MAE 162D & EE 183DA

Team Jeopardy

Critical Design Review

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❖ Part 1 – Project Definition

Formulate the Problem Precisely

Soil core sampling in marshland environments can be time-consuming, especially the soil core process itself and the process of tagging samples with their location data, and is susceptible to human error. Our project aims to minimize these issues by developing a hand-held tool that automates soil core sampling and tagging, and will focus on applications in marshland environments that can be modelled as flat terrain.

Position and Justification

Context: This problem was motivated by one of our students who spent a summer collecting soil samples for a lab with the Professor Engelhart, who had spent years collecting soil data to study rising seawater levels. This soil sampling process is what we aim to simplify. The goal is to both reduce the human labor involved in soil samples, which reduces sources of error, and to speed up the rate of sample collection and tagging. This problem also concerns other research laboratories and organizations like the United States Geological Survey (USGS), where soil samples in marshland are taken and then analyzed. Since soil sampling is the source of data for these practices, the issues with error and time in manual soil core sampling directly affect these practices.

General Interest: Monitoring rising seawater levels alone, which is what Professor Engelhart's lab was concerned with, is a compelling reason to pursue a solution to this problem, but there are many other fields that extract conclusions from soil samples. The USGS and many other research laboratories use soil cores to analyze data related to soil quality, makeup, and toxin levels. These data are of interest to land developers and owners, geo-historians, and also contribute to the topic of climate change. Therefore, improving the soil sampling process through automation will advance many different scientific labs, not just the one this project was inspired by.

Design and Computation: Our solution to this problem is to design a robot whose primary tasks are to navigate the user to a possible sample location, core and collect a soil sample, and tag the sample with location data. The device will be hand-held in order to keep the weight of the robot as low as possible (in contrast, an autonomous robot will be significantly heavier and faces the risk of sinking in the marsh), make the robot easier to adapt to for long-time manual soil samplers (who typically use handheld coring tools), and to minimize the scope of problem. Mechanical design will be vital in developing a coring tool and mechanism that can provide high quality samples in a short amount of time compared to manual soil sampling, and the coring tool must also be easily removable and exchangeable. The mechanism that will tag the sample with the appropriate location data will also need to be designed. As for algorithmic computations, the robot will direct the user to locations on a simplified model of a marshland environment; if more than one robot is used, the robots must be able to coordinate tasks between each other efficiently

Solvable: We have identified a few different functions our device will have to solve. Individually and as a whole, we believe that these functions are all solvable.

1. Navigation: The machine will be able to take in parameters for the working area from the user (the measured length and width of the field), and create a grid of points within that area where it wants to take samples from. We will make the density of this grid adjustable to fit the needs of the user. The machine will also model the field as planar with little irregularity in elevation. A hand-held robot would then direct the user to the next sample point; an autonomous robot would navigate itself.
2. Coring and Sample Collection: Coring is the process of taking a "core" sample of dirt that shows how the dirt is layered. We can outsource the coring tool itself (the nominal tool will be a PVC pipe that is often used in soil core sampling) and make the robot versatile in that it can adapt to use a variety of coring tools supplied by the user. The coring tool will need to be removable and exchangeable with an identical tool, especially if the user implements the method of soil sampling that uses the coring tool itself (typically a PVC pipe) as the soil sample container (See Figure 1, Left). So once a core is collected, the tool/container can simply be ejected for storage and an identical tool can replace it to be able to collect the next sample. It is imperative that tool removal and exchange is convenient and user-friendly.
3. Location Tagging: The robot must be able to identify elevation and GPS data for each point. This was a particularly time-consuming part of the data collection, so it is essential for the robot to be able to automate this process. GPS and elevation data can be taken using existing products, so we just have to integrate those products in with our design -- we can do this by attaching a reflector to our handheld device and using a separate, commercially-available laser beam tool to determine the elevation (Figure 1, Right). A tagging mechanism such as a stamp can then appropriately label the sample container.

***Figure 1**. **Left:** An example of a PVC pipe as the coring tool, which is then used as the storage container for the sample. **Right:** Tool set that measures elevation using a laser beam and a reflector.*

Root Cause Analysis

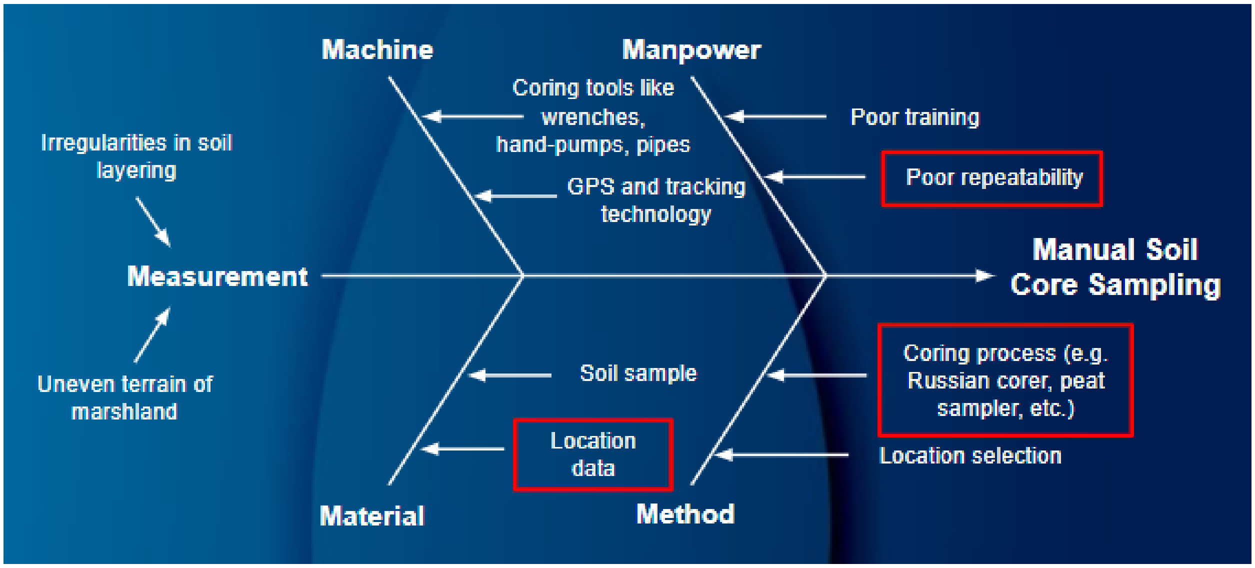


Figure 2. *Root cause analysis diagram. The major sources of problems with manual soil core sampling that can be practically addressed are boxed in red.*

After performing a root cause analysis on manual soil core sampling [1] in marshland environments based on issues sourced from "measurement", "material", "machine", "method", and "manpower", we found that the primary problems with this process are:

1. Manual soil core sampling has poor repeatability in terms of quality due to human error and the type of coring tool used. Human operators of coring tools lack the precision to be able to take samples with consistent depth and low soil disturbance, which can significantly affect the quality of the sample. It is especially difficult in marshland soil sampling because the softer soils can amplify these issues, and applying consistent pressure can be hard to achieve. Soil disturbance can also increase depending on the type of coring tool used, where thin-walled pipes have the lowest amount of soil disturbance and therefore the best quality compared to other tool types.
2. The coring process and tagging the sample with its location data are the most time-consuming parts of manual soil core sampling because of the methods and tools used. The coring takes a long time because of the manual labor involved -- the tool needs to be aligned orthogonally to the surface, consistently twisted and pushed into the ground, and then pulled out. Measuring the elevation also takes a significant amount of time, as observed by our team member. For manual soil sampling, the sample is first collected and the location is marked with a flag. After all the desired samples have been taken, then each location must be revisited twice (once to get elevation data, and the second time to get GPS data) with the appropriate elevation and location measuring tools. This entire process adds up so that it takes several hours to collect all of the samples and their location data.

These issues can be addressed and resolved by implementing a hand-held device that automates soil coring and location data collection.

Define Resources

Sources of the Problem: The most time-consuming part of manual soil core sampling is the coring process itself and tagging the sample with location data, based on the first-hand account by a team member. The issue of human error is mostly due to the repeatability that soil core sampling requires, which often cannot be achieved by a human sampler (manual sampling can have up to 20% error) [2]. This issue can be more pronounced in marshland environments, where uneven terrain, a copious amount of plantlife, and differences in soil quality exist. All these factors combine such that it can be difficult to vertically align the coring tool (which is ideal) and different forces are required to get samples at different locations. As such, automating the coring process and thus increasing its repeatability results in more accurate and higher quality samples and decreases the time required to sample compared to manual soil sampling.

Define Strategy & Methods

Explicating the Problem:

We have thoroughly discussed the soil sampling process with our team member that has first-hand experience with this, read various scientific articles about soil core sampling and how to improve its process, and also reviewed manual hand-held coring tools and a selection of robotic soil core samplers that are currently in the market (e.g. Soil Hawk).

1. Observation: Based on the first-hand experience of one of our group members, coring and tagging the samples with location data takes a significant amount of time and resources (a team of 15 people was required to manually collect soil samples from a marsh). This issue could be addressed and resolved by automating the soil core sampling process using a hand-held device, which will decrease the time needed to core significantly and reduce the number of people needed.
2. Scientific Paper: To get more information on soil coring in marshlands, we looked at journal papers by Giannopoulos et.al. (2019) and Reinhardt et.al. (2000) [3, 4]. Both agree that the quality of a soil core sample increases significantly when the coring tool (typically a cylindrical pipe made of aluminum or steel with a sharpened or sawtooth edge) is twisted into the ground. This action decreases soil disturbance along the sides and surface regions in the sample, and thus increases the quality of the sample. We will apply this to our device by choosing relatively thin-walled PVC pipes as the nominal tool that our device will use, and by using linear and rotational actuators in our coring mechanism to ensure that torsion is applied to force the tool into the ground.

   Our robot will also be navigating the marsh in the sense that it will be directing the user to the next ideal sampling location using a path planning algorithm. To simplify the model of the environment, we will develop a grid-based algorithm. This requires positional and obstacle sensing feedback, representing the 2D environment as a soft body, and the use of cost grids to determine the best path [5].
3. Similar Products: There are a few products currently in the market that are similar to our own idea. The SoilHawk is a commercial product that automates the soil core sampling process in the agriculture industry, and it takes the form of a self-contained and trailer-mounted system [6]. It also uses grids to model the landscape. It can sample 3 cores per minute and has about 10% error in samples. The cost is about $29000 per unit. The SoilHawk is similar to our project in that it addresses the issues with repeatability and speed in manual soil sampling by automating the coring process. Our project will also make use of grids to map out the landscape and locate desired soil sampling points. However, there are significant differences between this product and our solution. The primary difference is that the SoilHawk is trailer-mounted while our device will be hand-held, for ease of use and practicality. Second, our device will additionally

implement a GPS and elevation tagging system to label samples.

On a different note, there are many manual coring tools like the Varomorus Soil Sampler Probe [7]. They are the standard in soil sampling today, primarily due to simplicity and cost. We mention that specific model as it is the Amazon Recommended soil sampler, but there are many models from various companies. With how abundant these tools are, we have an opportunity to incorporate them into our design. Instead of creating our own coring tool, we could have a standard mounting point where researchers could mount their own tool. This would take off some design load from us as well as allow researchers to utilize specialized tools that they've bought for their own purposes.

Background/Related Work/References:

1. Foundation and Fundamentals: To address our problem we need to understand soil core sampling -- how it works, what parameters are necessary for a high quality sample, and where errors are introduced. We have been able to do this by learning from the first-hand observations of our teammate, reading scientific papers and articles, and looking at how existing tools and products approach soil sampling. We also need to know about navigation algorithms. This is especially important as our device will have to allow the user to input parameters for the sampling location, form its own grid using those parameters, and then navigate the user to each sample location from there. Since the terrain of the marshland is random and unknown to the robot, this will need to be considered during navigation. Finally, we also need to understand signal processing in order to correctly communicate with the GPS and elevation device we could pair with our robot.
2. Previous Work on Problem: Since this is a research field, not a commercial field, there have not been many optimizations to marshland soil sampling. Most advancements have come from increasing the quality of the coring tool by developing various coring mechanisms, but all of these tools are still handheld and manually operated which still suffers from human error and significant time requirements.
3. Previous Work on Related Problems:There are some instances of automized coring tools, such as the SoilHawk that was mentioned above, but these are used for agricultural soil sampling which faces different challenges in design and terrain that do not apply to the problem of marshland soil core sampling (flat and consistently solid terrain and dry conditions exist in farmland but not in marshland, for example). Rather, these automized coring tools serve as proof that this problem can be successfully resolved, and our project can focus on improving the automation process and adapting it to marshland environments.

   On a different note, there are many commercially available elevation and location measuring tools. For example,the Emlid Reach RS2 is a positional system that has the user set up a base pole that is the initial position [8]. From there, it shoots a laser to determine where a second pole is currently located. It can then calculate the X,Y, and Z coordinate location of the second pole relative to the base. This type of system is very common, and many companies manufacture these products. Professor Engelhart's lab used a similar tool to determine the locations of each of the soil samples. It is safe to assume that a laboratory that would invest in a highly efficient coring product like the one we are proposing would also have one of these systems available for use. We can take advantage of this by adapting the second pole directly onto our device. Not only can this solve the problem of how to retrieve geo-tag information for each sample, we may even be able to pull a continuous stream of data from the GPS rover base to feed our navigation system.

4. Previous Work on Unrelated Problems: One UCLA MAE capstone group last year made an autonomous robot that drilled fence-post holes for farms [9]. We would use a similar navigation system that would require our robot to direct the user to the next point of interest to take a soil sample.
5. An Unsolved Problem: During our research, we were unable to find any successful attempts at automating soil core sampling in marshland environments. Most of the research done on our specific problem has dealt with developing various different hand-held tools and decreasing soil disturbance, and have not addressed the issues with the time required to core and tag samples. There has not been any effort into automating this process specifically for marshland environments, although agricultural products demonstrate that this is possible. This lack of automation attempts is likely due to the fact that marshland soil sampling is a very niche market, and as such there have been no notable attempts to integrate a hand-held device that can autonomously core and geo-tag soil samples in marshland.

Fundamental Questions

What is the overall problem that this project is trying to solve?

Manual soil core sampling is vital to research laboratories and the USGS; however, it is a time-consuming process and the data harvested from samples can be inaccurate due to difficulties with repeatability.

Why should people care about the problem?

This problem is important because the high error associated with manual soil core sampling can significantly skew the data collected from these samples. Errors in this data, which is used by many research laboratories and government agencies like the USGS, can be used to address key issues such as climate change, to enrich our knowledge of geological history, and can also provide vital information about soil makeup to landowners, farmers, and associated stakeholders.

What has been done so far to solve this problem?

To solve this problem, researchers have developed various methods of manual soil core sampling; these efforts have been primarily focused on altering or designing coring tools that will decrease soil disturbance during the coring process and therefore reduce error. However, these developments have done little to decrease the time required to sample a field. There have also been a limited number of products that automate the coring process, all of which focus on agricultural soil core sampling. These products have been successful in making the soil sampling process highly repeatable and quick. However, the cost of these products have created a barrier to their widespread use in agriculture or in other industries in which they have potential use.

Scope

Problem Subset

Based on the overall problems associated with manual soil core sampling, our project will focus on the automating soil core sampling in marshland environments, and will address the two primary issues associated with manual soil core sampling: the error in collected samples as a result of poor repeatability, and the time-intensive nature of manual soil sampling (especially while coring the tagging the sample).

Solution to the Larger Issue

Solving the issues with speed and repeatability in soil core sampling in a specific environment (e.g. marshland) will prove that accuracy and efficiency in marshland soil core sampling is achievable, and ideally lead to further developments in automated soil core sampling.

Solution Approach and Quantification

Our approach to solving this problem is to develop a hand-held device that will navigate the user through marshland environments to collect soil core samples with high accuracy and precision (sample depth and soil disturbance should be repeatable up to 95%) and speed (at least twice as fast than manual coring, which has an average speed of 3.75 samples/hr). Some secondary goals of this project are to keep it at a reasonable cost (aiming to be under $5000 per unit) so that this device can be more accessible to researchers and stakeholders, and to require only 3 operators per unit (a significant improvement to the typical 15-person team required by manual soil sampling).

Requirements Definition

Intended Practice / Other practice

Our device is designed to significantly reduce the difficulty of soil core sampling. Rather than manually collect samples, users will simply have to deploy the device.

Artifact

Our device is based around the technology used in a manual soil coring device. It utilizes similar tools and techniques to those used by manual samplers.

Problem

Our problem is that manually collecting soil core samples is a difficult, imprecise, and labor intensive process. It is difficult to both utilize the manual tools as well as to navigate the sampling region.

Technology

The technology used pertains to two fields: coring and portability. The device will eliminate most of the physical labor involved with core sampling. The device will also be easily able to reach many destinations in a relatively fast time period; either by portability or by locomotion.

Uses

Our technology is used to produce soil core samples and to navigate the marshland environment.

Perception

Manual soil core sampling is perceived to be a tedious and difficult task. It cannot be completed in a time or labor-efficient manner. Manual soil core sampling is perceived to be low in accuracy due to improperly taken samples.

Addresses

Our device will significantly reduce the time and manpower required for soil sampling by eliminating the majority of manual labor required and speeding up collection times.

Environment

Our device is designed to be very effective in marshland environments. Its collection mechanism functions well in the marshland, and it is navigable through typical marshland terraign.

Function

The function of our device is to reduce or eliminate the human involvement with the coring procedure. After being deployed, it collects soil cores for collection. The device benefits users by offering an easier and more efficient method to collect core samples.

Behavior

Coring, Drilling, Collecting, Navigating, Storing, Cleaning,

Structure

The device's structure is composed of a coring mechanism, a body or chassis, and any locomotive structures used.

Intended Effects

The device is intended to collect geotagged soil core samples, aid in the navigation of the marshland environment, and reduce overall human labor.

Side Effects

Local marshland ecosystems could be impacted by frequent sampling. The habitats of animals could be destroyed during the transportation or sampling process.

Objective Tree Method

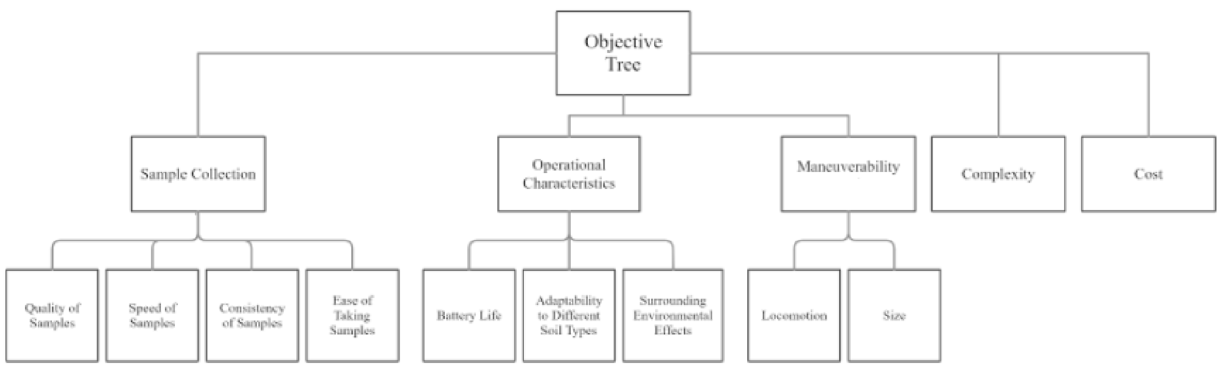


Figure 3. *Objective Tree showing the process of deciding the design objectives and sub objectives.*

Performance Specification Method

Collect Quality Samples	Device must correctly collect core samples to ensure they remain fully intact, and accurately and precisely collect samples of specific depth (at least 95% accuracy, and at most 5% error in sample depth)
Collect Samples Quickly	Device must be able to collect a single sample in 30 seconds or fewer
Maintain Consistent Quality	Device must contain a coring mechanism cleaning method to be utilized after each sample is taken
Low Labor	The maximum physical effort expended should be carrying the device (if necessary) and starting the device
Work All Day Without	Battery Life should last at least 8 hours

Charging	
Adaptable to Soil	Device must be able to navigate across and sample from soft, irregular, wet, and muddy terrain
Avoid Environmental Damage	The device should not cause significant long or short-term harm to the environment
Maneuver Through Wetlands	Device must weigh less than 20 lbs or be self-driving.
Store Samples	Device must be able to store 10 collected samples
Navigation	Device must be able to determine sampling locations and geotag samples within a range of 20-25 feet
Price	At most $5000
Operation	Require no more than 3 operators
Sample Type	Vertical soil sample from marshland

Figure 4. *Performance Specifications Table*

Quality Function Deployment Method (QFD)

Our project was initially motivated by one of our team members who had first-hand experience doing manual soil core sampling in marshland environments. As such, his experience and observations will primarily act as the "voice of the customer" for this analysis. The customers, in this case, are researchers and laboratories that currently perform manual soil core sampling in marshland environments.

Customer Requirements and Engineering Product Attributes

Customers want a device that will collect samples and tag them with location data quickly, which requires a device with a large load capacity, high coring speed, and an accurate and near-instantaneous positioning system. High quality samples are also desired, which translates to a quality tool tip and weight requirements. Making the device simple, and easy to use and maintain can be defined in terms of its weight and shape. Weight and shape will also heavily affect how easily the user can move the robot through the marshland. Finally, customers want a device that has a reasonable cost, which can be traced to its weight, shape, and coring speed. Customers also value speed and quality over any other requirement, while the device's simplicity and ability to traverse marshy terrain is not as important.

The engineering characteristics and product attributes were found to have a strongly significant relation between Force and Shape. Our product must be designed so that it is compliant with and can withstand the forces required during coring without affecting the sample quality.

Competition Assessment

One comparable product to our own is the handheld pipe tool, which is often a PVC pipe. The pipe is superior to our own device in terms of cost, simplicity, and its ability to be easily moved across marshland. This is due to the simple nature of the PVC pipe, which is readily available at any hardware store and is often used in manual soil sampling.

Another product that serves as competition is the SoilHawk, a trailer-mounted system that performs soil core sampling for agricultural land. The SoilHawk has improved sample speed compared to our product, and for all other customer requirements our goal is to make our own handheld device better by having improved sample quality, ease of operation, cost, and maneuverability in marshland environments.

Target Specifications

Our product will aim to have a sample speed of 120 cores/hour. It will also be a maximum of 20 lbs to ensure that it is easy for the user to carry around while sampling. The shape will also be ergonomic and withstand the forces applied during the coring process without damaging the soil sample. We will also design the product to have the most effective tooltip type to use during coring, to make the process accurate and precise compared to our competitors. The tagging feature in our device will also make sampling and tagging simple for the user and decrease the time taken to soil sample as compared to competitors.

