measure Nitrogen, Phosphorous, Potassium content (x2)	Amazon	*$47.12*	*$-*	*15-Feb-2025*
Soil Moisture Sensor	Measure moisture content of soil (x5)	Amazon	*$8.68*	*$-*	*15-Feb-2025*
Soil Tempreature	Soil Tempreature content (x3)	Amazon	*$9.99*	*$-*	*15-Feb-2025*
24V/5V Battery	Battery for Motors and ESP 32 (x1)	Amazon	*$61.99*	*$-*	*15-Feb-2025*
Motor Driver	Motor controller to ESP 32 module (x2)	Amazon	*$31.98*	*$-*	*15-Feb-2025*
12V/5V Dual Battery	Battery for DAQ System (x1)	Amazon	*$23.99*	*$-*	*15-Feb-2025*
High Torque Motors	For pinion gears mechanism (x2)	Walmart	*$98.00*	*$-*	*15-Feb-2025*
Electrical Switches	To turn mechanisms on and off and other controls (x1)	Amazon	*$7.99*	*$-*	*15-Feb-2025*
OLED Display Module	Real time data shown to user (x1)	Amazon	*$14.98*	*$-*	*15-Feb-2025*
Wires	Electrical Cables (x1)	Amazon	*$14.99*	*$-*	*15-Feb-2025*
Soldering Iron	For all electrical circuit making (x1)	Amazon	*$9.99*	*$-*	*15-Feb-2025*
Heat Shrink wraps for wires	Connecting wires together (x1)	Amazon	*$5.99*	*$-*	*15-Feb-2025*
Pinion Gear	Part #1 for drill mechanism (x2)	McMasterCarr	$71.87	*$-*	*15-Feb-2025*
Rack Gear	Part #2 for drill mechanism (x2)	McMasterCarr	$101.87	*$-*	*15-Feb-2025*
Square Tubing	Part #3 Soil Payload for mechanism (x1)	McMasterCarr	$110.25	*$-*	*15-Feb-2025*
Plexigalss	1/8" thick plexiglass (x2)	Amazon	$14.99	*$-*	*15-Feb-2025*
Machining Cost	If additional metals or machining is required	Fabrication Shops	$-	*$-*	*NA*
3D Priniting	No cost as Purdue labs will be used	Rapid Prototyping Lab	$-	*$-*	*NA*
		TOTAL	**$650.66**	**$-**	**$650.66**

Apart from the above outlined materials, only the key for the gear will be made by the TerraProbe team. All other parts will be bought from the respective vendors listed.

L. Test Feasibility

The feasibility test of the device focuses on testing practicality and reliability under real-world conditions. Some key feasibility aspects include the accuracy of soil sampling, the durability of the pinion and rack system (digging machine), and the effectiveness of the real-time data analysis. The simulation model developed by the team will verify the load and type of gears needed for successful objective and will assess the device's performance across different soil types of moisture levels and environmental conditions to confirm the device's capability. Additionally, integration of moisture, NPK, and temperature will be validated to ensure accurate timely measurements. The field test will also test the modeled numbers for force and gear selection. These tests will determine the design and if it meets the benchmark standards.

From a manufacturing standpoint, feasibility depends on cost-effective production and stability. A rough model of the Bill of Materials review will confirm the component availability and affordability, keeping the budget of $1000 on target. The test will also evaluate the efficiency of the assembly process, ensuring the design refinements do not introduce more complexity to the design and if it hinders the production of the device. Reliability testing, including stress tests and endurance tests, will also help identify potential failure modes and guide the team in necessary improvements before finalizing the prototype. If these tests validate the system’s functionality, durability, and cost-effectiveness, the TerraProbe will be well-positioned for commercialization in the growing soil testing market.

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