Rolling Miners II

Systems Engineering Paper

New Mexico Institute of Mining and Technology

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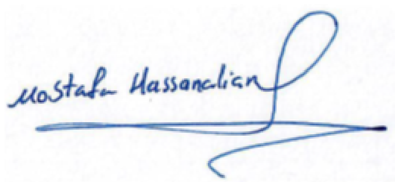
04/02/2023 

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1 Introduction

Humanity still has much to learn about its close astronomical bodies before it can explore the universe beyond. Only 5% of the moon has been explored [1]. Exploring the universe can be considered a result of the natural human curiosity to explore the unknown and search for a deeper understanding about humanity's place within the universe. Furthermore, space exploration plays a vital role in understanding our planet and the survival of humanity. Along with the search for knowledge, a longstanding goal in space exploration has been to colonize other planets and astronomical bodies. Colonization will offer the opportunity for expansion of the human race, acquisition of resources, and technological improvements. Currently, there are several companies and institutions attempting to reach Mars. Advancing our current technological capabilities and exploring the Moon are vital steps in accomplishing this goal.

NASA and the Artemis mission aim to return humans to the Moon and establish a permanent base on the lunar surface. To accomplish this, the Moon must be made sustainable for humans, which requires that scientists discover methods to create habitats and provide various tools required to set up a human colony. The first Artemis Missions will occur at the South Pole of the Moon so that resources, such as water, minerals, and various metals, can be obtained from within the regolith and crust. Consequently, it is crucial to develop new technologies that will assist in detecting, mapping, and collecting such resources. [2]

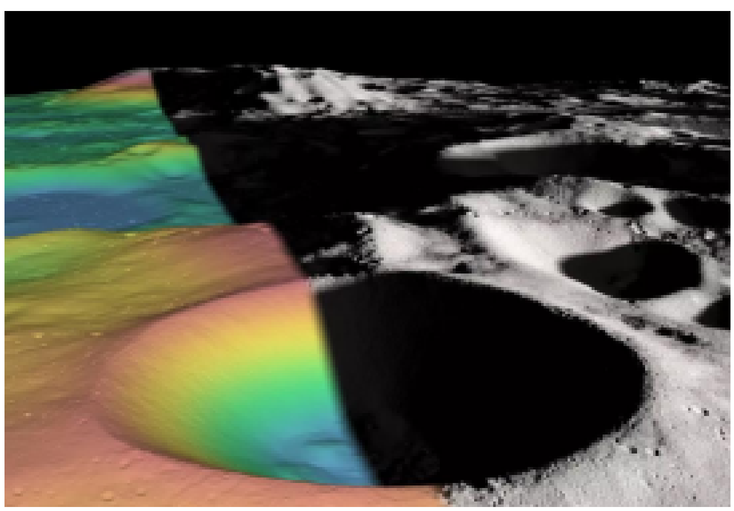


Figure 1: Shackleton Crater, South Pole of the Moon (Image: NASA/Zuber, et al. 2012).

The Artemis missions pose inherent challenges to robotic design, specifically in regards to the difficulties associated with conducting ground research. The lunar environment complicates exploration, a primary obstacle being the abrasive nature of the lunar regolith. As the regolith is extremely small and has a crystalline structure, it introduces a high risk of damage to equipment and poses a risk to filtration systems due to its ability to permeate EVA suit fabrics [3]. Astronauts and electrical components are both susceptible to the hazards resulting from radiation emission equivalent to 13.2 ± 0.7 μGy per hour [4], which is comparable to an x-ray stretched over a day, and temperatures fluctuating between -170℃ to 117℃ [5]. Due to these risks, Rolling Miners aimed to minimize human exposure to the lunar environment, and thus improve astronaut safety, by designing a robotic swarm capable of transporting various payloads. The Fengaribots (Fengari is Greek for Moon) will have durable shells to protect sensitive electronic components, contain a dandelion-sensor launching mechanism to enhance surveying capabilities, and be capable of carrying scientific equipment. Additionally, the bots will have the ability to roll into a ball for improved mobility and energy conservation while traversing through various terrains. The bot design is intended to provide protection and improved endurance against lunar hazards, thus allowing for exploration to occur in regions such as lava tubes or craters, which are typically unreachable for traditional rovers. Figure 1 above shows the environment that will be explored by the bot for the first Artemis Missions.

Two of the primary scientific goals for the Artemis missions – “Understanding Planetary Processes" and “Understanding the Character and Origin of Lunar Polar Volatiles" – require further investigation of the lunar surface. It is desirable that such operations will be possible for long term missions without the involvement of an astronaut [6]. The Fengaribot is ideal for this purpose, as it can easily protect and carry equipment in its shell. The bot is designed to be highly mobile on the lunar surface, as it will use its twelve individual legs to walk on relatively flat terrain but also be able to transform into a ball to roll down slopes. Both the walking and rolling capabilities are depicted below in Figure 2. These two features assist navigating and collecting samples from craters, such as the Aitken basin. By navigating craters, the Fengaribots may be capable of locating sources of ice, which is considered an essential resource for future lunar missions. Samples are valuable in exploration as they can reveal information about the interior and geologic history of the Moon [7]. The bot’s rolling capabilities allows for lava tubes to be more easily navigated, thus giving the Fengaribot an advantage over traditional rovers which typically cannot traverse in such regions. Having access to lava tubes would be beneficial due to their connection with impact melts, which could reveal additional information about the Moon’s geochemistry.