	Force	Weight	Speed	Shape	Tooltip Type	Positioning System
						+
					+	-
				++	-	-
			+	+	-	+
		+	-	+	+	-

Relative Weight	Customer Importance (Scale of 1 - 5)	Customer Requirements	Force	Weight	Speed	Shape	Tooltip Type	Positioning System	Our Product	Typical Manual Soil Sampling Tool (e.g. PVC pipe)	Soil Hawk (agricultural soil sampling)
		Functional Requirements							Customer Competitive Assessment		
		Direction of Improvement	▲	□	□	▲	□	▼			
18%	5	Device collects samples quickly	●	▽	●	▽	○	▽	2	3	1
18%	5	Samples are high quality	●	○	○	▽	●	▽	1	3	2
14%	4	Device tags samples quickly	▽	▽	○	○	▽	●	1	3	2
14%	4	Device is easy to use	○	●	▽	●	▽	▽	1	2	3
11%	3	Device is easy to maintain	▽	○	▽	○	●	▽	2	1	3
7%	2	Cost is reasonable	○	▽	▽	▽	○	○	2	1	3
11%	3	Can traverse marshland environment easily	▽	●	▽	●	▽	▽	2	1	3
7%	2	Simple and intuitive	○	▽	○	○	○	▽	2	1	3
		Importance Rating Sum (Importance x Relationship)	442.86	357.14	321.43	364.29	392.86	228.57			
		Relative Weight	21%	17%	15%	17%	19%	11%			
		Units	N	lbs	cores/hr						
		Our Product	100	20	120	1	1	1			
		Typical Manual Soil Sampling Tool (e.g. PVC pipe)	0	5 lbs	3.75	2	2	2			
		Soil Hawk (agricultural soil sampling)	>100	>>20	180	3	3	3			
		Technical Competitive Assessment									

Correlations	
Strong	++
Medium	+
Weak	-

Relationships		Weight
Strong	●	9
Medium	○	3
Weak	▽	1

Direction of Improvement	
Maximize	▲
Target	□
Minimize	▼

Assessment Scale	Rank
1	Best
2	Middle
3	Worst

Figure 5. *QFD Method Analysis*

System Design: Block Diagram – Function Analysis Method

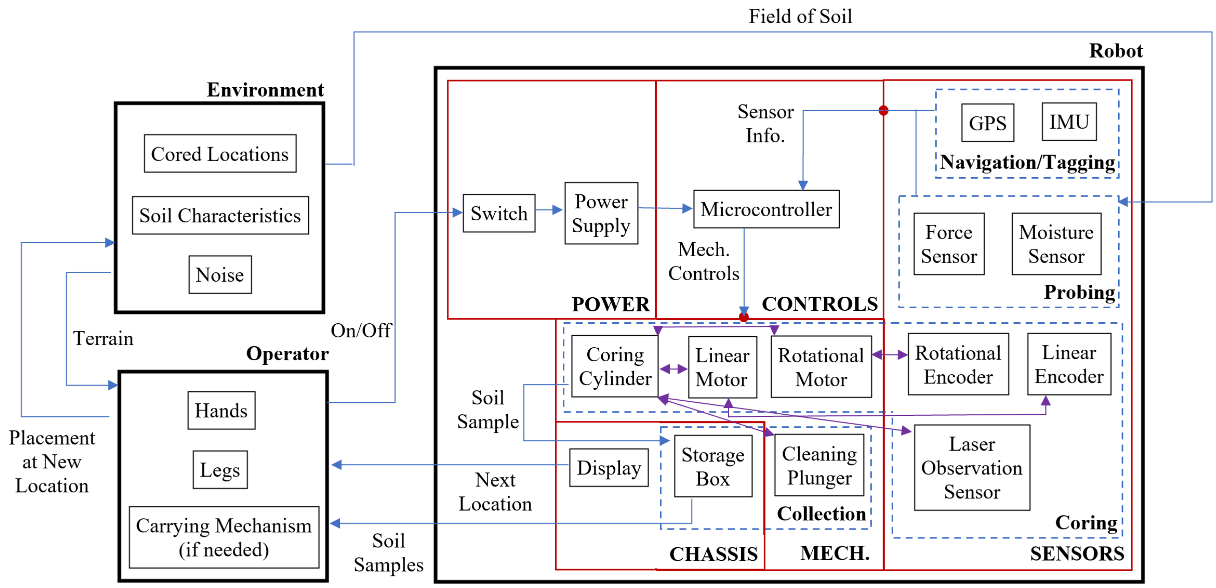


Figure 6. *Block diagram for soil core sampling robot.*

This subsystem breakdown is justified as every essential element of the robot is contained both within a group, such as power or controls, as well as a subsystem task, such as navigation or coring. Note that the microcontroller connects to the motors which connect to their encoders which connect back to the microcontroller, forming a feedback loop that can be used to maintain constant force during drilling.

Requirements for the subsystem blocks mostly pertain to the accuracy of measurement and extraction. For example, the force sensor needs to be highly accurate to determine small differences in soil toughness throughout the field.

Development of Design Candidates

Multiple brainstorming sessions were led across several weeks where the entire group came up with possible solutions to each sub problem associated with the overall problem statement, and we then evaluated those ideas based on the problem and their feasibility. Based on the critical design requirements defined in Part 2, a general idea for the robot was formed with its main functionality broken up into 5 subsystems: locomotion across the marshland, the sampling tooltip design, the sample collection system, the tooltip decontamination system, and the localization method. Each idea brought up was analyzed and organized in Figure 7 using the morphological chart method:

Features	Individual Solution Candidates				
Marshland Locomotion	Handheld Device	Multi-Wheel Drive	Tank Treads	Quadcopter	4-Legged System
Sampling Tooltip	Hand Soil Auger	Aluminum / Acrylic Cylinder	PVC Pipe	Screw-Shaped Drill Bit	Wedge Coring
Sample Collection	Manual Collection	Eject via Piston (Pneumatic or Servo)	Opening Latch Mechanism	Tool Storage Using Swappable Tooltips	Robotic Arm
Tooltip Decontamination	No / Manual Cleaning	Passive Cleaning Brush	Active Cleaning Brush	Compressed Air	Water Jet Wash
Local Positioning System	Laser Altimeter	9DOF IMU	Global Positioning System (GPS)	RTK-GPS (Real Time Kinematic)	Ultra-Wideband Positioning

Figure 7. *Morphological chart for the soil core sampling robot – 5 main features were extracted based on the requirement definitions and several possible solutions were listed for each. The order of each element was picked specifically to indicate the relative difficulty/complexity of implementation; the leftmost column contains ideas with primitive solutions while the rightmost column contains more sophisticated systems that require more design but could yield better results. A careful examination of each element was required to come up with full design candidates used later in the weighted objectives table.*

Marshland Locomotion:

One of the most difficult aspects of this project was figuring out the method in which the robot traverses the given environment. Unlike other similar robots that operate on a farm, this robot must be able to navigate a marshland which is more treacherous and unpredictable compared to an open field. There could be regions within a marsh that have different soil moisture contents that affect the stiffness of the ground, while other regions could be completely submerged in water. To be able to navigate such terrain on its own, the robot must be able to reliably detect such hazards using external sensors and have a locomotion system that allows itself to get out of the mud:

1. ***Handheld Device*** – Instead of bothering to overcomplicate the system, one of the very first ideas brought up was to offload the locomotion problem to an operating user who would carry the device themselves to the next sampling site. Scientists and researchers have already been doing marshland research themselves, thus it is reasonable to have the

user use their own pair of legs to go collect data.

2. ***Multi-Wheel Drive*** – A multi-wheel drive would be a common drive system that would probably consist of an all-wheel drive which enables better traction and handling, both crucial for letting the robot get out of the mud. One major concern with all other ground locomotion ideas, especially for the wheeled drive, is the issue dealing with mud which gets stuck on the tires. A mechanism for periodically cleaning the dirt/mud off of the tires would be needed for stable operation, which further complicates the entire system.
3. ***Tank Treads*** – One of the benefits of using a tank tread over a wheeled drive system is that treads have a larger surface area that makes them less susceptible to sinking into the muddy terrain thanks to being able to distribute the weight of the robot across a larger area. This however also means more of the land would be in contact with the robot, causing unwanted environmental disruption.
4. ***Quadcopter*** – The quadcopter would completely resolve the issue of getting mud stuck on its locomotion system due to being able to hover above the surface and accomplish the sampling task without ever touching down on the ground, minimizing its effect on the environment. However, it has its own set of issues, mainly being the load that a quadcopter would be able to reliably carry since the samples are going to be entire rods of packed soil and mud.
5. ***4-Legged System*** – Having 4 fully-actuated legs allows the robot to have better balance overall, possibly even being able to lift itself up again in the case that it tips over unlike the other designs. There are many issues with this idea, one being that a special leg shape must be designed to prevent the robot from sinking into the mud. Another could purely be the cost of the entire system, which presumably would have at least 12 actuators which would be excessively complicated.

Sampling Tooltip:

Another critical part of the project was the sampling tooltip, which directly dictates the quality of the samples taken by this robot. The primary objective of this sampler is to take an undisturbed soil core sample that could be taken back to a lab for further analysis, where it is important to ensure that the soil is an accurate representation of the sampled region. This is very difficult to do especially for soft soils found in a marshland, thus the tooltip must be ideal for collecting these samples:

1. ***Hand Soil Auger*** – Utilizing existing hand soil auger tools which researchers use for soil sampling would enable researchers who already have the necessary tools to reuse their own tools, now with the added consistency and accuracy thanks to using a motorized actuator. This approach is convenient for existing researchers, but also simultaneously difficult to generalize across all researchers due to many different tool designs being in use today for different purposes. Auger tools are expensive on their own, thus this approach would be costly for new customers who are going into soil core sampling for the first time.
2. ***Aluminium/Acrylic Cylinder*** – The general shape of a soil core sampler consists of a long cylinder that has a detachable lid which allows the soil inside to be pulled out using air pressure. Instead of purchasing a specialized tool, this method could allow for drastic cost savings compared to purchasing professional tools. Using such tools could also allow greater adaptability across various soil types due to the design not being specialized to a particular soil type.

3. ***PVC Pipes*** – Very similar to the previous idea of creating a custom-made auger, but focuses on the commercial aspect by selecting regular PVC pipes as the cylinder that collects samples. PVC pipes are widely available at any hardware store, enabling the user to select their own length and thickness that suits their own needs. If a modular design for the tooltip is considered, purchasing large amounts of PVC pipes is much more realistic compared to buying custom-made samplers directly from us. This grants customers freedom in how they would like to use the device [3].
4. ***Screw-Shaped Drill Bit*** – A slightly different approach, which sacrifices being able to collect a uniform soil core for more reliability in the actual soil collection thanks to having a physical object blocking the soil from falling underneath. Other methods primarily rely on the air pressure method to maintain the shape of the sample, so the extra complexity is assumed to be unnecessary for now, but could possibly change in the future through more testing and simulations.
5. ***Wedge Coring*** – A drastically different approach also used by modern researchers for collecting undisturbed soil core samples, which involves a V shaped wedge with rails that initially gets placed into the ground. Afterwards, a thin metal plate is passed along the rails which allows the two tools to completely seal off the section of soil inside the wedge. This completely isolates the soil core from the surrounding soil, letting the user easily remove a pi-shaped soil core out of the ground. Its effect on the environment is predicted to be minimal due to the thin profile of land that the method actually removes from the ground, and the tooltip geometry also makes it easy to clean after use [10].

<u>Sample Collection:</u>

Even if the robot is successful in initially digging up an undisturbed soil core sample from the ground, it is also crucial to ensure that the undisturbed state of the soil core is preserved until the sample is brought back to the laboratory for in-depth testing. Special care must be taken to let the researcher know that the sample is pure, letting them conduct experiments without worrying about extra contamination or disturbances.

1. ***Manual Collection*** – Similar to the idea for the locomotion subsystem, a naive solution to the issue would be to have the operator manually remove the soil sample from the tooltip after the motorized auger takes a sample. A common method used by researchers today involves storing the cores inside a ziploc bag, so the same method could be used to remove the sample from the tool and placing it inside a bag for later inspection.
2. ***Eject via Piston (Pneumatic or Servo)*** – An automated mechanism for extracting the soil core sample from the tool could involve a piston mechanism that pushes a rod inside the tool to eject the soil into a separate container/compartment. The extra force applied on the soil core would however result in extra compression of the core, possibly messing up the sample integrity.
3. ***Opening Latch Mechanism*** – To avoid unnecessary compression in the soil sample itself, an opening latch mechanism can be built into the tooltip itself such that the tool splits open in half and lets the core inside easily slide out of the tool into a separate container that would be sealed off.
4. ***Tool Storage Using Swappable Tip*** – Another way to avoid unnecessary tampering with the taken sample would be to keep the sample in the original sampled state, i.e. using the tooltip itself as a container for preservation. This would require a system that enables the robot to have modular tooltips which could be easily attached and detached on the spot. A

new tooltip could be attached once a sample is taken, and the sampled tooltips could be stored elsewhere.

5. ***Robotic Arm*** – The most complex method of sample collection would involve a robot arm that would mimic the set of motions that a human would take in order to remove the sample from the tool. This manipulator would be able to open the containers on its own, place the samples inside it, and could even be combined with the decontamination subsystem to also help clean off the tool after use. However, cost and project scope concerns make this system seem unnecessary when other simpler mechanisms accomplish the same result.

Tooltip Decontamination:

After a successful soil core sample is taken, it is assumed that the researcher would want to go ahead and take multiple subsequent samples, either at the same location or at a new sampling site. Either way, ensuring that no contamination occurs across different samples is important to maintain consistency and reliability across multiple samples.

1. ***No/Manual Cleaning*** – If one of the modular tooltip designs is selected, special cleaning procedures are unnecessary since the same tooltip would not be used to collect another sample, simplifying the overall design. There could be small concerns about some mud getting stuck on the underside of the device, but these aren't specific concerns regarding maintaining the integrity of the collected sample, thus are outside of the scope of what was envisioned as part of the project.
2. ***Passive Brush Cleaning*** – A primitive way to have excess dirt removed from the tooltip would be to have a circular brush firmly attached right above the point that the tool enters the ground. The vertical motion of pushing the tool into the ground would also act as the linear motion to brush off excess soil attached to the exterior of the soil, providing a very basic form of cleaning.
3. ***Active Brush Cleaning*** – A slightly more advanced version of the previous idea would incorporate several servos dedicated for actuating the brush in an oscillating motion to ensure all soil is removed from both the exterior and interior of the tool. Considering that interior contamination is more critical, this method is prefered in terms of accomplishing complete decontamination across samples.
4. ***Compressed Air*** – A quick blast of air down through the tool using a compressor loaded on the device would remove the complicated moving mechanisms found in other solutions and make the overall task very quick. The major downfall of this idea comes from the extra payload that the device would need to carry in order to accommodate a compressor.
5. ***Water Jet Wash*** – Washing using water would ensure complete decontamination across samples, but also suffers from the larger issue also found in the compressed air idea regarding payload. Maintaining a working water pump system along with a reservoir of washing liquid is excessive and troublesome, and possibly even harmful due to the nature of ejecting cleaning water which was brought in from outside of the sampling site.

Local Positioning System:

The last component needed to make the project work is a method to accurately determine the current location of the device, not only in terms of latitude and longitude but also elevation, the most critical information needed associated with the sample taken. Traditional methods relied on laser rangefinders which used lasers to measure the distance and angle from elevation markers located on site in conjunction with GPS signals received from special satellites that informed them of the precise world location. Rather than selecting a single solution for this, multiple solutions were selected in conjunction with others to improve quality and quantity of the collected data.

1. ***Laser Altimeter*** – Similar to the traditional method, a laser emitting device would be mounted to the robot and detect the laser being reflected back from the reflector located at an elevation marker. This data would be internally analyzed and converted into an elevation value given the elevation at the marker, allowing the robot to precisely indicate the elevation information associated with each sample. The elevation values obtained from this method ranges approximately by ±1ft.
2. ***9DOF IMU*** – An inertial measurement unit would be useful for measuring the smaller depth changes whenever the device is in the process of sampling soil, giving precise reading about how deep and what kind of forces were present while taking those samples at a given elevation. Many common IMU chips have a resolution of 16 bits, which are more than enough to gather information about the device's local movements [11].
3. ***Global Positioning System (GPS)*** – A traditional GPS-enabled chip could retrieve signals sent from 4 or more satellites to calculate its location on Earth. A typical GPS signal is said to have an accuracy of around 6.5~11 yards [12].
4. ***RTK-GPS (Real Time Kinematic)*** – RTK-GPS is a special type of GPS which infers errors that are caused as a result of signal transmission delay when passing through the atmosphere, greatly increasing the positional accuracy of the data in exchange for sensor sampling time. Some devices are capable of achieving an accuracy down to less than an inch [13].
5. ***Ultra-Wideband Positioning*** – A local positioning system commonly used indoors allows a user to track the position of a chip utilizing distance information from each of the 4 anchors attached to the corner of the room. Although this solution requires some method of placing anchors at known locations around the swamp, it has an accuracy down to less than 4 inches [12].

After considering individual solution candidates for each subsystem, 3 design candidates were developed by combining solutions that tailored towards a similar feature. The results are shown below:

<u>Design #1 – Autonomous Coring Rover:</u>

Being a robotics capstone class, the first design idea that formulated within the group consisted of a system that fully automated the sampling process. This meant that a researcher would bring the robot onto a marshland, release it on its generated trajectory, and essentially monitor its actions from a distance while the robot would be hard at work out in the field. To enable such operation, automation of every action was essential, which led to selecting features that focused on autonomy:

- Tank Treads
- Wedge Coring
- Opening Latch Mechanism
- Actuated Brush Cleaning
- GPS, 9DOF IMU, etc.

Many of these solutions were chosen based on the design philosophy of minimizing the risk of failure while on a sampling mission. Using tank treads allows the rover to have a larger surface area to distribute its weight across, decreasing its chances of sinking into the marsh and getting stuck on its own. A wedge coring sampler is much easier to incorporate into an autonomous rover, especially considering that it is easier to clean out relative to a pipe and only consists of two linear motions that could be precisely controlled using a motor. A set of brushes would be attached in a way that allows it to remove excess soil and mud after each sample collection procedure, which would eject the soil core samples inside an internal compartment that the researchers would be able to access later. Lastly, both GPS and an inertial measurement unit were needed for autonomous navigation around the marsh, with additional peripheral sensors needed to aid the rover in understanding the environment such as cameras and ultrasonic sensors.

<u>Design #2 – Handheld Automated Sampler with Detachable Commercial Auger Tooltips:</u>

Many of the autonomous tasks that a fully automated rover design would need to accomplish throughout a sampling mission can be easily replaced by a human to greatly simplify the mechanical and algorithmic design of the system. The second design enables this by replacing simple tasks that a human does with automation, but keeps more complicated tasks that would make more sense for a human to just do on their own:

- Handheld Device
- Hand Soil Auger
- Manual Collection
- Manual Cleaning
- Laser Altimeter, GPS, 9DOF IMU

Due to predictable difficulties in designing a reliable locomotion system capable of navigating the marshland, this design avoids the issue entirely by relying on a human operator who would carry the device around by hand and place it down at the specified sampling locations. Traditional sampling expeditions have been done on foot, which proves the versatility of human legs that are capable of navigating the marshland. A novel feature allows researchers who already own expensive auger tools to attach their own tools directly to the machine, letting them motorize any tool that they have to precisely monitor the amount of force applied to a soil core sample. This also grants adaptability to various soil types as long as they have access to the particular auger tooltip. However, this also means that a majority of the sampling procedure is now reliant on human aid to operate, such as removing the sample from the tool and cleaning the tool in between samples.

<u>Design #3 – Handheld Automated Sampler with Modular PVC Tooltips:</u>

The second design heavily relies on the human operator for much of the sampling process which defeats some of the purpose of automating the sampling procedure. To avoid this, another approach is taken for the handheld design to maximize the usefulness of a motorized auger by altering the design of the auger to a modular one:

- Handheld Device
- PVC Pipes
- Tool Storage Using Swapping Tooltips
- No Cleaning
- Laser Altimeter, GPS, 9DOF IMU

Many similarities are observed compared to the second design, with the major difference being the actual tool that would be talking the soil core samples. The use of PVC pipes were specifically chosen due to their wide availability at any hardware store and relative cheapness compared to specialized auger tools. Making the tooltips cheap and modular allows samples to be taken and stored directly within the PVC pipes, where a new PVC pipe would be reloaded onto the machine before collecting another sample. This design simultaneously solves both the sample collection and tool decontamination issues by removing the need to clean the used tool after each sample. An operator would simply go to a new sampling site, load a PVC pipe onto the machine and detach the PVC pipe once it is finished, which the operator can carry on his own using a backpack.

Design Candidate Selection

To decide on the best design candidate, a weighted objectives tree was devised in order to create weights for different features, shown in Figure 8. Broad categories were first identified, then broken up into smaller subcategories. It was determined that sampling was the primary concern, while complexity and cost were also weighted highly in order to keep the design realistic. The operational characteristics and maneuverability categories were considered to be non-essential to the problem and weighted less. After obtaining our weights, we can score our designs and apply our weights. The results are shown in the weighted objectives chart shown in Figure 9:

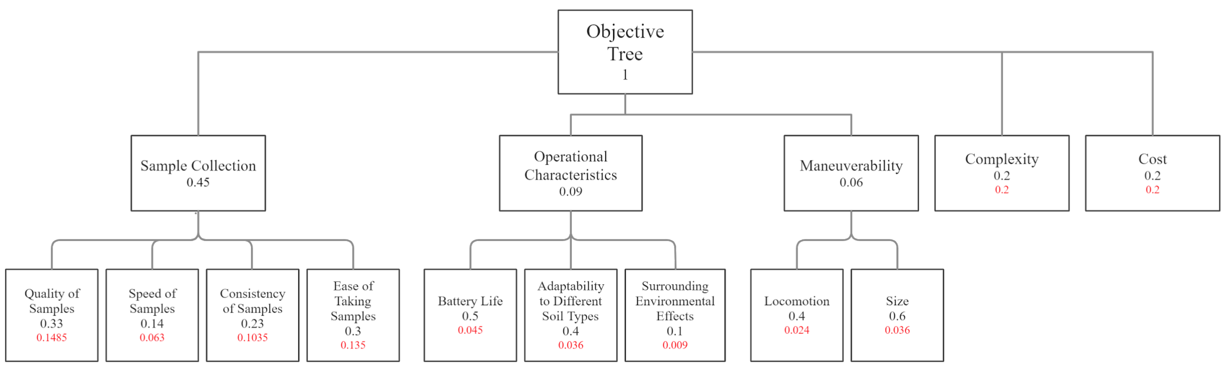


Figure 8. *Weighted objectives tree – Each of the blocks in the objective tree were given a percentage that represents the relative weights/importance of each element. The red values at the bottom were the final weights used to compute the weighted objectives table in Figure 9.*

		Traditional Auger		Design #1		Design #2		Design #3	
Criteria	Weight	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Sample Quality	0.1485	5	0.7425	8	1.188	8	1.188	8	1.188
Sample Speed	0.063	1	0.063	7	0.441	5	0.315	5	0.315
Sample Consistency	0.1035	3	0.3105	10	1.035	9	0.9315	9	0.9315
Ease of Sampling	0.135	1	0.135	10	1.35	3	0.405	8	1.08
Battery Life	0.045	10	0.45	2	0.09	8	0.36	6	0.27
Adaptability to Soil	0.036	1	0.036	6	0.216	6	0.216	5	0.18
Environmental Effects	0.009	9	0.081	3	0.027	6	0.054	7	0.063
Locomotion	0.024	10	0.24	8	0.192	2	0.048	2	0.048
Size	0.036	8	0.288	4	0.144	5	0.18	5	0.18
Complexity	0.2	10	2	1	0.2	7	1.4	6	1.2
Cost	0.2	2	0.4	1	0.2	5	1	5	1
			4.746		5.083		6.0975		6.4555

Figure 9. *Weighted objectives table – Each criteria/feature of the designs were given a percentage weight based on the computed values found in Figure 8, and each design was given a score out of 10 for each of the criteria. As comparison, the three designs were compared against a traditional auger operated by hand, where the final score is out of 10.*

As shown in the table above, the handheld design still maintains a high score on the important sampling criteria, but eases the burden on design complexity and cost. While the autonomous design scores high in some areas the handheld versions do not, such as in locomotion, it instead comes with the downsides of decreasing battery life, complexity, and cost amongst other aspects. The traditional auger is useful as a baseline, which is obviously very simple and portable, but has inferior performance with the core sampling tasks and is still expensive for the amount of features. The handheld designs take many of the advantages of the autonomous design while making the design more viable in terms of cost and complexity. In deciding between the modular PVC tooltip design and the commercial auger design, the designs were similar, but ultimately the added hassle of having to use the auger tooltip adds too much burden on the user in the process of taking the sample. Because of its high score, we will be picking the handheld PVC tooltip design as our design candidate.

❖ Part 2 – Design/Engineering Work

The following sections describe the engineering work that was done for the past six weeks. The work and design (and subsequently the capabilities/deliverables) were generally divided into the following subsystems:

1. Drill Head/Corer: The mechanical design of the drill head that works with the nominal PVC pipe coring tool
2. Chassis and Legs: The mechanical design of the main body of the device and the actuation unit (which incorporates the drill head). The design of the stabilization components, specifically the legs and gimbal, is also included in this subsystem.
3. Navigation: The design of the navigation algorithm that will direct the user from one sample point to the next.
4. Motor Control: The design of the motor control algorithm that will control the motion of the motors in the actuation unit.

Week 1

Deliverable: Determination of the most effective methods for coring, and estimation of the force(s) required to collect a soil sample in marshland.

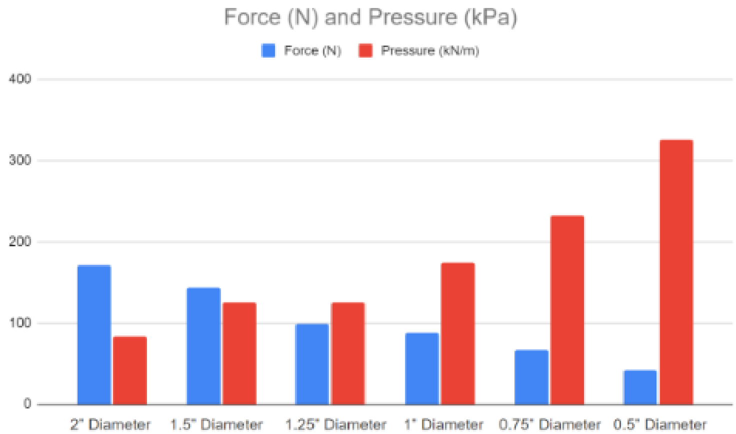
Niravroh:

The head of the coring tool would be critical to the rest of the assembly, as it is the main point of contact between the dirt and our machine. Therefore, we had a few criteria with which we looked for solutions:

1. The head had to be able to penetrate the dirt, and pull a core of soil back up as it is lifted.
2. There had to be a feasible way we could transfer the dirt from the tool to a storage unit so the sample could be taken back to a lab for analysis.
3. The head would then have to be cleaned so that the next sample isn't contaminated.

With these in mind, we decided to use PVC pipes. There was already existing literature from labs that didn't want to pay for coring tools and instead used PVC pipes to successfully collect soil cores. The pipes are able to penetrate dirt on their own, and if labs are willing to sharpen the ends of their pipes, then the force is decreased even more. This also solves the issue of having to somehow securely move dirt from the tool to a sample holder. By detaching the pipe itself while it still had the dirt inside, the PVC pipe would double up as both coring tool and soil sample container. Finally, since we would change out the pipe for every sample, this would eliminate any major concerns of contamination.

As there has not been much research that we could find on the actual force needed to drive a PVC pipe into marsh ground, we decided to head to Ballona Marsh, and do our own force testing to determine what diameter PVC pipe we would use for our machine.



Diameter (Inches)	Force (N)	Pressure (kN/m)
2	170.4978	84.12042798
1.5	143.226	125.6267228
1.25	99.081	125.1448668
1	87.7995	173.2745294
0.75	66.2175	232.3233914
0.5	41.202	325.252748

Figure 10. *Force and pressure required to insert PVC pipes of various diameters into ground.*

After this testing, we decided that 1.25" diameter PVC pipes offer us the best balance of force, pressure, and volume of sample.

Deliverable: Determination of the most effective methods to stabilize the robot during coring, make tagging and sampling simple and ergonomic for the user.
Jaewon:

The stability/leveling mechanism is the contact between the chassis and the ground, and needs to be able to balance the machine on uneven terrain, while being portable. It also needs to be able to easily level the chassis so that the pipe is oriented vertically. The entirety of the chassis, including the leveling mechanism, needs to be able to maintain stability against the force from the ground as the pipe digs into the ground. Keeping the center of mass close to the ground increases stability as well. For these reasons, two options were considered.

1. Tripod
    a. Pros: Can balance on uneven terrain. Portable. Lightweight. Easier to change the orientation of the pipe
    b. Cons: Not as stable as a rectangular robot base
2. Robot base
    a. Pros: More stable than a tripod
    b. Cons: Hard to balance on uneven terrain. Heavy and less portable. Difficult to change the orientation of the pipe

The cons of the robot base idea outweigh the pros. The lack of portability, difficulty of maintaining balance, and difficulty to change the direction of the pipe make this a less viable choice to operate in the marshlands. Meanwhile, tripod's only cons, the relatively lower stability, can be addressed by other means if necessary, such as pegs that secure the machine to the ground.

Tripods can change the angular orientation of its head by adjusting the lengths of each leg. Therefore, using two telescoping parts for each leg and implementing a linear actuator inside sufficiently addresses the leveling requirements. Therefore, A cylindrical chassis with the three legs attached to its side can change the angular orientation of the chassis by adjusting the length of each leg. In order to automate the leveling process, an IMU on the chassis can determine the current orientation, compute the desired length of each leg according to the orientation, and send a signal to the linear actuators to adjust the lengths of each leg.

Michael:

Laser Reflector: During week one, we operated under the assumption that we would be using laser reflectors to determine the relative altitude of various sampling locations based on a standard “given” site altitude. This was chosen to simplify the collection of altitude data for each sampling location. In order to accomplish this, a socket-joint mounted laser reflector would be used. Based on the complexity of the requirements for usage and calculations associated, a laser reflector is an ineffective tool for measuring altitude. Significant error also is introduced in the relative comparisons used. The usage of a laser reflector as an accessory tool could be used, but shows significant inferiority to other methods of altitude determination.

Tagging Samples: In order to tag samples successfully, two processes must occur: geolocation and geotagging. In order to accomplish either process, a GPS unit must be utilized. This unit can be either integrated into the overall design or come as a separate external device, such as a smartphone.

1. Geolocation
    a. Geolocation is the process of obtaining digital location data. This data should be obtained from GPS satellites to ensure the most accurate data is obtained. Since the accuracy of GPS units do not depend significantly on the device itself, neither option shows a significant benefit in that regard. An internal GPS system holds the advantage of a fully integrated system, while an external system can allow for the easy access of data. However, external systems like smartphones rely on cellular signals that may not be accessible in many marshland environments.
2. Geotagging
    a. Geotagging is the process of associating the previously obtained digital location data with an object to allow for further study. This itself is not a very difficult process, however; a method of marking or noting which samples are associated with which locations is necessary as well. Our device can be designed to mark the samples itself, or the user can be expected to mark them with a writing implement of their choice.

Linda:

Sealing: For our device, the pipe would need to be sealed only at one end. Once the sample is removed from the ground, the exposed end would be sealed and the vacuum created by sealing one end would be enough to secure the sample within the pipe so that the pipe could be removed from the device. There are various methods that can be used to seal the pipe that can either be automated in our device or be left to the user to execute:

1. Heat sealing with a plastic
    a. Pros: Heat seal would be easy to remove for the user
    b. Cons: Plastic could be more costly than the other options; depending on strength of plastic, may not be able to hold the vacuum within the pipe
2. Tape ends
    a. Pros: Duct tape is readily available and inexpensive; based on our team member's experience, this method is already used in soil sampling
    b. Cons: Could be difficult to remove
3. Use commercially available end caps
    a. Pros: Already used in soil sampling [3]; sturdiest seal yet still easy to attach and remove from pipe
    b. Cons: Automating this type of seal would be the most complex because the seal needs to be aligned with the pipe's end and then be pushed into the pipe

For all of these methods, developing a sealing mechanism and incorporating it would add bulk and increase the weight of the device. According to our teammate with soil sampling experience, sealing samples was a menial task that didn't take much effort or time. The benefits of adding an automatic sealing mechanism is that it eliminates this menial task and makes the job of soil sampling more convenient for the user. The issues with adding such a feature is that the problem we are addressing with soil sampling is that coring and tagging are time-consuming and inaccurate. However, sealing the sample does not influence tagging or coring directly, and the time savings would be minimal. After discussing these points with the team, we determined that adding a sealing mechanism would be a nice feature to have, but is not needed to address the problems with soil core sampling and is therefore unnecessary to include in the device. Instead, the user will be expected to seal the pipe.

Actuation: In manual soil sampling, twisting the coring tool while simultaneously pushing it into the ground helps decrease the amount of soil disturbance and increase the sample quality, and this method can also be used to pull the sample out of the ground. Therefore, this device will need to actuate the coring tool with 2 degrees of freedom (DOF), a vertical linear and a rotational DOF about the vertical axis. There are a couple primary methods that can be used to achieve this motion:

1. A screw with one motor
    a. Pros: Only need one motor
    b. Cons: The motions are coupled, which makes it less flexible in terms of force or speed control of each DOF

2. Stacking motors to achieve 2 DOF
    a. Pros: DOFs are decoupled, which allows for greater control of each motion
    b. Cons: Two motors required

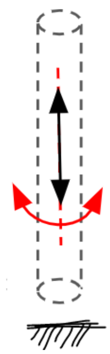


Figure 11. *Representation of the necessary DOFS for the coring tool.*

For consistent soil sample disturbance, it is desirable that the torsional speed of the coring tool remains constant throughout. However, the vertical speed of the corer may need to be variable depending on the soil layer that it is crossing and whether any disturbances are encountered and need to be overcome. Based on this, stacking DOFs is the best method of actuating the coring tool so that better quality samples are collected.
Motor types were also researched. At this point in the project, stepper motors were determined to be the best option to use because they allow for precise position control, which would help to ensure accurate and repeatable sample depth [14].

Ergonomic Design: Based on the ergonomic design principles, the following should be considered during design to prevent injury to the user and ensure ease of use [15]:

1. The center of mass (COM) of the device should be closely aligned with the COM of user during transport and be kept in the power/comfort zone during coring
2. Keep buttons easily accessible from nominal position but not easy to accidentally press a button
3. The display that will be used for navigation should accessible
4. If vibrations are a concern, apply damping to the system
5. Handholds with a comfortable grip shape and easy access can be used during transport and during coring (to steady the device)

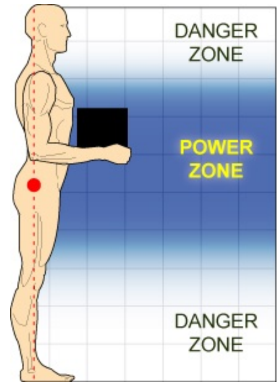


Figure 12. *Representation of the power/comfort zone.*

Deliverable: Various approaches to traveling salesman problem (TSP) that could be applied to our problem of navigation in a 2D environment.

Hayato:

One of the main objectives of our device was to increase the productivity of the user by shortening the time it takes to collect each soil core sample. A sampling procedure consists of two main phases: the drilling phase and the transition phase in between. Thus, the main goal for the navigation system was to enable the user to follow simple commands that maximize their efficiency during the transition phase. By analyzing the nature of the problem at hand, we explored topics such as the traveling salesman problem (TSP) and different clustering algorithms.

Farooq:

The TSP is considered an NP-hard problem within the field of combinatorial optimization. This means that it is substantially easier to approximate solutions to the problem than it is to find and verify if one achieved the optimal solution. Thus, we considered various methods of implementing navigation for our purposes. Our goal was to find a method that produced a navigation path that was an approximate optimal solution and one that was good enough for our purposes rather than an exactly optimal solution for our problem.

The main types of algorithms we considered for our predefined field were the Brute Computation Force Method, the Nearest Neighbors Method, the Biogeography Migration Algorithm, and the Markov Decision Process (MDP) and K-Medoids Algorithm. The Brute Force Computation Method involves calculating every possible route given a set of nodes in order to find the most optimal path. While this method does find the exact most optimal path and is easy to understand, it has drawbacks we explored in Week 2. The Nearest Neighbor's Method works by starting at one node, and then traversing to the nearest node next, and so on until the traverser reaches the starting node having visited each node once. The Biogeography Migration Algorithm works based on factors specific to the type of environment within which the user is operating. Lastly, MDP works in conjunction with the clustering algorithm based on K-Medoids by combining reinforcement learning with iterative clustering while pivoting about the most central data point in each cluster.

Deliverable: Github repository to store algorithms, and development of the initial setup for a basic python simulator.

Hayato:

In addition to these analyses and research of individual topics, a basic foundation for a Python analytical simulation was created in anticipation of future prototyping of different algorithms. Python was selected as the programming language for its ease of use and proficiency by the three members of the electrical subsystem. This decision also enabled the use of premade Python libraries that were readily available on the internet, helping to boost the coding process. The primitive simulation consisted of a class structure holding a set of sampling nodes and helper functions that visualised this dataset in a 2D matplotlib plot. An example of the outputted plot is shown below:

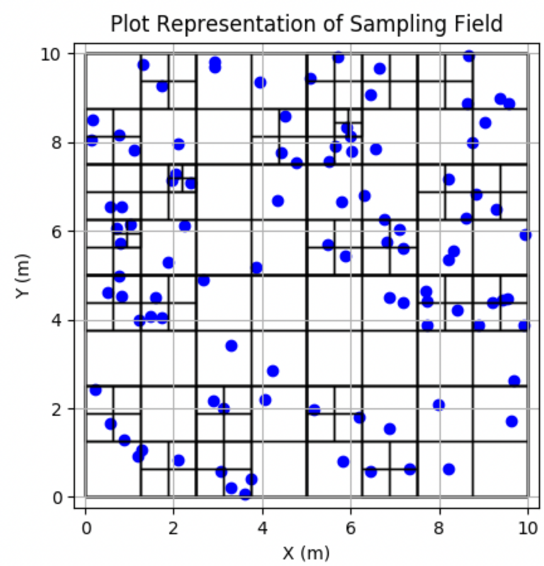


Figure 13. *Initial Python Simulation Results – The blue points represent each sampling node that was generated by randomly assigning X and Y coordinates within the range of the field. The black boxes represent the quadtree data structure that was implemented to help with proximity distance calculations later down the line of algorithm development. By observation, it can be seen how some samples are taken too close to each other, resulting in an uneven density of samples.*

As shown above, the primitive simulation only displays a blue point at each of the randomly selected locations and visualizes its location relative to other sample nodes within a given field size. Each sampling node was stored within a quadtree to enable faster searching and computing later down the line when different types of algorithms are implemented. The source code was pushed through git to log the progress made so far and to allow the sharing of code amongst our members.

Deliverable: Definition of the motor control problem in comparison to similar class problems and list of techniques that we can use to solve it.
Matthew:

In our original planning, we had intended for the motor control to be implemented using an MDP model, initial feedback led us to reconsider our design. We decided to begin work on a PID control design, and only moving on to more complex designs if necessary. When I researched the motor control problem, the overall motorized soil sampling problem proved to be a relatively isolated use case that didn't have much precedence. Research was initially focused on finding ways to drill adaptively through software, as much of which was done in industrial oil drilling. Many of the concepts or ideas were tangentially related to our problem, but were unfeasible or not applicable to our use case. Some of the error detection relied on advanced drill sensors, and the fact that we are using a pvc pipe instead of an actual drill bit made many of the concepts non applicable. What was taken from the research into drilling was monitoring the position taken from the concept of rate of penetration, which was what we initially used for our setpoint for our PID control, as well as the general relationships between increasing the weight on bit and rpm of the drill. In terms of research into the process of soil sampling however, not much could be found, as it is currently almost always done by hand. This meant that the specifications in terms of quality sampling would be up to use to determine.

Week 2

Deliverable: Development of the initial CAD of the nominal coring tool/drill head, and simulation of the forces acting on the drill head to check compliance (static FEA results).
Niravroh:

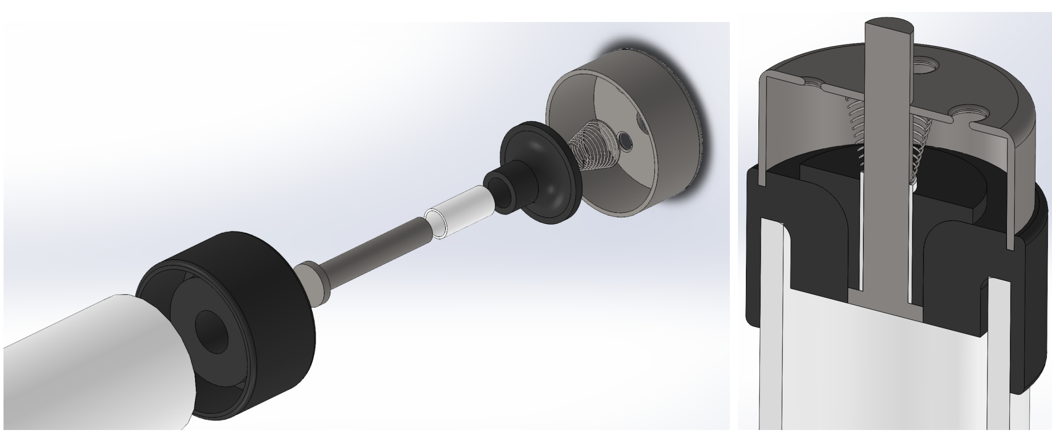


Figure 14. Left: *Exploded view of initial coring head design.* ***Right:*** *Sectioned view of design.*

This is the initial design of the coring head. The housing at the base of the PVC pipe has a valve built in to let out air as we are pushing the pipe into the soil. This valve will also double up as a quick-release system to allow the PVC pipe to be removed after a sample is taken.

Deliverable: Development of the initial CAD of the chassis and legs, and simulation of the forces acting on the chassis to check compliance (static FEA results).

Jaewon:

Initial design for the legs include three parts: the upper part of the leg to be connected to the chassis, the lower part of the leg to come into contact with the ground, and the linear actuator in the middle.

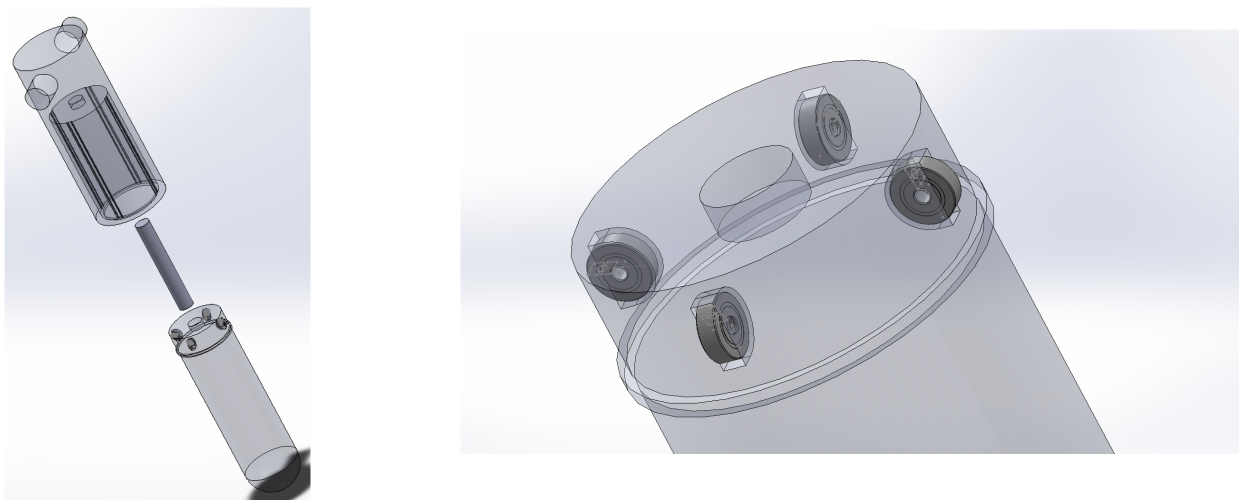


Figure 15. Left: *Exploded view of leg.* ***Right:*** *Magnified view of bottom part.*

Top part
- Hollow for the bottom part to slide in.
- At the center of the ceiling, there is a hole for the linear actuator to be lodged in.
- Shaft at its top end to create a joint that connects it to the chassis.
- Railing for bottom part to slide with reduced friction

Bottom part
- Round on its bottom end to equally address any angle at which the leg makes with the ground
- Small hole for the linear actuator to be lodged in
- Bearings to reduce friction as it slides up into the top part

Linear actuator
- Cylindrical shape as a placeholder
- Its change in length causes the top and bottom parts to slide toward and away from each other

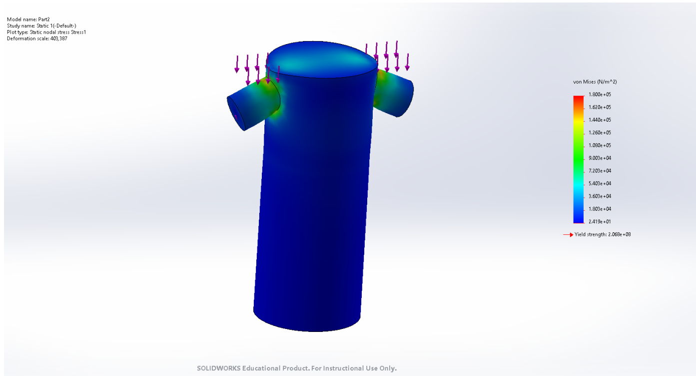


Figure 16. *FEA on the top part*

The picture above shows the force simulation results for the top part. Steel was tentatively chosen as the material. The shaft at the top can withstand the weight of the chassis, as it has a factor of safety larger than 1000.

As more research was done on linear actuators, we realized towards the end of the week that a design based on a cylindrical placeholder was not ideal. Using a ball screw mechanism turned out to be much more efficient and stable. It produces minimal friction, converts 90% of rotational motion into linear motion, and can bear heavy loads [16]. Next week's design was to change to best make use of the ball screw mechanism.

Michael:

Laser Reflector: Based on previous research, using a laser reflector is not an effective or viable method of determining altitude. There is minimal industry usage of altitude determination concepts using relative altitude due to the significant parasitic error associated with initial altitude assumption and subsequent data collection. In order to eliminate this error, this concept could be overwritten in favor of a digital altimeter. By using a low-cost digital altimeter, the error associated with collecting altitude data can be minimized. The altimeter could be included as a part of or connected to our GPS unit to associate the site altitude data with the site location data. Digital altimeters are widely available and utilized for these reasons, and their use would result in a significant increase in sample data quality and therefore design success.

Tagging Mechanism: Currently, soil core samples are collected and tagged by their collector directly. This is typically accomplished by noting the sample number and associated location directly onto the sample itself. Our device will be saving location data within its GPS unit, associated with a specific sample number, tag, or classification. We expect our users to label their own samples, as industry standard dictates. However, the associated location and altitude data will be accessible via the device's GPS unit. This will be accessible through a digital output such as a USB port. This will allow for easy user access and ability to perform sample analysis.

Based on the previous weeks' research, our device should include a digital GPS sensor and associated display. This will also include a digital altimeter. Our data will be easily obtainable and exportable into a spreadsheet for comparison with user marked samples.

Additionally, our initial chassis concept designs were formulated. Two designs were completed, a rectangular frame and a cylindrical one. Two views of each are shown below:

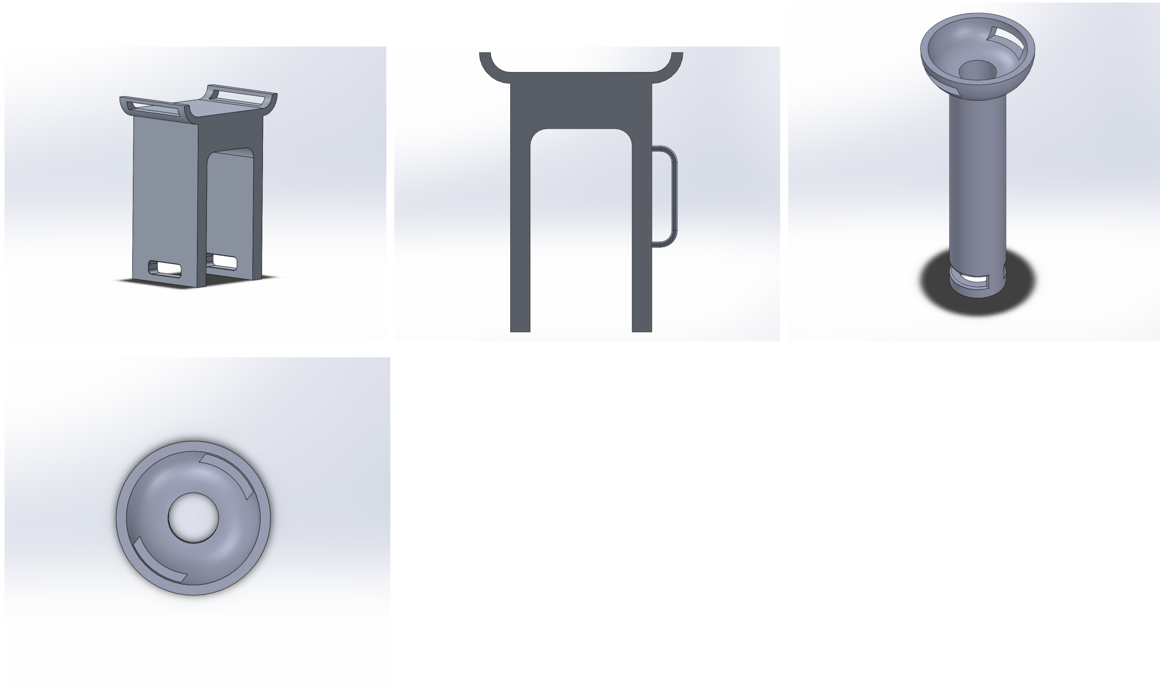


Figure 17.