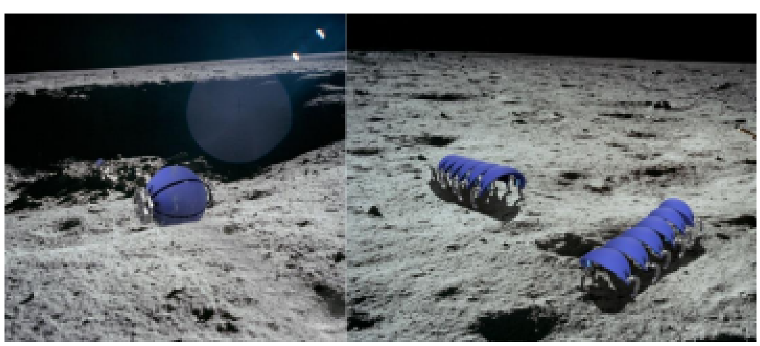
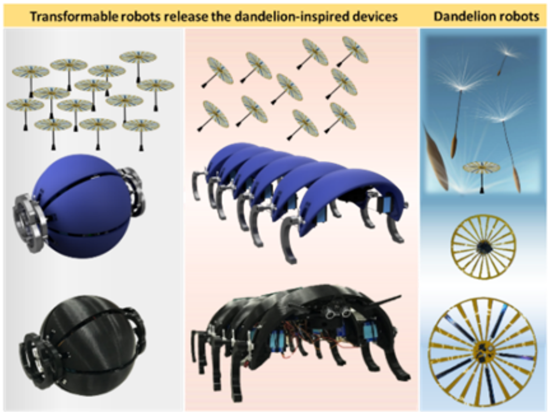


Figure 2: Fengaribots Swarm representation on the Moon. (Lanctot et al., 2022, page 3)



The Fengaribot and dandelion-sensor launching mechanism designs were both results of biological inspirations. The Fengaribots are based upon the Armadillidium Vulgare, also known as the pill bug, which originates from a gilled ancient crustacean. The pill bug's anatomy has various physical features worth mimicking due to their adaptive capabilities for terrestrial traveling [8]. Pillbugs use their sensory antennae to check the environment in front of them and will partially curl over an object's surface to assist in climbing. Furthermore, pill bugs will curl into their shells for protection against predators, threatening environments (such as arid environments or excessive heat), or dangerous falls (as a means to protect vital organs). Pillbugs have evenly sectioned organs which are sized appropriately for each section regardless of whether the pillbug is rolled or open [9,10]. The Fengaribots design incorporates a rolling mechanism, which focuses upon the pillbug's advantages regarding its protective qualities and improved mobility. The curling design feature will allow the bot to roll down hills and across relatively flat surfaces in which gravity can initially assist in setting the bot into the rolling motion. The Fengaribot is partitioned into six sections that take advantage of symmetry to ensure a balanced locomotion.

The dandelion-sensor launching mechanism is based upon the dandelion's seed wind dispersal process observed in nature. Dandelions are native to Eurasia and were spread to different regions of the world through European colonization. They belong to the Asteraceae family, which contains various plants that have compound flowers. A compound flower contains many clusters of tiny florets that resemble one large flower. For a single dandelion, there may be up to 10 circular flower heads with up to 200 florets per flower head. As each floret produces one seed, a dandelion is capable of producing up to 2000 seeds [11]. At development, the seeds have parachute-like bristles which will open wide in windy conditions and dry air to more easily be caught in the wind and detached from the flower head [12]. The seed is then carried in the wind away from the parent plant and can travel approximately 10 meters (32 feet) before falling to the ground [12, 13]. The Fengaribots launching mechanism utilizes the concept of the wind dispersal method and applies the dandelion seed behavior to atmospheric sensors within the bot. By mimicking the dandelion's reproduction process, the Fengaribot sensors will be forcibly dispersed while collecting valuable information of the lunar environment. While the Moon has no atmosphere to mimic this behavior, the launchers are designed to travel large distances with low gravity and air resistance. Additionally, the dandelion-like sensors are designed to drift with lunar gravity across the far side of the moon; enabling scientists to better research its surface and help Artemis II to plan for lunar colonization on the full surface of the moon rather than its proximal half to the earth.