A simple stress analysis was performed in order to analyze whether the concepts could function in our planned environment and considering our assumed conditions. These showed significant strength, allowing for further weight optimization in the future. The results are shown below:

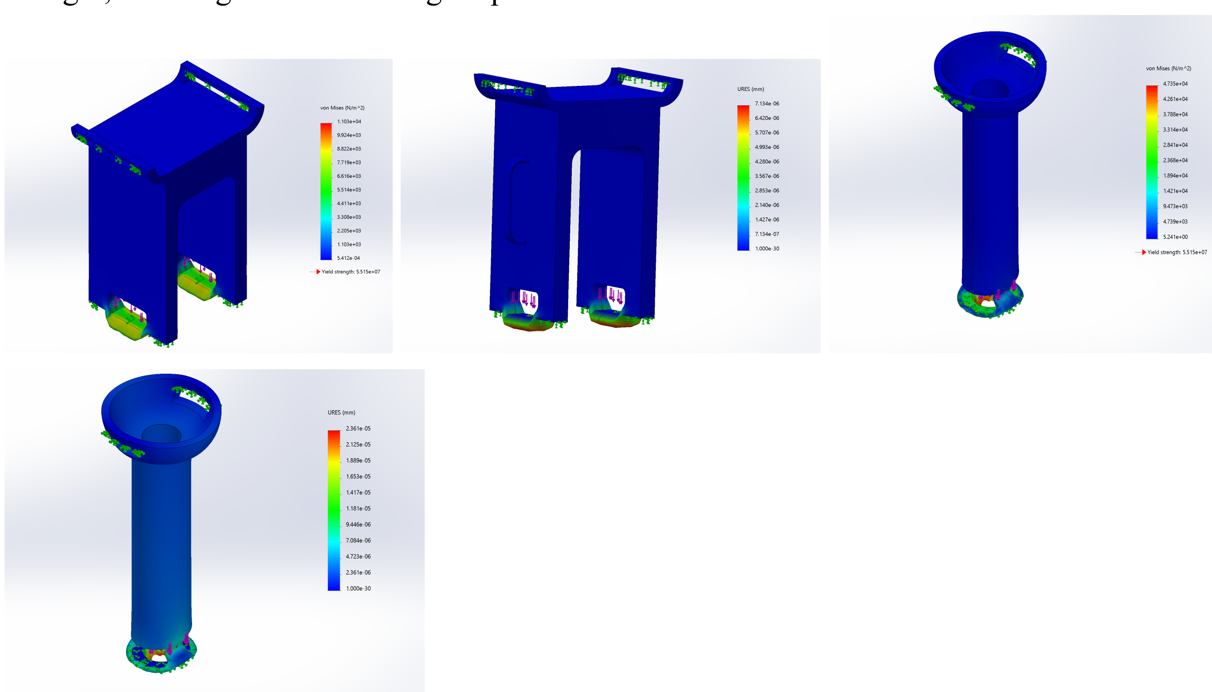


Figure 18.

Based on the above results, both chassis designs will be successful in withstanding our simulated operating conditions. However, the cylindrical chassis design had a significantly lower overall mass and should be explored further for optimization.

Linda:

Actuation: We determined that the translational motion could be supplied using a ball screw and a DC motor. We overwrote our previous choice of using stepper motors because we learned that they are precise only if there is little disturbance (which is not the case for our application where the soil type may vary and other impedances to the motion of the corer may exist), and are not suitable for feedback control (at this point in the project, we were considering either force control or velocity and position control). In the light of this information, we determined that a DC motor would be better suited to our device and allow us to use PID feedback to control the motion of the coring tool. A ball screw was chosen as opposed to other methods of linear actuation because they have better repeatability than other methods and can be calibrated for accuracy. Ball screws also have better performance for vertical applications than other methods [17].
For the rotational DOF, we decided to use a DC motor for similar reasons as previously mentioned; this choice of motor allowed us to develop our own feedback loop to precisely control either the force or velocity and position of the motor.

Damping: Based on Week 1's research on ergonomic design, we were concerned that the vibrations created during coring would be significant and possibly injure the user if they were using the handholds during the operation. The rotation of the motors would supply the largest vibrations, and since the motors should not be moving very fast in our application we predicted that the frequency of vibrations produced should be relatively small, such that damping provided by the environment itself (which is primarily composed of soft soils and water) should be enough to mitigate any injury to the user. Therefore, we concluded at this point that the damping was negligible in our design, and this would re-evaluated once the maximum motor speeds were known.

Tagging: The samples need to be tagged with location and elevation data. The location data can be found using a GPS sensor. For the elevation, we had previously considered placing a laser reflector on the device to be used in tandem with a laser beam tool; however, we found that we could also use an inexpensive altimeter sensor to accurately get the elevation data of a sample. Since adding this sensor would remove the need for the user to bring an extra tool to the field, we decided that this was a beneficial design choice for the user that decreased the required labor and did not add any significant costs. The data would be stored digitally for each sample, and could later be retrieved by the user through a USB. Since the PVC pipes are something that the user can buy themselves, the user would be expected to mark or number the samples themselves. By not creating a mechanism that prints or stamps the sample number on the pipe, the scope of our project remains focused on the most important aspects of manual soil sampling that we are aiming to improve: improve the speed and quality of soil sampling, and streamline the collection of location and elevation data.

Deliverable: Selection of an approximation algorithm of the TSP and understanding of the limitations of the brute force method.
Farooq:

The Brute Force Computation Method proves infeasible for TSP problems with more than only a few nodes because it becomes exponentially expensive proportional to the number of nodes to be considered. This is the classic example used to teach students that solving complex problems using raw computing power rather than finding approximate methods proves impractical. The advantages of the Nearest Neighbor's Method include that it is simple to implement, easy to understand, and is considered an efficient algorithm in general, but they are outweighed by the disadvantages, including a less-than-favorable time-complexity when the input is hundreds of nodes. Nearest Neighbor's need to store all branching pathways alone adds substantially to the time complexity. The Biogeography Migration Algorithm appeared promising at first given the marshland environment we're working within, but we soon found that it's reliance on factors such as the habitat suitability index (HSI) for performance proves too unreliable if we want to work in many different types of marshlands. We eventually selected the MDP and K-Medoids Algorithm as most suitable for starting off. This is because this approach would utilize our understanding of MDP from class experiences for path-finding purposes while combining that with a method of clustering (K-Medoids) allowing for a novel yet appropriate implementation.

At this point, we also reconsidered using MDP as explained in Week 3, but we decided to continue with K-Medoids as the planned method for clustering considering it's simple yet effective.

Hayato:

An individual using our device would have complete control over the method they choose to sample a given field. To simulate this fact within the Python script, we needed a way to generate a set of randomly selected sampling locations given a field size. A trivial sampling method would be a grid approach, where each sample is distributed evenly along the two axes of the cartesian coordinates. Despite its simplicity, this method is prone to artifacts that originate from all nodes perfectly lining up along rows and columns. Such effects cause aliasing, which is detrimental for our application when these samples are supposed to generate a realistic 3D diagram of the soil composition in the marshland.

Another trivial sampling method would be a purely random approach, where two sets of random floating-point numbers are generated and interpreted as cartesian coordinates for each sampling location. This method does remove the issue of aliasing but introduces new problems when two sampling locations are selected too close to each other, causing the density of the samples to fluctuate throughout the field. Such behavior is undesirable when the objective of the soil core samples is to obtain uniform data about the region.

We ultimately decided to use Poisson-disk sampling due to its simplicity and effectiveness against aliasing, as seen from its extensive application in computer graphics. Poisson-disk sampling is a technique for generating a random set of tightly packed data points in an area by defining a minimum distance required between each data point. By using an available library that takes advantage of Robert Bridson's algorithm for generating Poisson-disk samples, the sampling locations were generated, as shown below [19]:

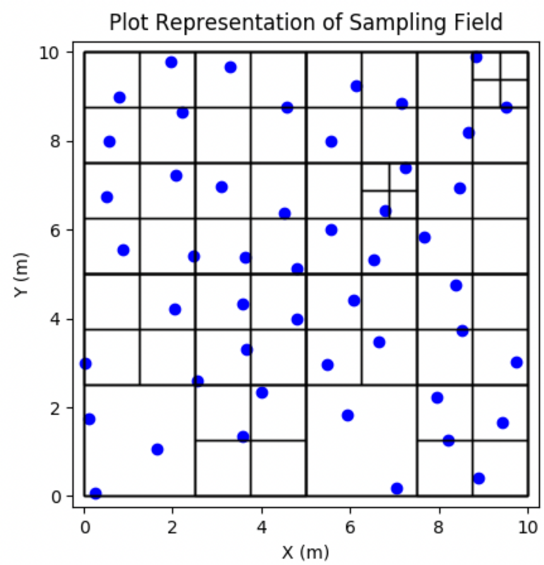


Figure 19. *Poisson-Disk Sampling to Generate Random Sampling Locations in a Field – The blue points represent a sampling node that was randomly chosen by the poisson-disk sampling method, which are all separated by at least a meter. By observation, this statement is proved to be true, since no two nodes are generated too close to each other.*

Deliverable: Development of the initial motor controller algorithm.
Matthew:

We had decided on PID control, but there were still questions left to be asked in terms of what to be used as our setpoint. We narrowed our options down to two, based on minimizing the disturbance to the sample, as well as how difficult they were to implement. Constant force could potentially have the least amount of disturbance to the sample, but could be difficult to implement. Constant speed would be easier to implement, but would result in varying force if the hardness of the soil changed significantly throughout the sample depth, potentially creating disturbance.

If the soil varied greatly in terms of soil density and hardness, constant force would still have little disturbance, but would have more varied sampling times due to not adjusting. Additionally, if the hardness was sufficient, the motor could potentially not output enough force to drive the pipe deeper, causing failure.   Constant speed has the tradeoff of varied force and likely more disturbance, but succeeds in many other areas. Sampling time is more consistent due to maintaining speed, and has a much higher threshold for stoppage due to hardness. In the case where there is relatively little variety in hardness, which is the use case we expect, constant speed also wins out. Constant speed and constant force should perform similarly in uniform soil, so the easier implementation of constant speed is beneficial. Ultimately, we decided on constant speed as our setpoint.

Week 3

Deliverable: Continued development in the drill head assembly's design (CAD), and check of its compliance with the drilling forces (static FEA results).

Niravroh:

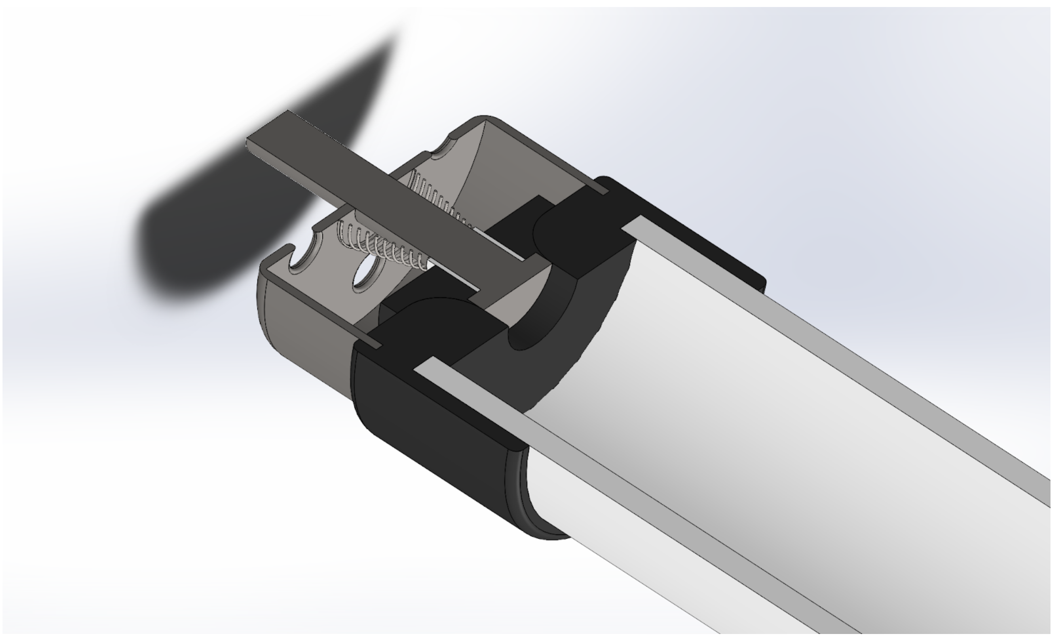


Figure 20. *Sectioned view of updated drill head design.*

The head assembly was refined, allowing for more smooth operation of the valve. The previous design had a neck that was too long at the center, meaning that it would take significant force of air to move the head enough to allow escape. This improved design was made to have much less resistance. There were also some overlapping elements that were fixed in this iteration.

Deliverable: Continued development in the designs for the chassis and legs (CAD), and chosen motors and ball screw (actuation).

Jaewon:

The legs design changed drastically as a new idea for stability mechanism arose: using a gimbal to naturally orient the chassis. This reduces the cost of production, as there is no linear actuator or wiring in the legs. However, the legs need to be a lot longer as it can no longer be attached to the side of the chassis, but rather above. The legs need to come together to a sturdy base, beneath which the gimbal can hang, followed by the chassis.

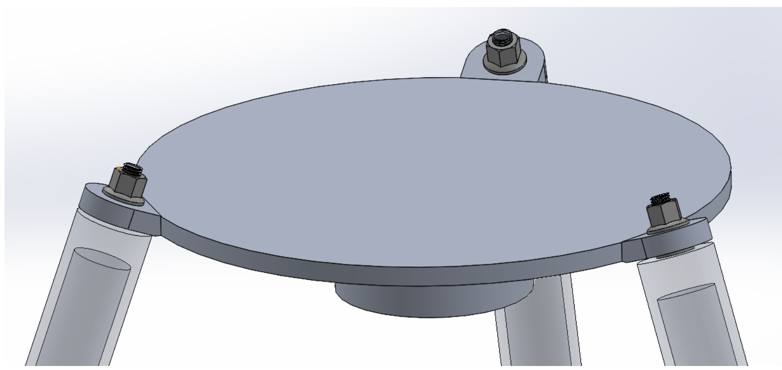
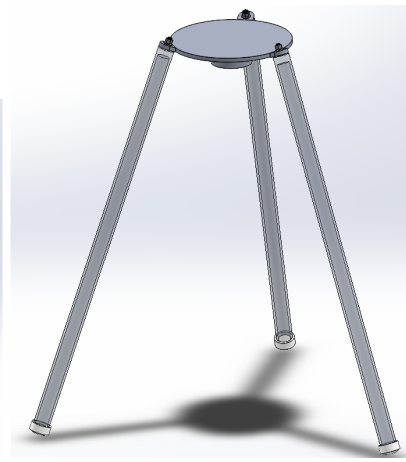



Figure 21. Left: *Tripod head.* ***Right:*** *Total view of tripod.*

Each leg is fastened to the tripod head with a flange nut. A placeholder of hollow cylindrical shape is beneath the tripod head to act as a mounting point for the gimbal. Each leg has a curved plastic leg cap at the end to distribute pressure evenly regardless of the angle between the leg and the ground. Material is changed to aluminum alloy 6061 since a lighter material is needed to reduce the weight. The leg angle is tentatively chosen as 20 degrees from the vertical axis. FEA analysis tells us the factor of safety of the tripod head is 5.2.

Michael:

Chassis Design and Optimization: Our chassis design was continued this week. After choosing to explore the cylindrical design due to the previously mentioned lower overall mass. The updated design is shown in the figures below:

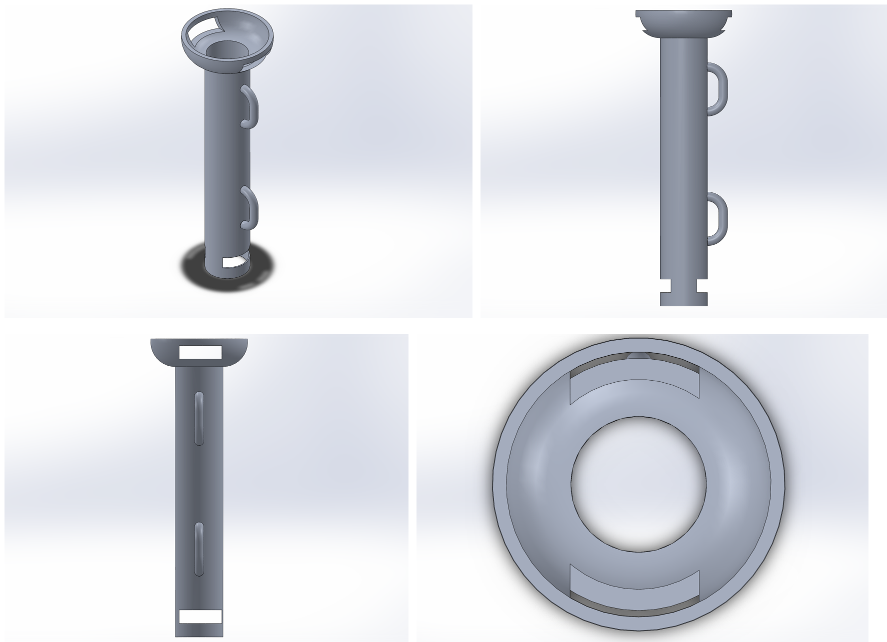


Figure 22.

In the above design, one can see that multiple handles were added to the side of the chassis to allow for easy transportation by one or two users. These handles are not expected to be used during operation. Instead, operators can use the lower foothold and upper bowl handholds to add additional support and dampen vibrations throughout the system. Additionally, the overall mass of the system was decreased significantly. Starting from over 90 lbs, the chassis mass was reduced by 87% down to 12 lbs. Despite a significantly reduced thickness of the chassis, a factor of safety of 2.5 was maintained throughout the entire design. This will allow for safe and consistent strength throughout the entire system, preventing material failure during carrying, use, or any drilling procedure. The massive overall reduction in weight was necessary to reduce the number of users required to operate the device and collect samples. Ideally, only one user will be required. Based on this, it was determined that our goal overall system mass is 40 lbs or fewer.

Linda:

Translational DOF: Calculating the requirements for the DC motor and ball screw was an iterative process in that the parameters of the ball screw (specifically the pitch) influenced the requirements for the DC motor. Since we are collecting samples that are 1.5 ft in length, and the distance between the ground and the bottom of the chassis can be variable (depending on how the chassis is stabilized by the legs), the stroke length of the ball screw was set to be 2 ft, or 609.60 mm. The accuracy of the ball screw also needed to satisfy our requirement of 95% accuracy in the depth of the sample; if the entire stroke of the ball screw was travelled, then the maximum allowable error would be ± 30.48 mm. Based on these specifications, the CHUANGNENG SFU1605 RM1605 ball screw was ultimately selected. The threaded length satisfied our stroke requirement, and the

accuracy is Class 7, such that the maximum error in depth would be ± 0.10 mm, which exceeds our requirements [19]. Since no friction or efficiency specifications were available for the product, we assumed typical values for ball screws where the friction is 0.01 and the efficiency is 0.90 [16].
Based on the pitch of the ball screw, we were then able to determine the torque requirements for the DC motor. The torque required was also found using the maximum force experienced during coring, which was found to be the experimentally measured force to push of 100 N rather than the force required to lift the weight of the pipe (which was calculated using the weight relation of 43 lbs/100 ft of PVC pipe and the upper limit bulk density of soil in wetlands, 1.7 g/cm^3) and sample (about 24 N) [20,21]. The speed requirements were determined using our speed specification, where coring is limited to 30 seconds. Based on this, we estimated that 20 seconds would be used to push the pipe into the ground and 10 seconds would be used to retrieve the sample. The calculations are seen in the table below. Based on these calculations and with a factor of safety of 2, the DC motor was required to have a maximum torque of 178.61 N-mm and a maximum speed of 36.67 RPM. The motor that was found that best suited these requirements while also having a reasonable cost was the PIS-0934, with a rated torque of 0.196 N-m and rated speed of 450 RPM.

Table 1. *Calculations for ball screw and DC motor requirements for the translational DOF.*

Known Parameters	*Symbol*	*Value*	*Calculated Values*	*Symbol and Equation*	*Value*
Pipe Radius (mm)	r	15.875	Downwards Force (N)	$F_d = F_{max}FOS$	200.00
Stroke Length (mm)	L	609.60	Lift Force (N)	$F_l = (0.43L + \pi r^2 L\rho g)FOS$	23.74
Ball Screw Coefficient of Friction	μ	0.01	Downwards Speed (mm/s)	$V_d = L/t_d$	30.48
Ball Screw Efficiency	e	0.90	Lift Speed (mm/s)	$V_l = L/t_l$	60.96
Ball Screw Pitch (mm)	p	5.00	Axial Load	$F_a = F_d\,(1 + \mu)$	202.00
Factor of Safety	FOS	2.00	Drive Torque (N-mm)	$T_d = F_a p/(2\pi e)$	178.61
Experimental Force (N)	F_{max}	100.00	Required Motor Speed (RPM)	$\omega = 60V_l l/(2\pi r)$	36.67
Time to Push (s)	t_d	20			

Time to Lift (s)	t_l	10			

Rotational DOF: The torque requirements were calculated for rotation about the vertical axis of the pipe after the sample has been collected, so that the maximum amount of inertia is considered. The maximum speed was also set to be 100 RPM, since the torsional motion of the PVC pipe should be relatively slow. With a factor of safety of 3 to account for frictional effects, the required torque is 9.59×10^{-3} N-m. The motor that best fit these requirements was the PIS-0930, with a rated torque of 0.013 N-m and rated speed of 149 RPM.

Table 2. *Calculations of DC motor requirements for rotational DOF.*

Known Parameters	*Symbol*	*Value*	*Calculated Values*	*Symbol and Equation*	*Value*
Time to Accelerate (s)	t	0.50	Angular Acceleration (m/s^2)	$\alpha = 2\pi\omega/(60t)$	20.94
Maximum Speed (RPM)	w	100.00	Moment of Inertia ($kg\text{-}m^2$)	$I = mr^2/2 = F_l r^2/(4g)$	1.53×10^{-4}
Factor of Safety	FOS	3.00	Torque (N-m)	$T = I\alpha FOS$	9.59×10^{-3}
Lift Force (N)	F_l	23.74			

With the motors chosen, a CAD model of the actuation unit, including the drill head, ball screw, and representations of the DC motors, was made.

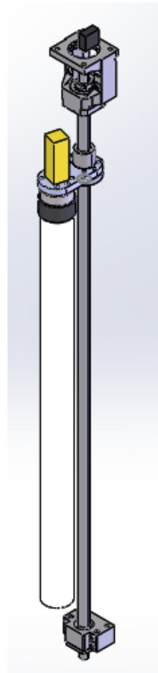


Figure 23. *CAD of actuation unit (yellow represents the motor for rotational DOF, black is the motor for linear DOF).*

Deliverable: Results of tests of the navigation algorithm with the chosen TSP approximation.
Farooq:

We switched from planning to solve the TSP using the Markov Decision Process to using Ant Colony Optimization. This is because implementing MDP for our purposes proved unnecessarily complex and over-optimal given the margin of error we were aiming for in our estimated solutions [22].

Ant Colony Optimization relies on two main heuristics: distance traveled and pheromone levels. The best edges between pairs of nodes are selected based on shortest distance and highest pheromone levels, with each heuristic having an associated weight inputted by the user. Pheromones are left behind by all virtual ants traveling along pathways - popular pathways given the network of nodes will tend to have higher pheromone levels. The full pseudocode for the algorithm is the following:

Begin
    Initialize
    While stopping criterion is not satisfied do
        Position each ant in a starting node
        Repeat
            For each ant **do**
                Choose next node by applying the state transition rule
                Apply step by step pheromone update

End for
Until every ant has built a solution
Update best solution
Apply offline pheromone update
End While
End [23]

Also suggested the clustering algorithm uses a central point defined by the user around which the clusters are formed. This way, the user would end up in an optimal, relatively central location between the clusters that would ensure the user would end up near the home base after collecting the final sample per cluster.

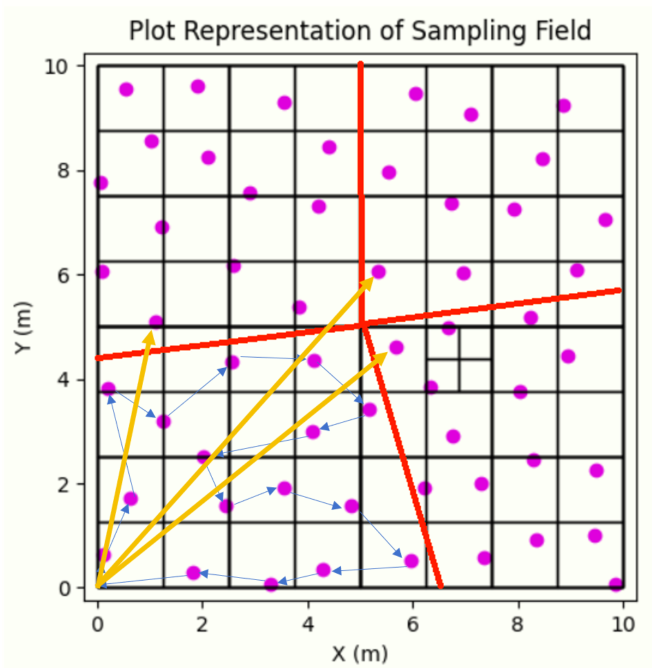


Figure 24. *Yellow lines demonstrate the lengthy distances users would have to travel per cluster if home base is not relatively centralized relative to sampling location clusters.*

Hayato:

We researched different types of clustering algorithms that would simplify the traveling salesman problem by dividing all sampling locations into smaller clusters traversable in a single expedition. Each path would travel through a limited number of samples dictated by the maximum capacity of soil cores that a user can carry comfortably. The clustering approach enables less load on the algorithm that solves the traveling salesman problem thanks to the reduced count of cities the agent needs to visit. The method also mimics a human behavior of accomplishing local tasks by region, which are proven to be more efficient over other traversal methods.

Due to its familiarity and use in one of the research papers referenced, we decided to investigate a K-means/K-medoids approach for the clustering algorithm [24]. The basic theory behind K-means is that each iteration of the algorithm repeats a sequence of finding a centroid node representing a particular cluster and using those nodes to assign each sampling location an ideal cluster by minimizing the distance to that centroid. The algorithm is known to converge for Euclidean distance functions, making it ideal for our application. By referencing several sources to understand the underlying algorithm of k-means, a simple example was coded and tested, as shown below:

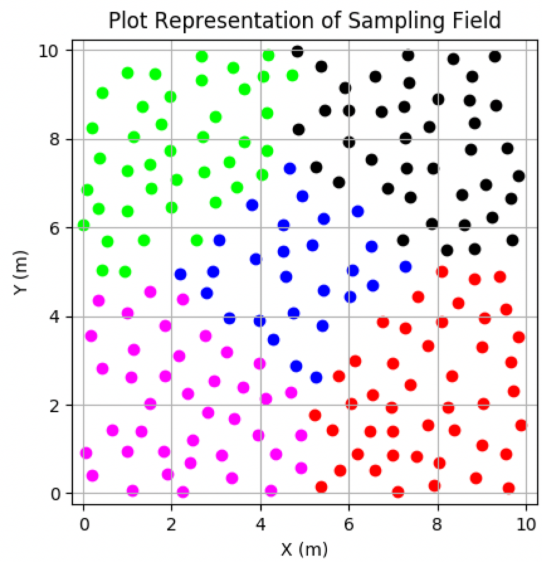


Figure 25. *K-means Clustering Algorithm Applied on a Random Set of Sampling Locations – Each colored sample represents that point belonging to a particular cluster. Here, it can be observed how the blue cluster seems to have less samples compared to all other 4 clusters due to it being sandwiched in between the others.*

Results of the test gave several insights into the capabilities of this algorithm, with one major issue being the way the clusters end up being divided. The figure shown above depicts the algorithm properly identifying 5 distinct clusters, but the current algorithm does not let us define a specific number of samples that are allocated to each cluster. This results in an uneven distribution of samples across clusters, which does not take advantage of the maximum capacity of soil cores that an individual could carry at a time. In extreme cases, several clusters ended up having no nodes assigned to it, leading that cluster to go extinct and reducing the number of clusters generated at the end of computation. Such restrictions meant some modifications were needed for the raw K-means algorithm to allow for more specific control over how the program generates each cluster.

Deliverable: Finalization of the details of the motor controller and initial formulation of the algorithm.

Matthew:

With the design mostly finalized, work started on the algorithm in code. The controller was initially in Matlab/Simulink, but was switched to Python early on to be consistent in language with the navigation algorithm, as well as for easier integration into Webots, with which we had more experience with the Python implementation we had done for the 2-wheeled car. We knew our desired setpoint would be a constant speed and the measured output would be the drill's depth, obtained using an IMU. Our plant was quite simple at this stage, simply being velocity multiplied by time. The motor system was also abstracted to a point to where it was given a number and outputted a velocity.

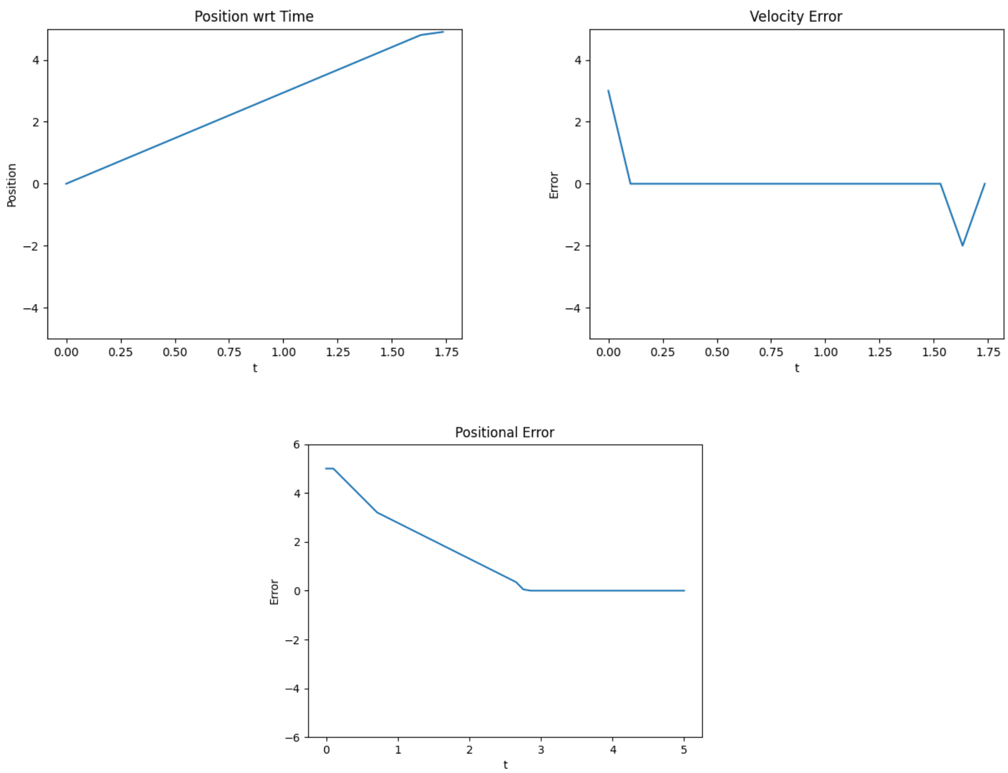


Figure 26. *Early results of the control algorithm.*

In this early stage of the algorithm, the model was very simplistic. The controller itself was mainly proportional, with little integral or derivative component due to being very linear. During development, two different ways of implementing constant speed were made apparent. Position could be used as a setpoint, with bounds on the range of speeds, or speed could be the setpoint, with the algorithm terminating when reaching the target destination. This would be decided on later.

Week 4

Deliverable: CAD design of a mount that can be attached to the drill head that can comply with common existing coring tools.

Niravroh:

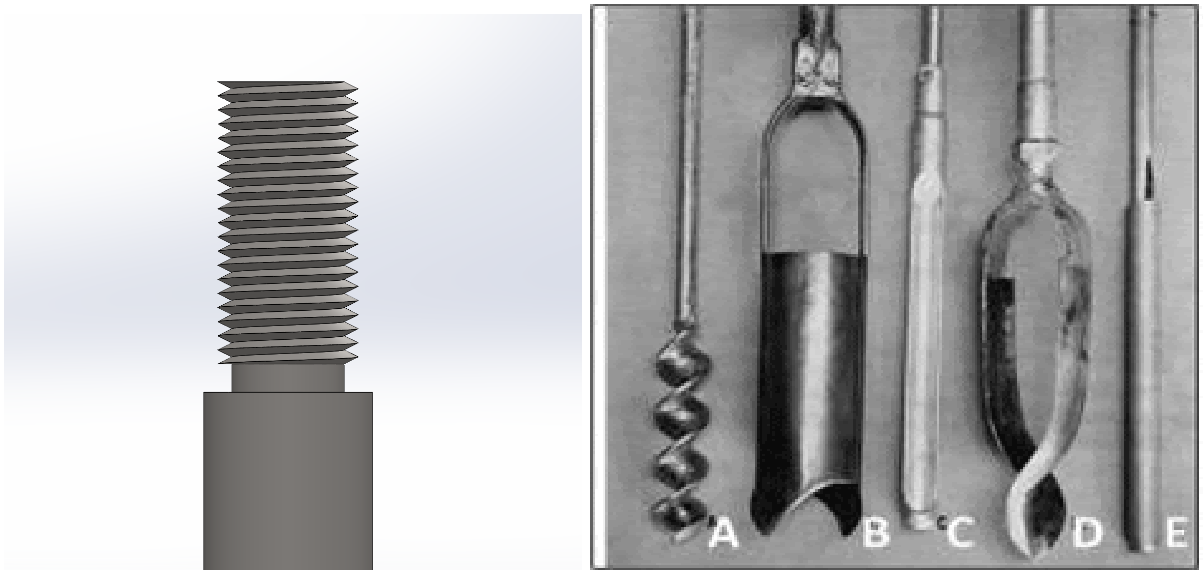


Figure 27. *Attachable mount to allow for existing coring tools to be mounted to our device.*

Most commercial coring heads have a standard thread dimension that I used for this mount. While this would allow labs to use their own specialized heads if they wanted to, it would remove the easy sample storage system with the PVC pipes.

Deliverable: CAD of legs, implementation of ergonomic improvements into the chassis design, and chosen material for the chassis and legs.

Jaewon:

In order to add a new feature of foldability to the legs, the design is greatly changed again. Braces are added to the legs design. Having braces not only adds the function of foldability but also helps stabilize the legs. Pegs are added to each leg cap to offer an extra layer of stability to the system.

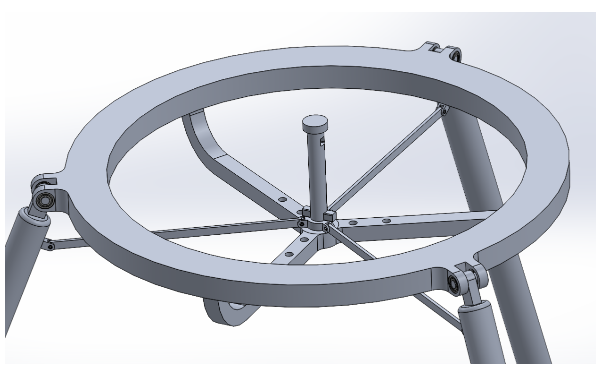


Figure 28. *Tripod head with deployed legs.*

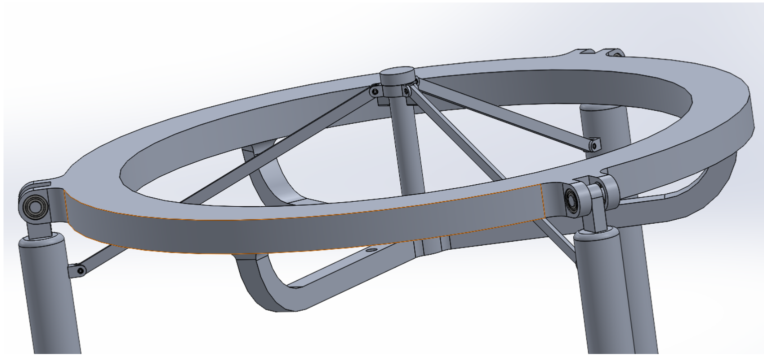


Figure 29. *Tripod head with folded legs*

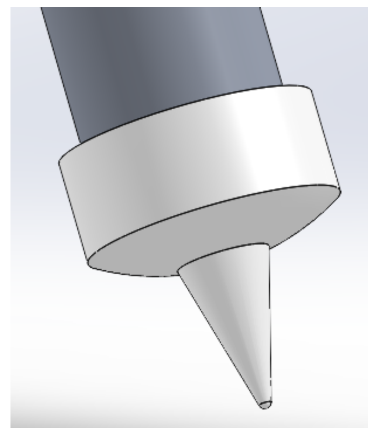


Figure 30. Left: *Total view of tripod.* ***Right:*** *Leg cap.*

Since the gimbal and the chassis need to be positioned beneath the tripod head, putting the brace shaft beneath the tripod requires longer legs, which decreases portability and stability. Allowing the brace shaft to go above the tripod head solves this problem, and decreases the weight of the tripod head at the same time.

The pegs are ABS-plastic for resistance against mud and water.

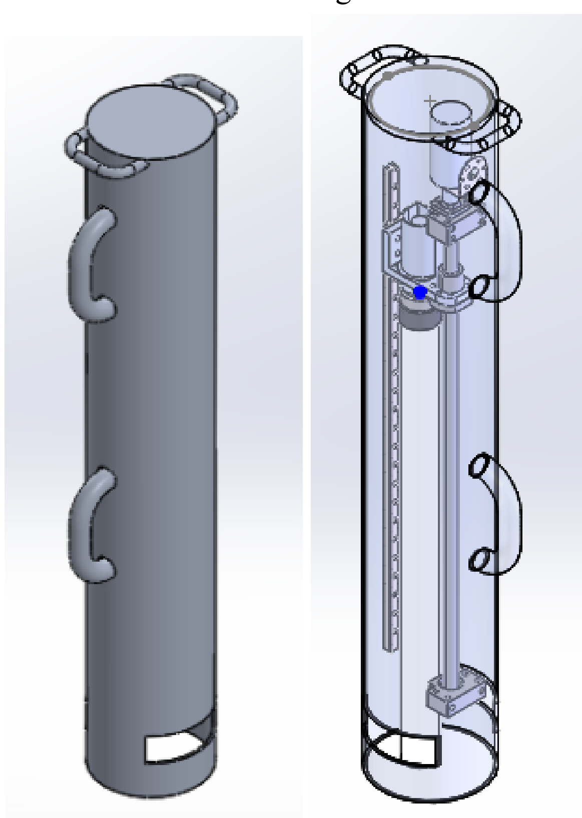
In order to fix the angle of the legs to two states--deployed and folded--a means to lock the legs is needed. Therefore, the brace shaft has two holes through which a pin can be slotted. This pin prevents the vertical motion of the brace ring when it is positioned at the top (folded legs) and at the bottom (deployed legs). The deployed leg angle is tentatively chosen to be 20 degrees from the vertical axis.

Static FEA results show that the tripod head's factor of safety is larger than 10.

Michael:

Material Selection: Based on our expected use, our device must be capable of functioning within a moist and particulate-filled environment. Based on this, our chosen material must be corrosion resistant. Additionally, our device must be capable of withstanding the forces, torques, wear, and fatigue associated with device operation and transportation. For these reasons, we have chosen to utilize Aluminum 6061 alloy as our chassis material. Aluminum 6061 is incredibly strong,with a yield tensile strength of 276 MPa. Additionally, Aluminum 6061 is resistant to our water and mud-filled operating environment. By naturally forming an external layer of oxide, our chassis will not be reactive with corrosive elements that may be encountered during drilling or transportation. Aluminum 6061 Alloy is also a standard material in the manufacturing of device frames for large machinery, including aircraft and automobile frames. With an overall density of merely 2.7 g/cm^3, our overall mass is able to be maintained within our goal of 10-15 lbs. Aluminum 6061 was chosen over Aluminum 5052 alloy due to its easier machining processes despite the slightly lower material density. Additionally, the process of waterproofing electronic components was research. Polyurethane and Silicone coatings for water-sensitive components of our drilling and navigation units will continue to be explored as a method to prevent possible environmental damage to our electronics during use and transportation.

Chassis Design: Our chassis design continued to be updated this week. The latest design iteration is shown in the figure below:



From an initial glance, it is very apparent that many improvements were made. Our bowl-shaped top was removed in favor of a flat design to simplify the manufacturing process and further optimize overall mass. As replacements for the previous handles, external handles were added at the location of the new chassis top to continue to allow manual user support if deemed necessary. Internally, a guide rail system was added to allow for secure installation of our drilling system and associated actuators, as well as multiple motor mounts. Our device's central shaft and overall height was also altered to accommodate for our actuation system and all planned electronic components. Excluding our device's legs, our overall system mass is currently approximately 20 lbs, half of our maximum goal weight.

Linda:

Actuation: The design of the actuation unit was further developed during this week. The rotational DOF motor was mounted to the PVC pipe with a connector piece so that the rotation is independent of the linear translation of the pipe. Motor mounts were added and couplers were fitted to the motor shafts A thrust bearing specifically was used between the bracket and the shaft so that the PVC pipe could be rotated while still being able to withstand the pushing/lifting force applied by the ball screw system. A linear guide rail and slider were also attached to the bracket to add support so the actuation unit does not rotate undesirably. Although wires and electronics were not implemented at this point, we realized that the wires that would connect to the rotational DOF motor could possibly become tangled as it moves vertically with the bracket/ball screw nut. We determined that a sleeve could be used to bundle the wires together and prevent tangling.

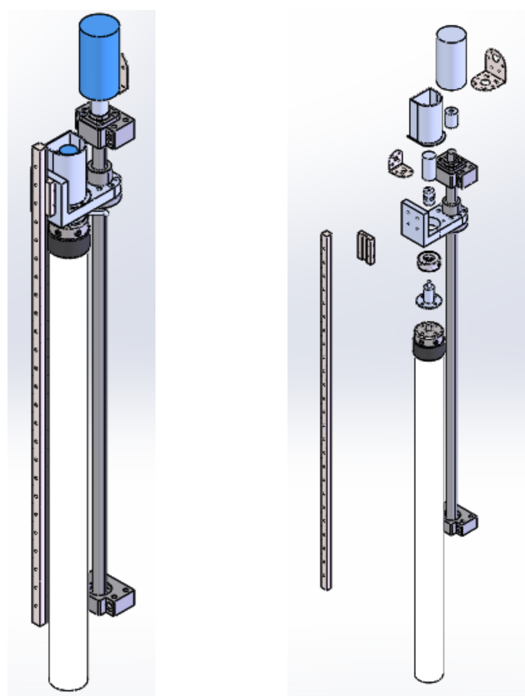


Figure 31. Left: *Updated actuation unit. The motors are highlighted in blue.* ***Right:*** *Exploded view of actuation unit. The linear guide rail, slider, ball screw, motors, motor mounts, couplers, bearing, and drill head assembly and connection pieces are shown above.*

Chassis: To improve the chassis in terms of ergonomic design to increase its usability, several changes were made to the chassis from Week 3. In our Week 4 iteration, the top handles were shaped to allow for a better and more natural grip and to decrease the weight, and the footholds were moved to reduce interference with the lower handle. Finally, the chassis was resized to accommodate the complete actuation unit with some excess space to mount electronics in later weeks.

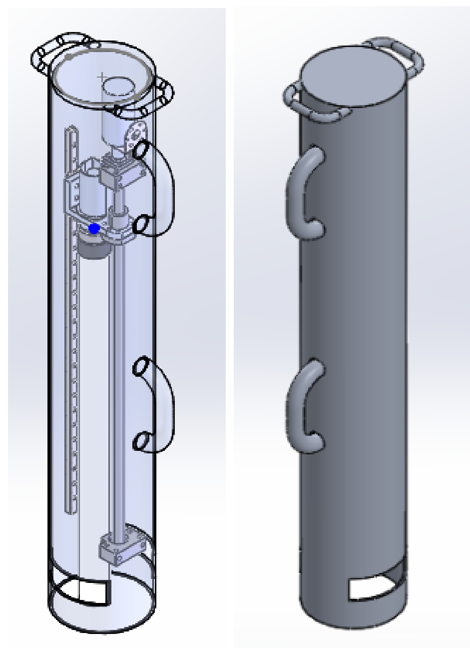


Figure 32. *Week 4 iteration of chassis design, with ergonomic improvements to the handles and footholds. The chassis was also resized to fit the actuation unit.*

Deliverable: Continued development in navigation algorithm by implementation of return waypoints.

Farooq:

To implement TSP navigation, we looked into the ACO python library called ACOpy. This library proved advantageous in that we would not have to write our own code to implement ACO. However, limitations included figuring out how to convert our representation of the sampling field to a format compatible with the format ACOpy utilizes. In addition, ACOpy examples utilize tsplib95, which is the library that loads in .tsp files [25].

Hayato:

While we did more research looking into specifying a particular number of samples in each cluster, we came across another clustering method possibly more suited for our application. A user returns to its starting location after each expedition to unload all of the soil cores collected along the way, meaning most paths would radiate outwards from the base camp. Taking advantage of this nature, we proposed a clustering method that divides the field radially originating from the base camp, analogous to cutting pizza slices. Despite not solving the fundamental issue of having uneven distribution of samples across clusters found in the K-means approach, we figured that there is a way to control the number of samples per cluster by adjusting the angle of each slice. A concept of such clustering algorithm is depicted in the figure below:

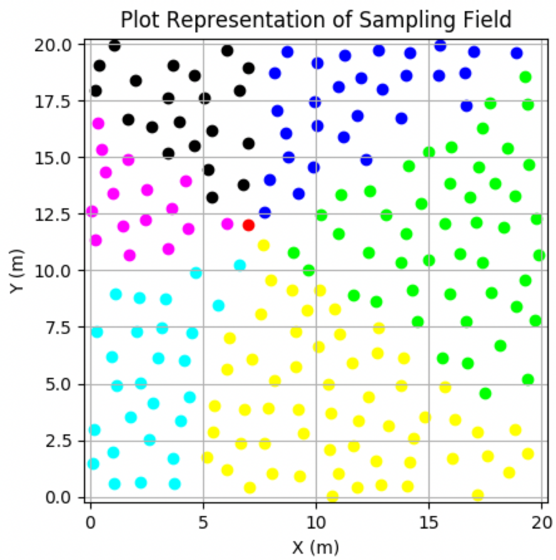


Figure 33. *Concept for a Radially-Biased Clustering Algorithm – The basecamp is located at coordinates (7.5, 12.5), as shown by how all of the borders of each cluster seem to originate from that point depicted in red. Similar to the issue with regular K-means, it can be seen how the yellow cluster has significantly more samples than pink for example, indicating a need to dynamically change each cut angle.*

The actual algorithm works off of a modified version of the K-means, where each centroid is restricted to being located at a certain distance away from the base camp such that each cluster is ensured to not be far away from the center. Although convincing, we do not have any evidence that suggests that this algorithm would yield a better result than the normal K-means algorithm, thus we would need to evaluate the performance of each algorithm once we are able to combine the clustering algorithm with the ant colony optimization code to run the full simulation.

Deliverable: Continued development in motor control algorithm.
Matthew:

A choice was made between the implementations in the motor algorithm between position or speed tracking. A speed-based setpoint was decided on due to a lack of flexibility in range of speeds in position tracking. After this, focus was shifted to the verification of the current model. Testing was not particularly useful on such a simple system. It was clear that the motor algorithm needed more work in terms of sophistication and depth of its model. The design was too abstracted and ignored too many potential factors, so work began on changing the drill model.

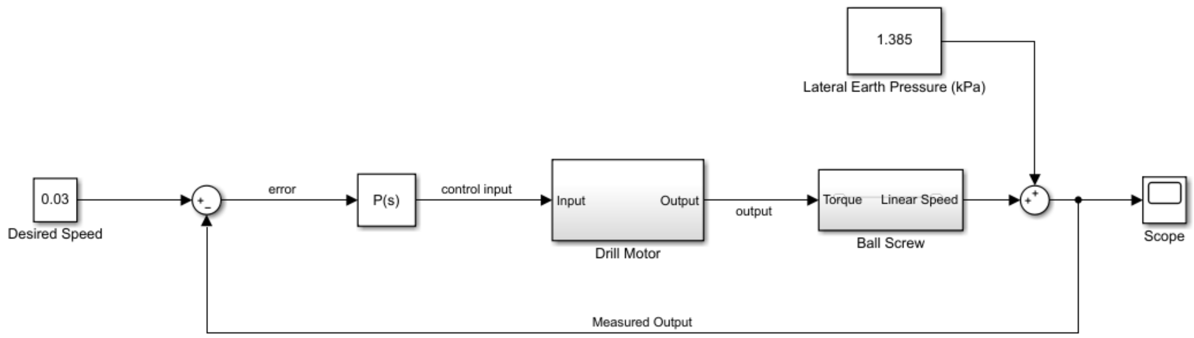


Figure 34. *Block diagram of the motor control.*

The plant was changed based on the calculations done on the drill/ball screw system calculations done for the DC motor requirements, and the motor was modeled more appropriately as torque being translated by the ball screw into thrust force. The next step was to implement the outside forces acting on the drill system. To get a better idea of what I needed to consider, I researched a paper on slurry pipe jacking [30], which had a similar issue of pipes traveling through soil. From this paper I added lateral earth pressure as a factor into my simulation, making sure to account for the proper changes in overall pressure as more of the pipe was buried into the ground. The new motor model also allowed me to calculate the overall effect on the drill's speed, now that the thrust force could be modeling, resulting in a more accurate simulation

Week 5

Deliverable: CAD assembly of chassis (integrate legs, actuation unit, and chassis), and static FEA analysis results.

Niravroh:

Our original plan was to have an automated self-leveling system to make sure that the chassis is perpendicular to the ground in order to collect a clean sample. However, this plan had several issues with it. First of all, this kind of self leveling would require actuated feet. This would severely bulk up the feet, and introduce a lot of complexity. The method we were planning to use for this was a ball screw. The leg would be actuated with the motion of the nut. However, this method was very complicated, and added a lot of friction to our system. Additionally, since we are operating in a marshland environment, our leg has to be as water resistant as possible, so electronically actuating legs are even harder to properly execute.

Instead, we decided to integrate a gimbal between the leg assembly and the chassis. This would allow us to use the force of gravity to level our machine for us. We still had some questions to answer about the optimal way we wanted to lock our gimbal in place so that it wouldn't move around while the machine was actuating.

Jaewon:

In order to facilitate the integration process, the tripod is redimensioned. First, the tripod head's diameter (from the center of the tripod head to the center point of the leg joint) is dimensioned to be 350mm so that it is closer to the diameter of the chassis, still maintaining a larger value than that of the chassis. This gives room for the chassis to have a range of non-vertical angles while the legs are folded. The reduction in size helps reduce the total weight of the machine.

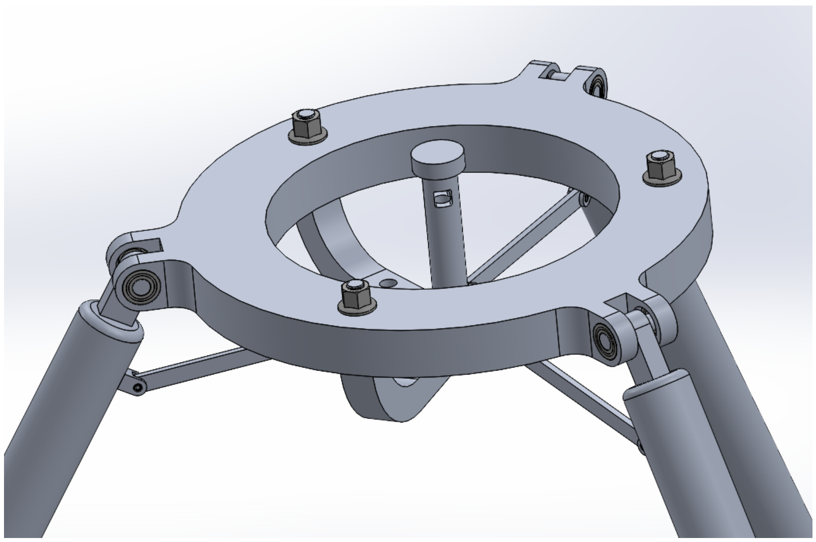


Figure 35. *Tripod head.*

The legs are redimensioned to ensure that the chassis doesn't touch the ground, while taking into account the decrease in stability and increase in cost as length increases. The distance between the bottom end of the leg to the center point of the joint at top is 1230 mm. This creates a minimum distance of 14.7mm between the ground and the chassis. A point on the foothold is used to calculate this minimum distance, as is the farthest point on the chassis from the gimbal centerpoint.

30 degrees were chosen to be the deployed leg angle from the vertical axis. This lets the chassis swing around by 33 degrees in any direction. If the chassis swings beyond 33 degrees, the edge of the chassis screen can collide into one of the legs. The 30 degree leg angle was chosen for its stability, needed material, and simplicity of dimensions.

The tripod support part is separated from the tripod head, in order to increase manufacturability.

The peg design is changed to more easily dig into the ground. It is now at an angle from the leg, so that when the legs are deployed, the pegs are normal to the ground. This peg design is inspired by existing products. The material has also changed to metal for higher strength.

Figure 36. Left: *Peg design.* ***Right****: Existing tripod product [27].*

Linda and Michael:

Display: We had previously decided to not include an onboard screen in favor of having a web application or smartphone app that could be used on the user’s phone. However, after some discussion with the professors and team, we decided that an onboard screen would be the better choice. Since the device will be used in a marshland, we can assume that the user may get mud and/or water on their hands, which makes it difficult to use a smartphone that may not be water resistant. The user may also want to use two hands to operate their smartphone; however, during transport, which is primarily when the map would be used, the user will need at least one hand to support our device. By assessing the needs of the user in the setting of soil sampling, we determined that an onboard screen would satisfactorily address these issues and provide a better user experience.

In the light of this change, a mounting point for the display was incorporated into the chassis, and was modeled similarly to other water resistant screens that are currently on the market. Because water resistant screens were much more expensive than the screen itself, we opted to use a water resistant screen cover (which will not affect the performance of the touch screen because it is a capacitive touchscreen) with rubber lining used at possible leakage points to tightly seal the screen. A desiccant can be used to help promote dryness in the screen electronics. The display is at a 30° angle from the horizontal when being transported, which allows for comfortable viewing of the navigation screen.

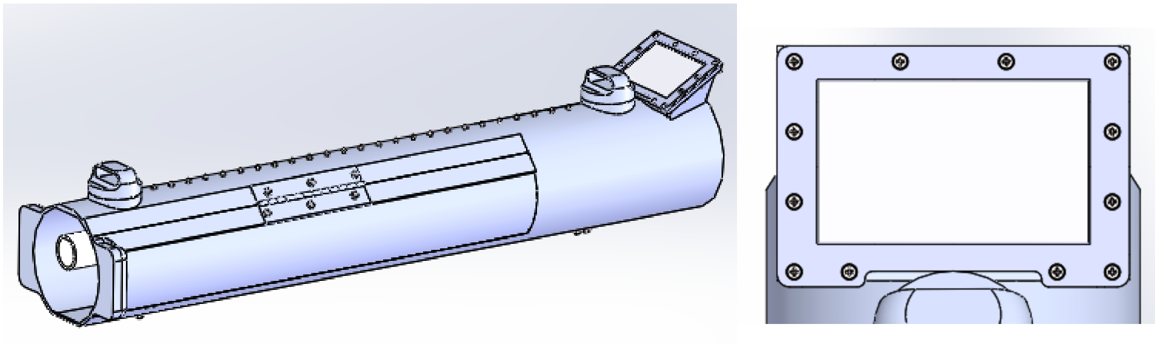


Figure 37. Left*: Orientation of display and chassis during transport.* ***Right****: Normal view of display mount and screen.*

Transport: We also changed our method of transport after some re-evaluation. Similarly to the display, we started to view the device from a more user-oriented perspective and considered other methods that the user could employ to transport the device other than handles. We ultimately decided to change the transportation method from handles to a single strap that could be carried on one shoulder, and also removed the topmost handles that the user could hold onto during coring. Because we intend our device to be relatively lightweight, a strap would be suitable to carry the device between sample locations. This change makes it easier for the user to carry the device, and the removal of the topmost handles also reduces interference with the gimbal and legs. With the previous design, the user was also expected to carry the device with two hands, which restricted the freedom the user had to comfortably view and use the navigation display.

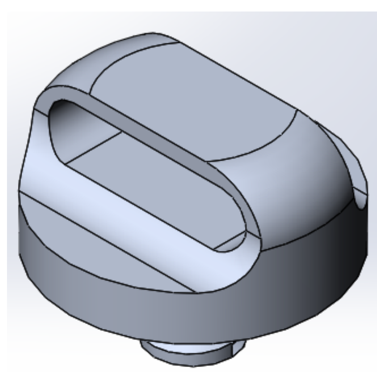


Figure 38. *Strap mounting screw. The strap should go through the ring, and two mounts are required as seen in Figure 37, left.*

Other Changes: A case for electronics was also designed and added to the chassis assembly, and mounted so that the screen is directly connected to the case. This is to make the assembly and wiring of the electrical components to the screen simpler. The electronics case also needs to be waterproof, so similar sealant and proofing methods as will be used for the display can be used for the case as well.

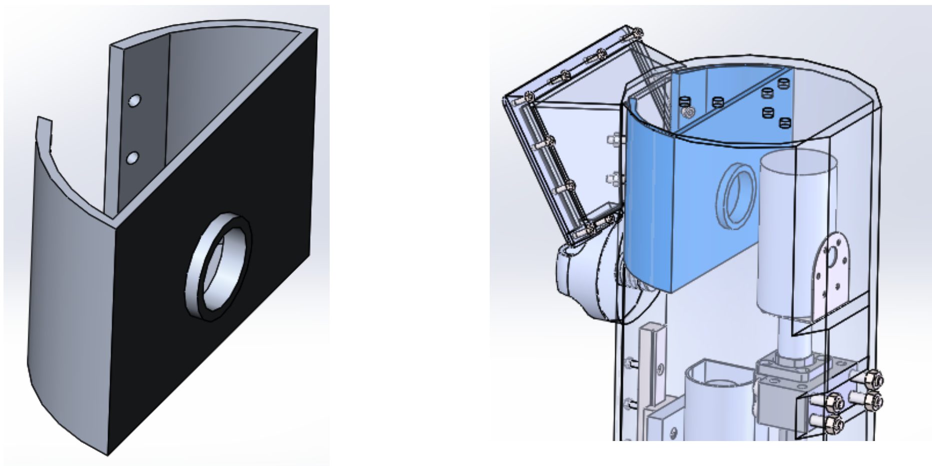


Figure 39. ***Left***: *Electronics case.* ***Right***: *The case is highlighted in blue, and is shown mounted to the chassis. The wires and connectors for the motors would emerge from the circular hole in the case, and the connections to the screen would go through the rectangular cut on the opposite side.*

We also changed the foothold design. Previously, the footholds were holes at the bottom of the chassis where the user could place their foot. However, this design made it possible for the user to accidentally interfere with the motion of the PVC pipe. To address this issue, the holes were replaced with footholds that protrude outwards from the chassis.

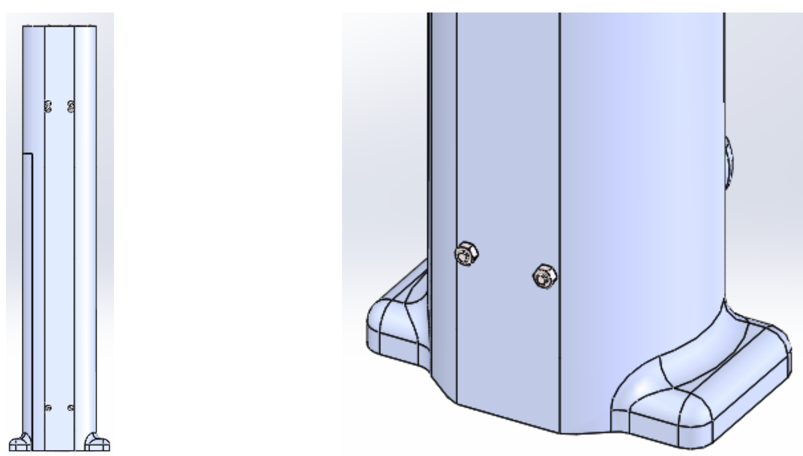


Figure 40. Left: *Side view of both footholds.* ***Right***: *Isometric view. The footholds now protrude out from the chassis, to prevent interferences between the user and the coring tool.*

Finally, a door was added to the chassis so that the user could easily access the drill head to remove and swap PVC pipes between samples.

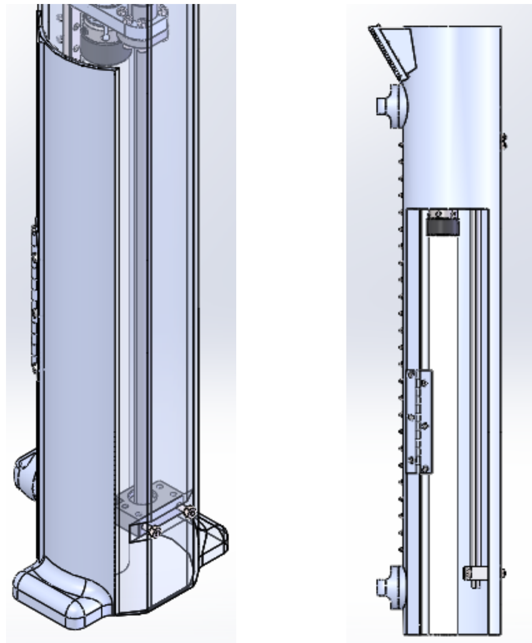


Figure 41. Left*: Isometric view of door on chassis, where the door is opaque while the chassis is transparent.* ***Right****: Side view of door opening. The drill head is easily accessible by the user.*

Deliverable: Select electronics.

Linda:

Display: For our application, the device will be used outdoors - this means that the screen should be usable in full sun and any other common weather conditions. It also needs to fit on the chassis without adding too much unnecessary bulk, where the diameter of the chassis is 5.9 inches. Knowing this, the display requirements were to be sunlight readable, waterproof (semi-rugged), and under 6 inches. Touch screen capabilities were also desirable as opposed to buttons to limit the number of points that would need to be made leak/waterproof. The option that best fit these criteria was the CFAF800480E1-050SC-A1-2 screen and development kit that includes a 5 inch 800x480 TFT LCD screen with capacitive touch and is sunlight readable. Waterproofed options were much more expensive (in the range of hundreds of dollars), and so we determined that designing our own waterproof casing for the screen would be the best course of action.

Motor Controllers: The ThunderBorg, the recommended motor controller for the PIS-0934 and PIS-0930 DC motors that we previously selected, was found to be the best option. It supplies dual motor control and complies with the motor requirements, and is also available at a reasonable price compared to other motor controllers that were available.

Deliverable: Full implementation of navigation system, with a path derived for any set of sampling nodes (also a week margin for any catchup if needed); results from tests
Farooq:

In order to utilize ACOpy effectively, it seemed that we needed to convert our sampling field to a .tsp representation, and possibly use networkX for graphing purposes. We eventually found this was not the case in Week 6. Additionally, most of this research was done preemptively in the event that we wanted to use an ACO library to compare to a self-implemented algorithm, which we eventually decided on creating [27].

Hayato:

Following a significant delay and a lack of progress getting the ACOpy library working in the current python script, we looked into implementing our own ant colony optimization code based on the given pseudocode found several weeks ago. First, we needed a new method of storing the paths traversed by the ants, which were ultimately defined using a set of NumPy arrays that held indices to each sampling node stored within the class. The order of this array dictated which sampling node came before another, letting the code directly interpret the already stored cartesian coordinates to draw connecting arrows between each node. The code initially selects a random sample node to be the starting location of the ant, after which the ant stochastically selects its next destination by weighting the probabilities based on the relative distances. A closer distance is preferable, repeating the process until it reaches all sample nodes within a given set. Multiple ants run through the sample nodes simultaneously, each contributing to leaving a pheromone mark on the path taken based on the score of the overall trajectory taken. One of the benefits of self-implementing the ACO algorithm allows us to define our own scoring system for leaving these pheromone trails, enabling greater freedom over how a path is chosen. Although we were unable to finish the implementation of the entire algorithm on time, a diagram of a single ant's path in one iteration already shows significant improvement over the completely randomized path, as shown below:

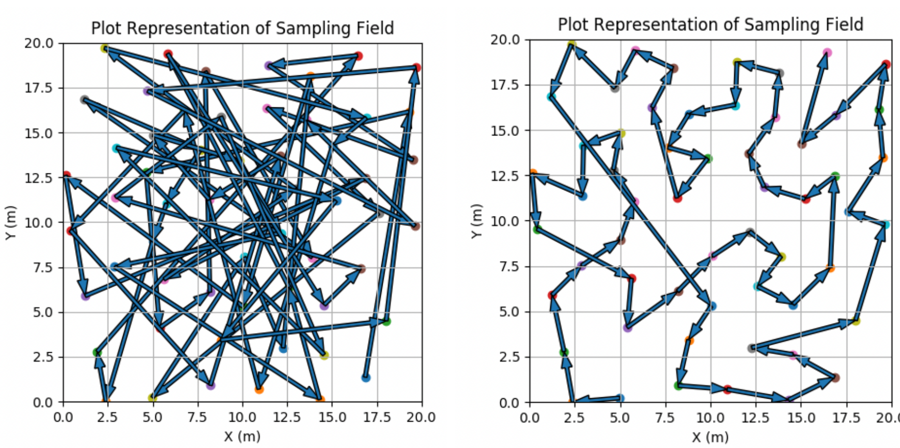


Figure 42. Left: *Randomized Sampling Trajectory* ***Right:*** *Single Iteration of Self-Implemented Ant Colony Optimization – The blue arrows represent the generated trajectory of moving from one node from*

another. Since the user ultimately returns to their starting position, the real trajectory should look like a complete loop, thus the starting and ending positions depicted in these diagrams are meaningless other than them being the first and last elements of the array.

As shown in the figure, the generated path results in less clutter near the center of the field where the randomized path repeatedly traverses due to it ignoring cartesian distances between points as a factor. The path generated by the ACO algorithm can also still be improved, as suggested by the several crossing of paths that extend across nearly half of the field. Running multiple iterations of this ant agent after assigning appropriate pheromone values would eventually result in a single path that would approach the ideal shortest path possible. Here, it is noted that we have yet to implement a solid method of evaluating the score of a particular path due to the multiple parameters that affect this score, mainly being the cost of traveling a distance while carrying a certain amount of weight. Such parameters will be estimated by finding a probabilistic range of all possible values and using it to determine a comprehensive combination of both the ACO and clustering algorithm that minimizes the cost.

Deliverable: Results from simulation of motor control algorithm.
Matthew:

Most of this week was spent implementing the research and planning done from last week on lateral earth pressure and the motor/ball screw calculations. The new considerations also led to recalibrating the PID constants, resulting in a higher integral contribution due to the resulting error that accumulates from the increasing lateral earth pressure as more of the PVC is buried. For testing, noise was also added to simulate uncertainty in sensor readings and other unknowns.

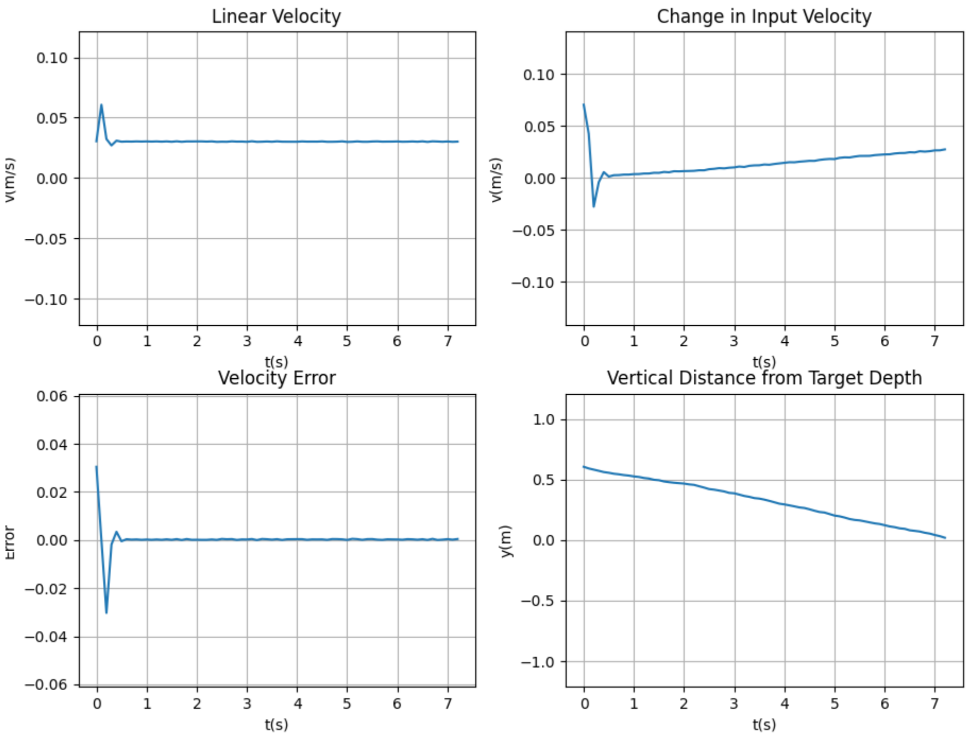


Figure 43. *Motor control results*

Aside from an initial overcorrection, the algorithm performs well. The velocity is able to be maintained for most of the duration of the sample, despite the added earth pressure working against the motor. The constants were tuned again to minimize sampling time, with a k_p of 9.2, and k_i of 13.96. The derivative component proved detrimental to performance, so the controller was finalized as a PI controller. The time of sampling is well within the goal ranging from around 7-10 seconds. The algorithm is mostly complete at this stage, with the overshoot fix being the last item to work on.

Week 6

Deliverable: CAD assembly of drill and chassis, results of static FEA, ~~engineering drawings and tolerances of all parts.~~

Because of some of the significant changes in design (such as the gimbal, transport method, and addition of the onboard display), the completion of individual mechanical subsystems took longer than expected. As a result, integration of these systems and the engineering drawings and tolerances will be completed in Week 7 instead. Since we included some buffer time in our GANTT chart for cases such as these, we will use that time to catch up with this deliverable. We will account for this change in Part 4 of this report.

Niravroh:

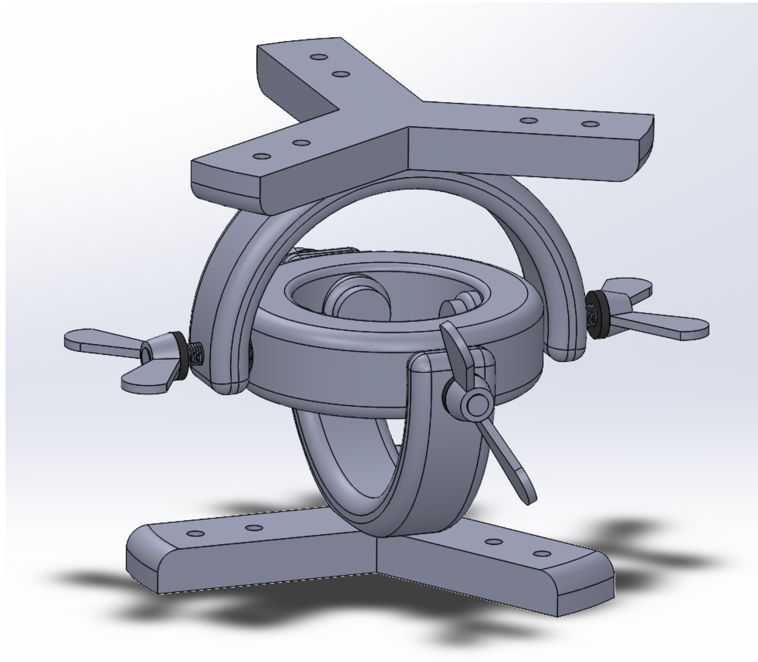


Figure 44. *Updated gimbal design.*

More work was put into refining the gimbal. Mounting points to attach the gimbal to the chassis/legs were added in, and had to be repositioned several times as we sorted out how to best prevent obstruction of parts. The gimbal will freely rotate normally, allowing the chassis to always point down due to gravity. The user could screw in the wing nuts on the sides to apply a friction force to keep the gimbal from moving while the machine is operational.

We considered a few different options of locking mechanisms, but ultimately, every one of them had the same problem of limited angles when in locked position. Comparatively, our solution may not have the same resistive power to lateral forces, but it has a much higher degree of freedom.

Jaewon:

Brace simulations indicate that it needed to be redimensioned to achieve higher strength.

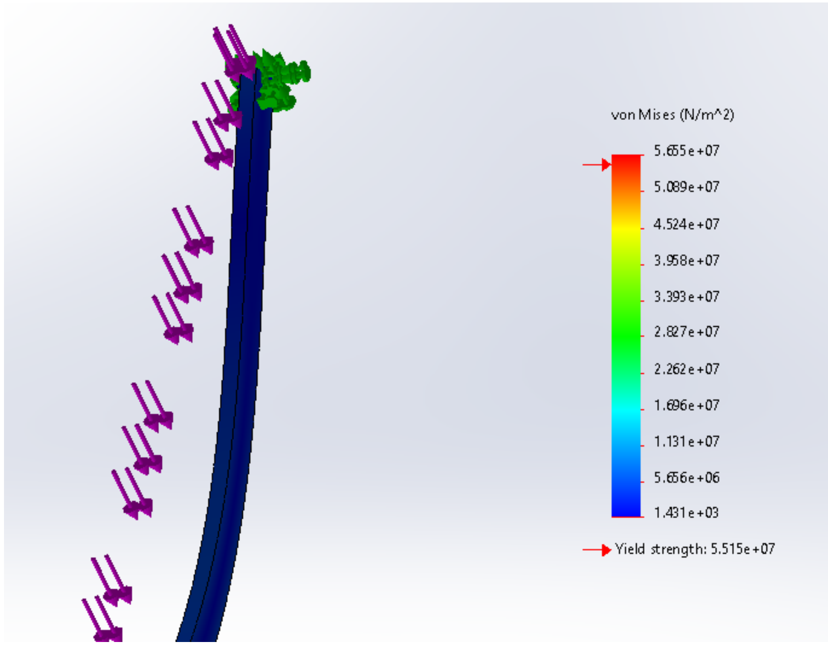


Figure 45. *Force simulations on brace*

The width and thickness of braces are changed, and bigger bearings are used for the leg-brace joints. The dimensions of the brace ring and the legs are altered to accommodate this change. The tripod head's dimensions are also changed to shave off unnecessary weight, while maintaining the outer diameter.

In order to prevent the leg or the leg brace from colliding with the gimbal, the links are mathematically formulated in order to calculate the final dimensions.

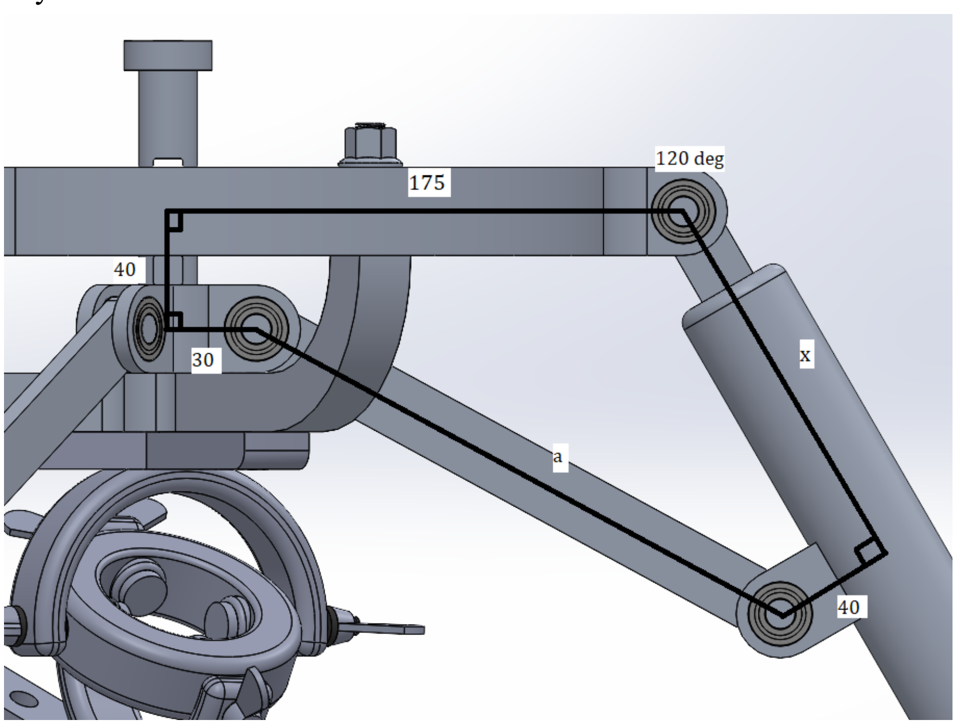


Figure 46. *Linkage diagram of deployed legs.*

This diagram establishes a direct relationship between x and a. The units are in mm. Larger value of x will increase the stability of the entire system. However, increase in x will cause the leg brace to collide with the gimbal.

The gimbal's point of rotation is fixed with relation to the tripod head, and the tip of its wingnut is the farthest point from it. The distance between the two points is 90mm. Simple calculations show that the minimum angle the brace (link a) makes with the vertical axis is 55 degrees in order to avoid collision with wingnuts. This constraint forces x to be between 23.1 and 188.5mm.

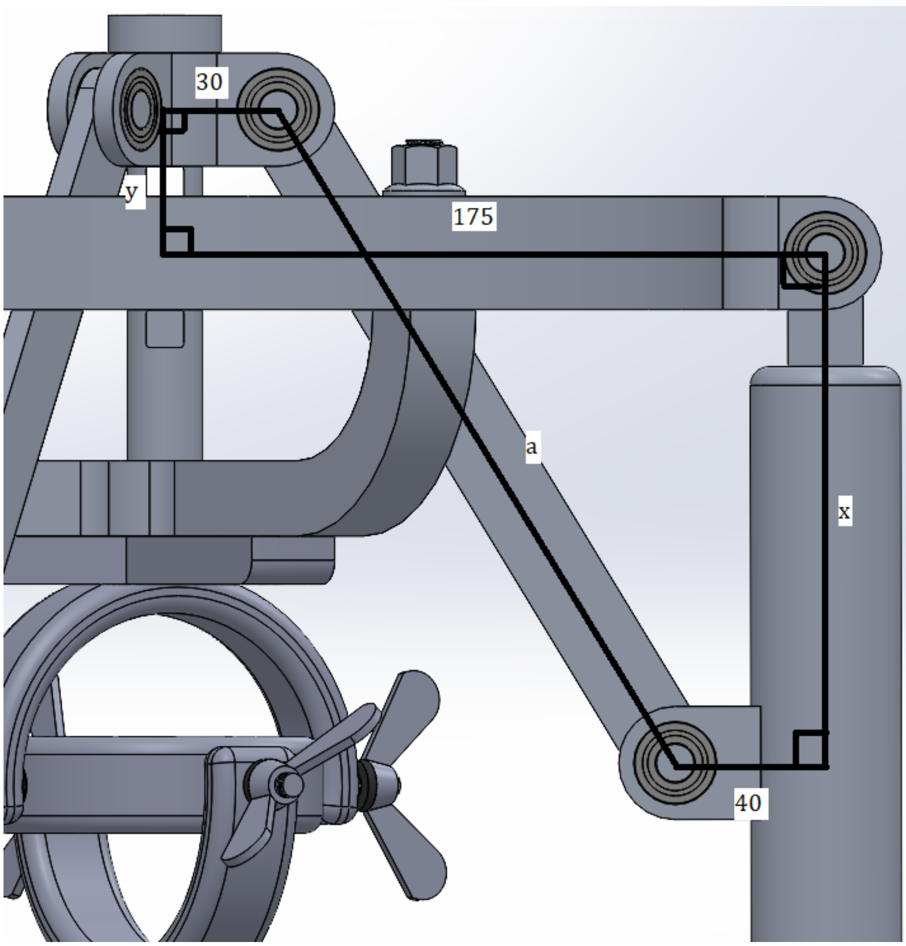


Figure 47. *Linkage diagram of folded legs.*

Since a is determined directly by x, y can be directly determined by x too. However, y also has to be large enough that the gimbal wingnut cannot collide with the brace.
Simple calculations were conducted to compare the y values found in two ways. One directly calculated by x, and the other by assuming that the wingnut can come in contact with the braces. For the range of x from 23.1 to 188.5, the directly calculated y values were larger, meaning that the gimbal will not collide with the braces within that range of x.

The value of y changes very little over the range of x. y = 38mm. The value of x is chosen to be 135mm. This forces the value of a to be 202.55mm. The height of the brace shaft is determined as it needs to restrict y to be 38mm.

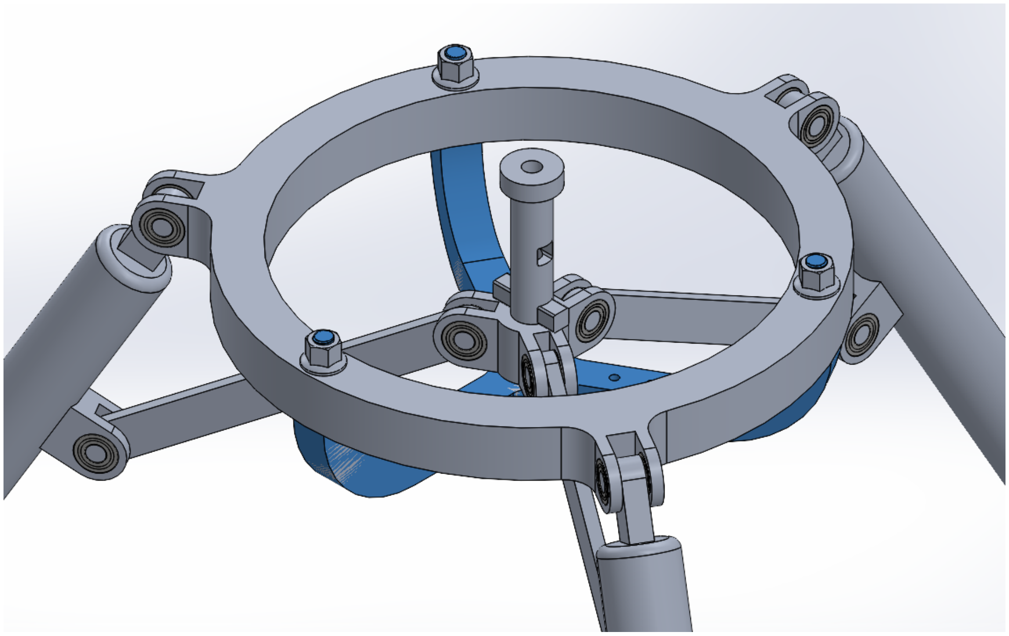


Figure 48. *Tripod head. Tripod support part is selected to show it is separated from the brace shaft.*

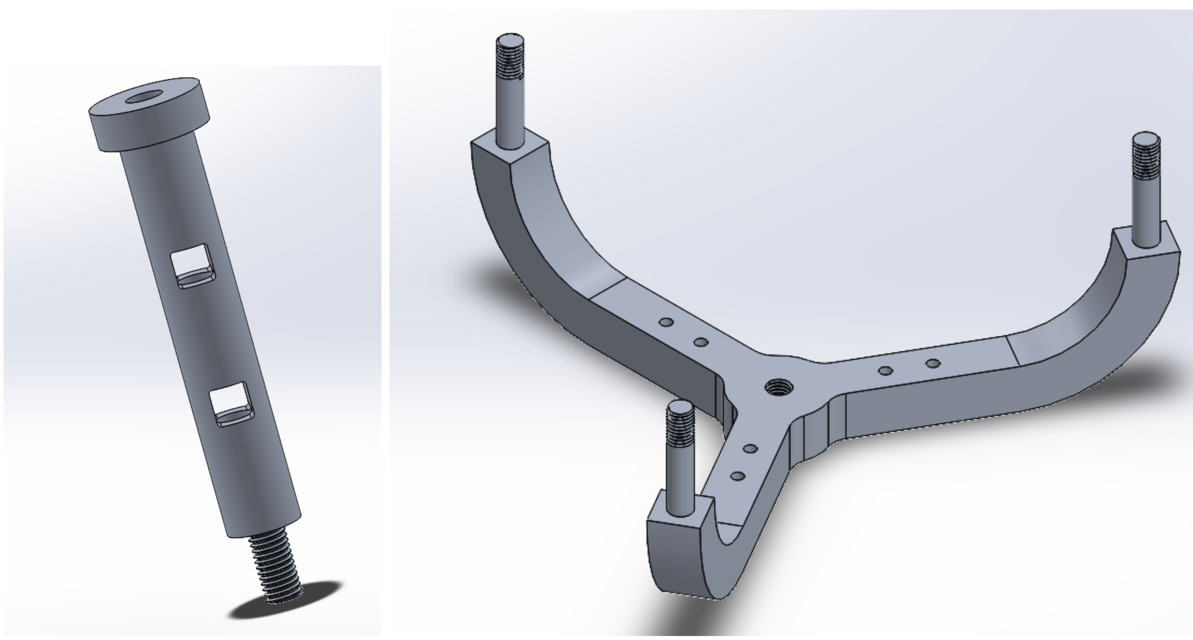


Figure 49. Left: *Brace shaft.* ***Right****: Tripod support.*

Hole dimensions are altered to match those of the gimbal. The tripod support is separated from the brace shaft for better manufacturability. The two parts are connected by a threaded surface.

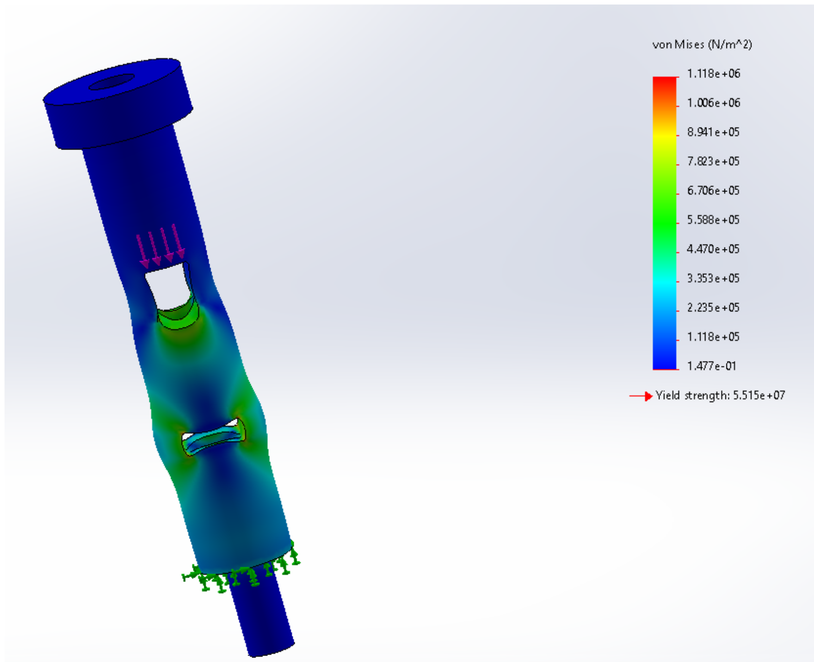


Figure 50. *FEA results on the brace shaft.*

FEA results show that the brace shaft can withstand the weight of the legs and the braces when the legs are folded, with a factor of safety of 50.

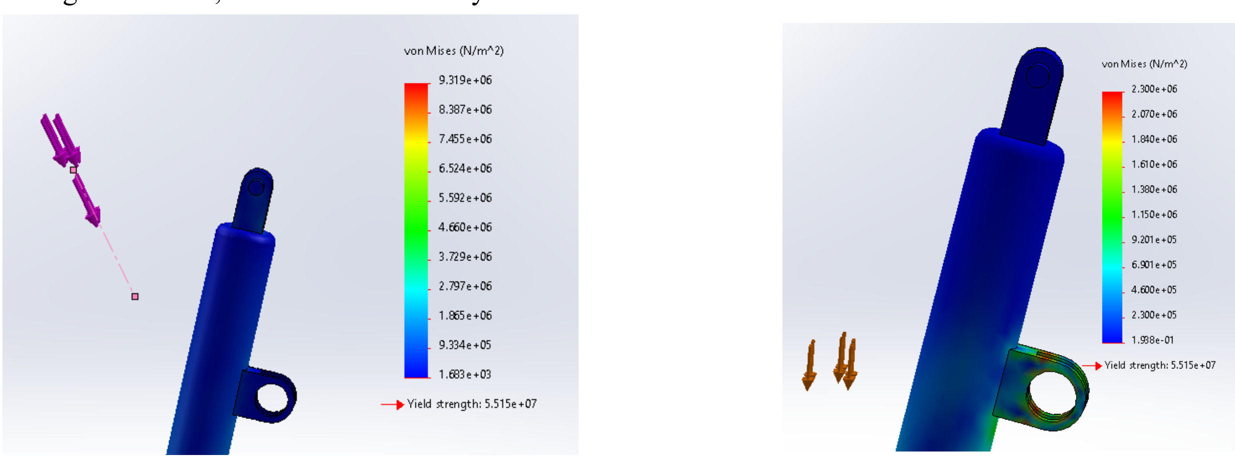


Figure 51. *FEA results on the leg.*

FEA results show that the legs can also support the total weight of the machine whether it be deployed or folded. Two different force definitions are used to verify that both joints are strong enough. The factor of safety is about 5.

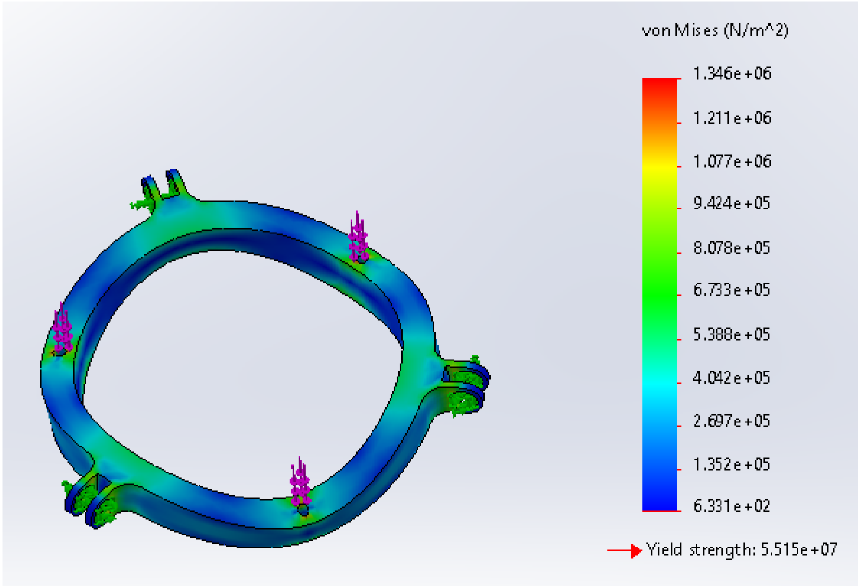


Figure 52. *FEA results on the tripod head.*

FEA results show that the tripod head can withstand the weight of the machine with a factor of safety of 40.

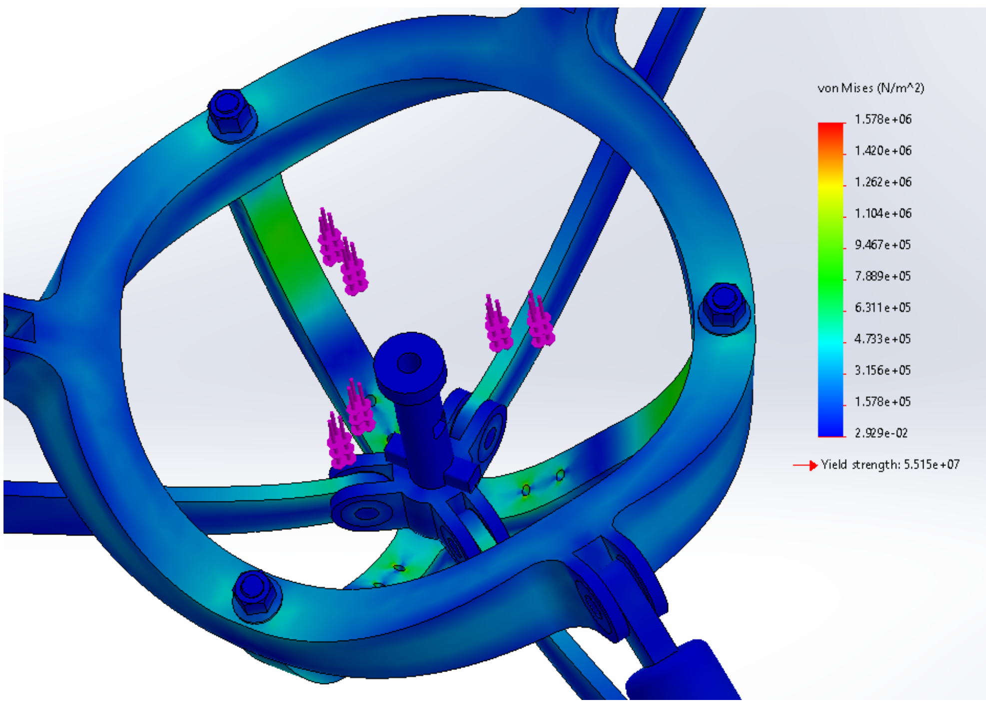


Figure 53. *FEA results on the tripod assembly.*

The tripod can support the weight of the gimbal and the chassis with a factor of safety of 35.

Michael:

Chassis: Appropriate fasteners were selected and added to the assembly to continue with the integration of the mechanical subassemblies. Our top piece was analyzed to determine whether it was worthwhile to make adjustable or removable for easy assembly and maintenance. This would be done using L-brackets or a hinge system. Ultimately, this was disregarded due to the large size of the side door and its use during assembly. Hinges and latches were added to the door allow for user access during maintenance, sample collection, and device cleaning and mud removal. M5 bolts and nuts, along with the associated holes necessary added to the chassis design. Through these additions, we are able to account for the manufacturability of over device, and have left sufficient room for electronic components to be securely fastened in their specified locations.

Linda:

Chassis:

We also realized that the swapping mechanism for the PVC pipe that had been designed in Week 3 had been encased with the connection/mount between the rotational DOF motor and the PVC pipe and was not accessible to the user. To remedy this, an opening was added such that a lever could be used to access the swap mechanism. This simple lever was chosen over other methods such as a crank-slider mechanism because of the simplicity and efficacy of it, and there is not enough space in this region to accommodate a more complex solution (approximately 10 cm vertically).

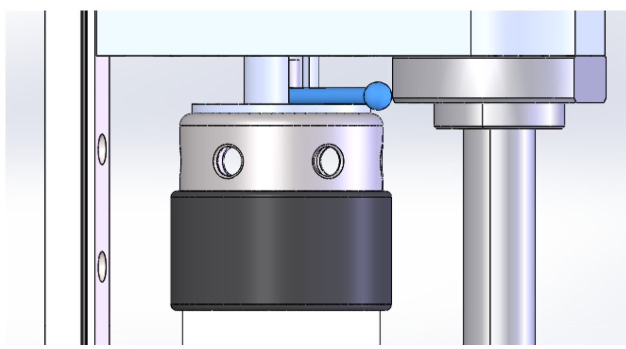


Figure 54. *The lever is highlighted in blue. It is essentially a pin with a threaded tip that screws into the swapping mechanism, such that when the lever is lifted, the swap mechanism is also lifted and the vacuum in the PVC pipe is released so that the pipe can be removed.*

A static FEA was also performed on the bracket and connection piece, which is the point that is most likely to fail during operation because the linear force applied by the ball screw is focused in this area. The results (shown below), demonstrate that the components are able to withstand the maximum drilling forces with a FOS > 2.

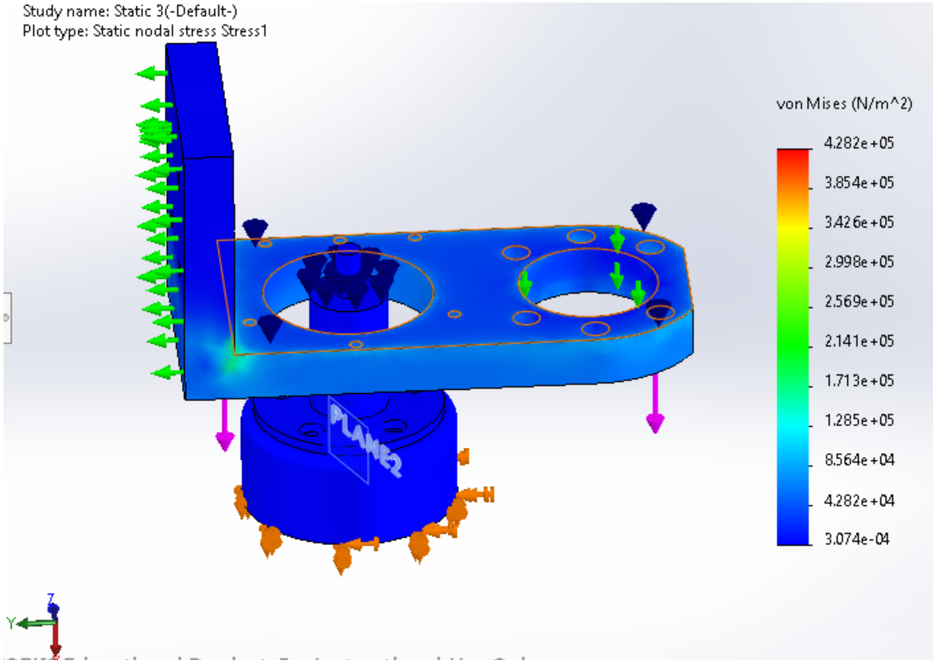


Figure 55. *Results of static FEA on the region with the highest likelihood of failure. The bracket (topmost) and housing (bottommost) components are made of AISI 304, while the connector component (middle) is made of Aluminum 6061. The connector and bracket are connected with a bearing; however, since there should be no relative motion between them the bearing was suppressed and a rigid connection was made between the two components instead. With an applied force of 200 N, the region has a factor of safety greater than 2.*

Vibration Estimates: The transverse vibrations are the primary concern during drilling operations, as they can enlarge the hole that is being created. In our application, such vibrations would cause undesirable disturbances in the soil sample and decrease its quality, and as such are the focus of our calculations (seen in the table below) [28]. The estimated frequency is about 0.043 Hz, with a maximum amplitude of about 0.0367 mm. For the nominal PVC pipe diameter of 1.25 inches, or 31.75 mm, the maximum error due to transverse vibrations is about 0.12%, which is within the specifications of 95% accuracy. Also, the frequency of the vibration is extremely small, and confirms our initial assumption that the vibrations are negligible.

Table 3. *Calculations of transverse vibrational frequency and amplitude in the drill head.*

Known Parameters	*Symbol*	*Value*	*Calculated Value*	*Symbol and Equation*	*Value*
Spindle Speed (RPM)	N	100.00	Spindle Speed (rad/s)	$\omega_t = 2\pi N/60$	10.47
Stroke Length (m)	L	0.61	Natural Frequency (rad/s)	$\omega_n = 3.835/(L)^{1/2}$	4.91

Pipe Diameter	d	0.03	Force per Second (N/s)	$F = \pi d\sigma/V_l$	0.3162
Feed Rate (m/s)	V_l	0.06	Speed (m/s)	$v = \omega_t\ d/2$	0.1662
Tensile Strength of PVC (MPa)	σ	52.00	Stiffness (N/m)	$k = \sigma\ v$	8.65
			Frequency (rad/s)	$\omega = v/L$	0.2727
			Amplitude (mm)	$A = F/k/(1-(\omega/\omega_n)^2)$	0.0367
			Frequency (Hz)	$f = \omega/(2\pi)$	0.0434

Deliverable: Results of the simulation/tests for the navigation and motor control algorithms.
Farooq:

Working on compiling all research and creating documentation in order to qualitatively and quantitatively justify why we chose ACO over other approaches like MPD for path-planning, why we chose the "pizza-slice" shape for clustering, and why we chose K-Means over K-Medoids. As it stands, we suspect that the K-Medoids approach is more computationally expensive than K-Means simply because of the extra end computation required to find the most middle node after clustering, compared to K-Means which simply operates based on the exact center of each cluster. The main issue faced is that most research done on clustering and especially ACO is not theoretical but rather experimental. This means we have to experiment for our specific case and it becomes difficult to theoretically justify why we chose ACO over other algorithms that may provide a similar estimated solution to the TSP at our scale [29].

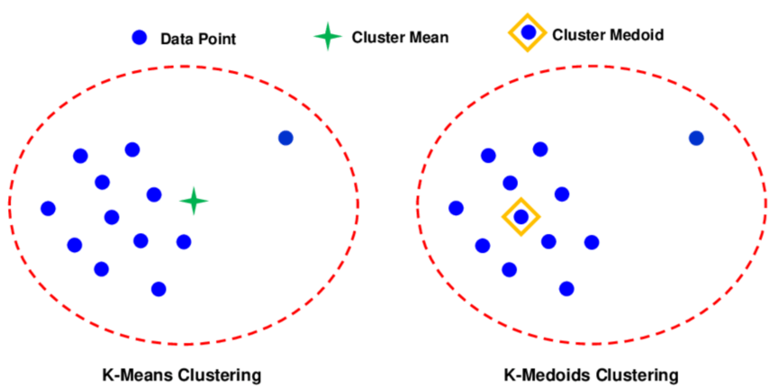


Figure 56. *Shows the difference between K-Means and K-Medoids clustering.*

Hayato:

After extensive research into modifying the K-means algorithm, we were able to find a branch of K-means called the same-size K-means variation, which is capable of controlling the specific count of each cluster. This algorithm fundamentally works by exclusively swapping the cluster assignments of one sampling node with another sampling node, which results in no net change in the overall sample count per cluster. By initially defining the exact number of samples wanted in each group and assigning that many nodes per cluster, it is ensured that this cluster count never fluctuates across iterations, preserving the balance throughout. Here, the number of elements per cluster were computed by taking into account the maximum capacity of an individual and evenly distributing the nodes such that two clusters would only differ by at most 1 sample. The modified K-means algorithm fundamentally works by evaluating a sample node's current cluster assignment versus the best alternate assignment and compares the distances to each cluster's respective centroid node. By taking the delta between the two values, the code evaluates the priority of nodes that want to swap and orders them in decreasing order such that high priority swaps come before others. Despite still having several outlier cases that need to be addressed, the base system works as intended, as shown in the depicted figure below:

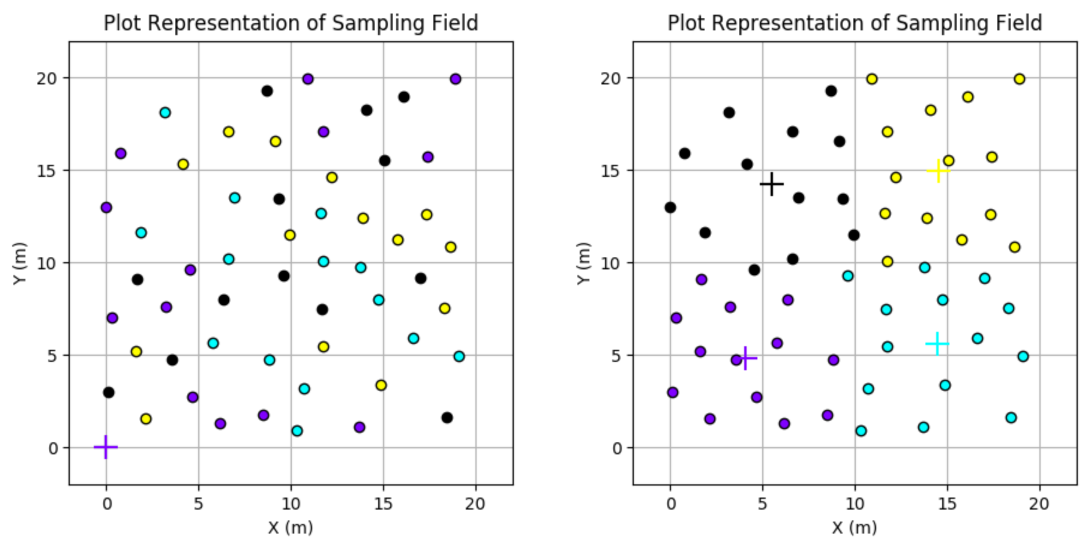


Figure 57: Left: *Random Cluster Assignment for Each Sample Nodes* ***Right:*** *Same Size K-Means Algorithm for a Cluster Capacity of 15 Samples – The different colors represent the 4 clusters that were used to divide this sample set, with the crosses depicted in the right graph indicating the locations of the centroid nodes.*

The diagram above shows a successful simulation where 54 random sample nodes were classified into 4 clusters of approximately the same size (13~14 per cluster). Unlike the previous version of K-means, this algorithm allows the program to put restrictions on the size of each cluster, giving further freedom in the way that the entire trajectory of sample collection is generated. This new method of computing clusters comes with the added benefit of the delta computations which enable quantitative evaluation of how well the current clusters are being divided, since it gives an evaluation of how much better each node would do if it were assigned to a different cluster. With this clustering method figured out, one of the immediate steps afterwards would be to merge this simulation with both ACO algorithms (library and self-implemented) to see which combination out of all of these algorithms yields the most cost-efficient path planner. Despite not reaching the final goal of having a fully working navigation system by the critical design review, progress so far and the quality of the individual Python simulations are promising indications that the integration process would be smooth and simple, especially considering both were built off of the same initial foundation established during the first few weeks of development.

Matthew:

With the motor control algorithm being ahead of schedule, the time spent on that was instead reallocated to trying to solve the ACO implementation problem. While other members spent time working on a self-implemented version, I worked on integrating the navigation simulation with the ACOpy library. Through some manipulation of the data formats, the integration was successful, as was the self-implemented version. From here, we decided to compare the performance of the two versions to determine the best performing algorithm.

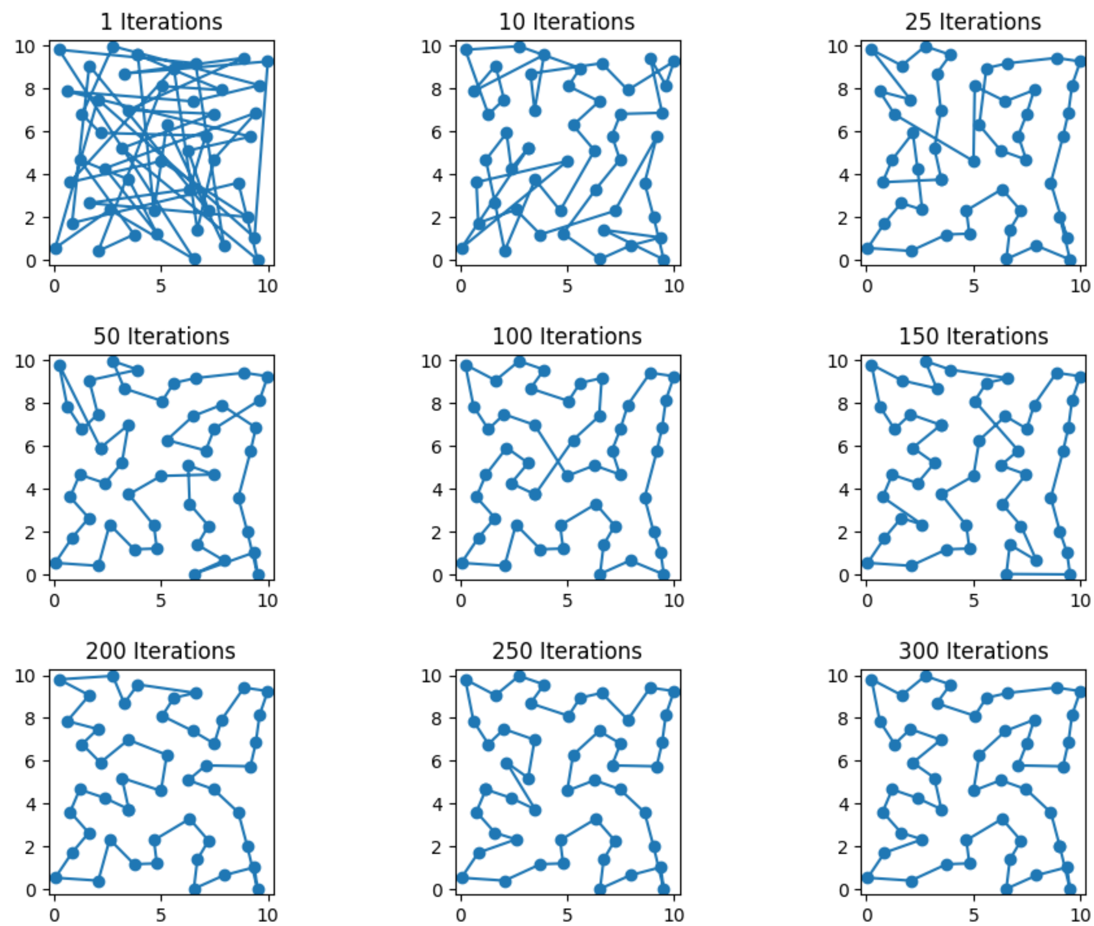


Figure 58: *Results of 9 different runs of the ACOpy implementation on the same set of data, using different limits on number of iterations*

ACOpy was tested with a variety of limits on number of iterations, and the time and cost of each run was monitored. While performance generally improved with greater numbers of iterations, the performance gain for the time trade off fell significantly after around 100 iterations. If this implementation is adopted, the limit on iterations will likely be around 150, as the navigation generation is not done frequently, making time a smaller concern for our use case. The next step in evaluating the performance of the two ACO implementations will be to integrate both with the clustering algorithm and compare the two.

❖ Part 3 – Unknowns and Concerns

Unknowns

Realistically and feasibly simulating the effects of the coring process on saturated wetland soils

Being able to simulate how the motion of the coring tool affects the amount of soil disturbance in the sample would be of interest to our project, so that we could quantitatively predict how the sample's outer region would be disturbed and thus be able to determine the quality of samples collected by our device. Ideally, a prototype could be built of the device with which experiments could be performed, and the actual performance of the device could be determined and measured; however this method is unavailable to us and simulations must be used instead.

Because of the granular nature of sand and dirt, it is difficult to simulate the effects of pushing and twisting a hollow cylinder (the PVC pipe) into the ground. The variation in saturation between layers, as would be expected in a wetland environment, should also be accounted for. In addition, it is a challenge to simulate disturbances caused by organic matter or rocks on the surface and in the soil. There are several methods and programs that have been proposed by the professors that we could possibly use, such as utilizing the Discrete Element Method, ANSYS, or modelling the soil as a high viscosity fluid. These proposed methods and others should be researched and evaluated to determine their relevance to our problem and application. However, it is unknown whether these methods would result in accurate simulations.

Concerns

Weight specification

Currently, our integrated assembly weighs over 40 lbs, which greatly exceeds the performance and QFD specifications set during the Preliminary Design Review (PDR) where the weight was limited to 20 lbs so that it would be lightweight and easy to carry around. Since the PDR, we have decided on a single shoulder strap as the method of transport so that the user can carry the device more easily and comfortably between samples and have a better view and access to the navigation screen during transport (as either one or both hands can be freely used with this method of carry). This design choice was made with our weight specification of 20 lbs in mind. Because the device is to be carried on one shoulder, the weight may need to be even lighter, based on medical recommendations such that the user should carry no more than 10% of their body weight on one shoulder to prevent injury. Thus, meeting the weight specification is paramount because user comfort and well-being, as well as critical design choices such as the carry method and navigation display placement, are dependent on this specification

The challenge that we have encountered with this specification and our design is that we have worked on optimizing the weight as much as possible, and currently estimate that only a few pounds could be removed from our design. This further optimization would not satisfy our specification, nor the recommendation. We are considering re-evaluating some of our material choices (which is primarily Aluminum 6061 at the moment) to possibly switch to lighter materials that are still corrosion and water resistant and meet our strength requirements. At this point in the project, it is uncertain whether changing the material would allow us to meet the specification. Changing the strap-carry design is also something we would prefer to avoid because we simply do not have the time to make such a significant change in the design.

❖ Part 4 – Refinement of Scope and Future Work

Changes to Scope/Capabilities

Because of the changes we made to the design - for example, the implementation of a gimbal to vertically orient the chassis, strap mounting points instead of handles to transport the device, and the addition of an onboard navigation display - the integration of these mechanical systems took longer than the expected time of one week and we are still adding final touches (namely, adding counterweight to ensure vertical alignment of the gimbal, re-evaluating the material choices, and testing the compliance of the swap mechanism lever). As such we did not have enough time to develop engineering drawings and determine the necessary tolerances for our parts. This requires us to remove the engineering drawing and tolerance deliverables from Week 6 to Week 7, and complete integration in Week 7 as well. Because we did allow a week of buffer time in our GANTT chart, this change will only be seen in our deliverables list, not in the GANTT chart.

A few capabilities have also been added to address the need for electronics in our system. Originally, we did not include any capabilities or deliverable for this subsystem. However, in Week 5 we realized that we needed to decide on the electronics as a part of our device design. This change in scope can be seen in the GANTT chart, and new capabilities/deliverables have been added.

The development of the navigation algorithm was also split into K-clustering and Ant Colony Optimization sections, to better reflect the specifics of the algorithm we are developing. The time frame has not changed.

Future Work

Mechanical Integration

To finish with the mechanical integration, we need to evaluate the center of mass of the assembly and possibly add counterweight to the chassis so that it can align properly with the gimbal. To address our concerns about the weight specification, we will reevaluate material choice to reduce weight and investigate other methods we can use to reduce the weight of the device. We also need to finish a few static FEA analysis, mainly to test the strength of the strap mounts, footholds, the swap mechanism lever, and the drill. We also need to calculate the maximum incline angle and tilt-over force so check the stability of our device. To find a method of simulating the effectiveness of pegs in the ground. To ensure that all of the components will fit as desired, engineering drawings will need to be made and tolerances of parts calculated.

Electronics

For the electronics, we need to select the encoders, sensors (IMU, GPS, lidar, and altimeter sensors), and battery. These components also need to be modelled to ensure that they fit in the chassis. Once these electronics are selected and the mechanical integration is satisfactorily completed, we can finalize the Bill of Materials and estimate the cost of our product.

Navigation (Hayato)

For clustering, we currently have a working version of the same size K-means clustering algorithm ready. The delta values mathematically prove that the clusters are approaching the ideal grouping, and we are confident that the current system would at least suffice for when we need to combine it with the ACO algorithm. Due to the current nature of how the clustering algorithm works, converting this version to the radial sectioning method is not as trivial, meaning we are most likely to proceed with this implementation of the clustering algorithm and compare it with all prior versions that were already completed, which includes the normal K-means and the original radian sectioning method. Thus, there would be three candidates for the clustering algorithm.

For the ACO algorithm, the self-implemented version is close to being completed with a few bugs currently that prevent it from stably running multiple iterations. Once those issues are taken care of, we would be able to compare performances against the ACOpy library's performance and observe whether there is an advantage in defining our own cost functions for the pheromone trails.

With both parts of the navigation close to completion, we are anticipating being able to merge each combination of clustering and ACO to quantitatively determine the most effective algorithm combination for calculating the sampling trajectories. Such evaluations would test each algorithm under predetermined user-defined parameters such as sample capacity and cost penalty, etc. Evaluations would be strategically done such that the algorithm that performs the best across all types of expected customer user cases would be selected. The navigation system would be complete once the algorithm is capable of surpassing the human performance on the traveling salesman problem and can generate a path in proximity to the true solution found through the brute force method.

Motor Control

Coring Simulations

To address the challenge of simulating the effects of coring with a PVC pipe on granular and saturated soil types, we will research methods on how to simulate interactions with different kinds of soil, and determine how we can best approximate the coring process. We also will need to integrate our work with Webots, and verify the results we produced in our Python simulation. There may be limitations in what Webots is able to simulate in terms of the actual soil sampling, however, so we may need to find a way to overcome this.

❖ References/Citations

1. "Assessment of Errors in Soil Sampling." *United States Environmental Protection Agency.* [May 1990].
2. Schumacher, D. "Autonomous robots enter fields to collect precise soil samples, help farmers improve yields, reduce environmental impact, save money." *Purdue University.* [28 August 2019]. Web: https://www.google.com/url?q=https://www.purdue.edu/newsroom/releases/2019/Q3/autonomous-robots-enter-fields-to-collect-precise-soil-samples,-help-farmers-improve-yields,-reduce-environmental-impact,-save-money.html&sa=D&source=editors&ust=1616186828689000&usg=AOvVaw3CvUHbnbCgXzNWxMIEY1ih
3. Giannopoulos, G., et.al. "A simple and effective sampler to collect undisturbed cores from tidal marshes." [09 January 2019]. DOI: https://doi.org/10.1101/515825
4. Reinhardt, C.H., Cole, C.A., and Stover, L.R. "A method for coring inland, freshwater wetland soils." *WETLANDS,* Vol. 20, No.2, pp. 422-426. [June 2000].
5. Balch, T. "Grid-based navigation for mobile robots." *The Robotics Practitioner.* [1996].
6. *SoilHawk.* Web: https://www.soilhawk.com/
7. https://www.amazon.com/Varomorus-Sampler-Stainless-Tubular-T-Style/dp/B07Q2W3K4G/ref=sr_1_3?dchild=1&keywords=Soil+Sampling+Tools&qid=1616192934&sr=8-3
8. "Reach RS2." *EMLID.* Web: https://emlid.com/reachrs2/
9. UCLA - MAE - Capstone Senior Design - MAE162E. "2020 Comprehensive Video - Earth Team - Autonomous Agricultural Hole Digger." *Youtube.* [25 June 2020]. Web: https://www.youtube.com/watch?v=cU-ESDOkfQ8&ab_channel=UCLA-MAE-CapstoneSeniorDesign-MAE162E
10. Inglett, P. & Viollier, Eric & Roychoudhury, Alakendra & Van Cappellen, Philippe. (2004). A new idea in marsh coring: The wedge. Soil Science Society of America Journal. 68. 10.2136/sssaj2004.7050.
11. Townsend, Kevin. "Comparing Gyroscope Datasheets." Adafruit Learning System, 14 Mar. 2017, learn.adafruit.com/comparing-gyroscope-datasheets.
12. "Real-Time Locating Systems with UWB." Pozyx, 4 Mar. 2021, www.pozyx.io/?ppc_keyword=pozyx+uwb&gclid=CjwKCAjw9MuCBhBUEiwAbDZ-7vefJpxo9bDGcOHsQLMW-EvD0c_6cPytsMWgCj-mtCiOPVUPbd589RoCHToQAvD_BwE.
13. Racelogic. "How Does DGPS (Differential GPS) Work?" RACELOGIC Support Centre, RACELOGIC, 22 Aug. 2018, racelogic.support/01VBOX_Automotive/01General_Information/Knowledge_Base/How_Does_DGPS_(Differential_GPS)_Work%3F#:~:text=DGPS%20(Differential%20GPS)%20is%20essentially,signals%20to%20eliminate%20pseudorange%20errors.&text=DGPS%20has%20no%20effect%20on,such%20as%20brake%20stop%20results
14. "Different Types of Motors andTheir Use." *DESIGN SPARK.* [5 May 2016]. Web: https://www.google.com/url?q=https://www.rs-online.com/designspark/different-types-of-motors-and-their-use&sa=D&source=editors&ust=1620673047599000&usg=AOvVaw3c7ib8rPNhYwpknj-IQqTu
15. Elmansy, Rafiq. "Principles of Ergonomics: Designingwith User Comfort in Mind." *Designorate.* Web: https://www.google.com/url?q=https://www.designorate.com/principles-of-ergonomics-design/&sa=D&source=editors&ust=1620673047598000&usg=AOvVaw0vC4JsdcJwNi7

CWJQh21KV
16. "What are the Pros and Cons of Using Ball Screws? *Monroe.* [1 February 2019]. Web: https://www.google.com/url?q=https://monroeengineering.com/blog/pros-and-cons-of-using-ball-screws/&sa=D&source=editors&ust=1620681253221000&usg=AOvVaw3qyDlcXCoJgrjaOXKu2gUn
17. Eitel, Lisa. "Five things to consider when choosing a linear actuator." *Linear Motion Tips.* [28 April 2021]. Web: https://www.google.com/url?q=https://www.linearmotiontips.com/five-things-consider-choosing-linear-actuator/&sa=D&source=editors&ust=1620673047597000&usg=AOvVaw3uDgAjsVpqBOpwZNPM8Jph
18. Bridson, Robert. "Fast Poisson Disk Sampling in Arbitrary Dimensions." University of British Columbia, 2007.
19. "Accuracy of the Ball Screw." *THK.* Web: https://www.google.com/url?q=https://tech.thk.com/en/products/pdf/en_a15_011.pdf&sa=D&source=editors&ust=1620673047604000&usg=AOvVaw1FVOqrg8-dHvSVY5yiDU1i
20. "PVC & CPVC Dimensions." *Mid-States Supply Co.* Web: https://www.google.com/url?q=http://www.midcoonline.com/web/Pages/Products/Pipe/Info/PVC_CPVC/&sa=D&source=editors&ust=1620673047606000&usg=AOvVaw2rN9Kll_iUVhUMGxzkBFqc
21. Gilbert, J.M., et al. "Soil properties of three newly created wetlands." Web: https://www.google.com/url?q=https://kb.osu.edu/bitstream/handle/1811/513/1/(98)%25202.11%2520Soils.pdf&sa=D&source=editors&ust=1620673047606000&usg=AOvVaw0DpQrWH4D2E1xo8aOZ38vv
22. Liu J., Li C., Ji C. (2012) "Study of MDP and K-mediods for TSP Problem." In: Zhao M., Sha J. (eds) Communications and Information Processing. Communications in Computer and Information Science, vol 289. Springer, Berlin, Heidelberg. Web: https://doi.org/10.1007/978-3-642-31968-6_39
23. Kumar, D.N., Reddy, M.J. "Ant Colony Optimization for Multi-Purpose Reservoir Operation". Water Resour Manage 20, 879–898 (2006). Web: https://doi.org/10.1007/s11269-005-9012-0
24. Liu, Jianhui, et al. "Study of MDP and K-Mediods for TSP Problem." School of Electronic and Information Engineering, Liaoning Technical University, 2012.
25. "Usage." *ACOpy.* Web: https://acopy.readthedocs.io/en/latest/usage.html#quickstart
26. "AdirPro 740-03 Wing Nut Heavy-Duty Wood / Fiberglass Tripod." *Tiger Supplies.* Web: https://www.tigersupplies.com/Products/Heavy-Duty-Wood--Fiberglass-Tripod__ADI740-03__ADI74003-.aspx?invsrc=adwords_ts&gclid=CjwKCAjwhMmEBhBwEiwAXwFoEQ7MfQdLmey_Z_7qj45j_VcPkRc3J8Gz5Lv1axwbsC1aT214KMZFIhoCeyAQAvD_BwE
27. "ACOpy." *ACOpy.* Web: https://acopy.readthedocs.io/en/latest/readme.html
28. Wani, A.S., et al. "VIBRATION ANALYSIS OF DRILLING OPERATION." International Journal of Students Research in Technology & Management Vol 1(2), April 2013, pg 163-175. Web:

https://www.google.com/url?q=https://core.ac.uk/download/pdf/268005919.pdf&sa=D&source=editors&ust=1620680260407000&usg=AOvVaw2Q8QA3ZHGRblt5-FRbwVQN

29. Entezami, A., Sarmadi, H. & Saeedi Razavi, B. "An innovative hybrid strategy for structural health monitoring by modal flexibility and clustering methods." J Civil Struct Health Monit 10, 845–859 (2020). Web: https://doi.org/10.1007/s13349-020-00421-4
30. Weichao Yang, et al. "Calculation of Friction Force for Slurry Pipe Jacking considering Soil-Slurry-Pipe Interaction.", *Advances in Civil Engineering*, vol. 2020, Article ID 6594306, 10 pages, 2020. https://doi.org/10.1155/2020/6594306