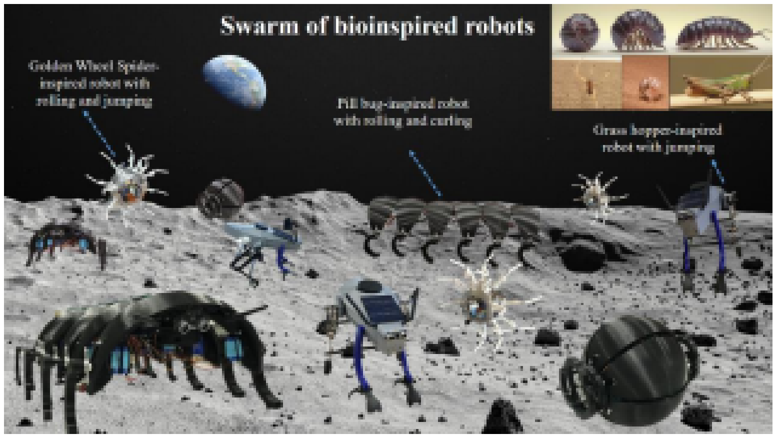


Figure 3: Swarm of bioinspired robots for lunar exploration. (Lanctot et al., 2022, page 4)

Future iterations of the Fengaribots would implement multiple bots working together as a swarm mechanism, in which the bots all interact with each other to carry out missions. Additionally, a swarm of Fengaribots would improve the efficiency of exploring the lunar environment as the extent of surveying being conducted would increase for each individual bot, thus allowing for a swarm to cover far more terrain within a shorter duration of time. Ideally, each Fengaribot will eventually be capable of rescuing other bots if damage or malfunctions occur. In Figure 3, the swarm of bioinspired robots for lunar exploration is shown.

2 Project Management

The objectives of the project directed the foundation of the team's management style where team members contribute in different ways, and communicate throughout the different project stages. Considering how the team has had much of the shells and selection of electronics completed, the remaining goals of the project focused on refining issues from the previous year, and implementing new technologies. There was a larger emphasis on the reliability in the design, and with the addition of the dandelion sensor launcher which uses CO2 canisters, safety was made a higher priority. Testing of the launcher from the robot was deemed unsafe from possible combustion of the capacitors and overheating of systems, and its close proximity to the battery. This required each team to focus on the Fengaribots and dandelion sensors as separate objectives that will eventually coincide. Each objective then had its mechanical, electrical and software aspects, all of which is visible in the block diagram in figure 4.

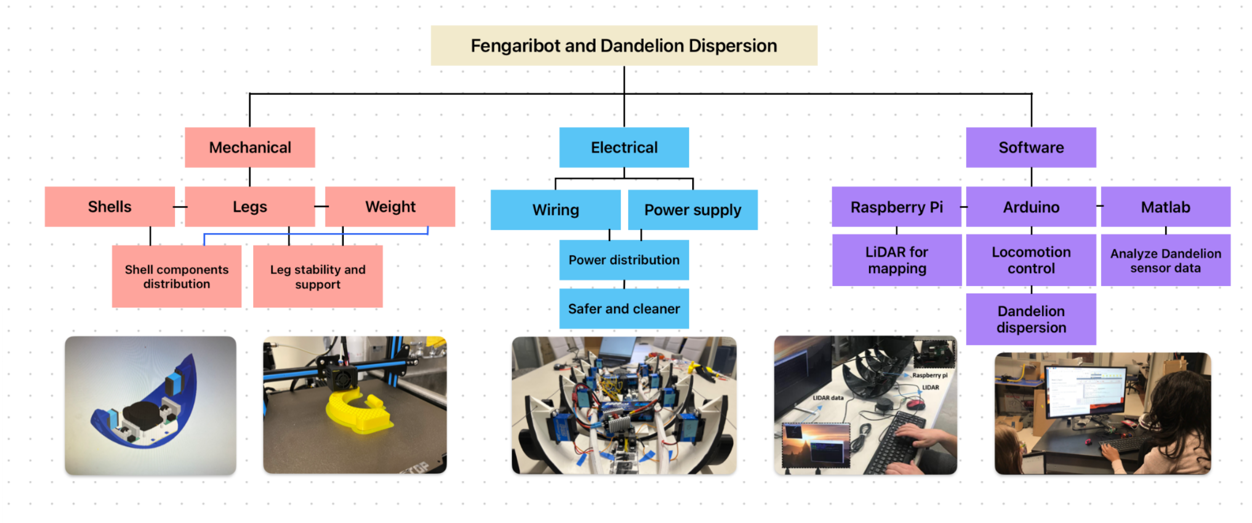


Figure 4: Division of components of the Fengaribot and the Dandelion Dispersion.

2.1 Critical Design Review

Our Fengaribots are capable of traversing a variety of lunar surfaces, such as deep craters and lava tubes, doing so with stronger legs than the last model, but with the same rolling technique as the last model. Armadillidium vulgare, or pill bugs, are able to roll into a ball to protect their internal components; they do not roll down hill. The idea of a rover rolling into a ball to conserve energy as it travels downhill is bioinspired. The common method of locomotion through its legs can be carried out on flat lands or uphill to allow the rover to get back out of whatever crater or crevice it explores. In addition, this rover can be deployed in many locations, has the ability to navigate using an algorithm, and can communicate to other rovers to create a map of the far side of the moon's terrain and thermal sources. The Fengaribot is equipped with LiDAR that can only see things on its plane. The LiDAR works by emitting a laser that's then reflected by nearby objects. It then uses triangulation to estimate the distance and angle of the objects in order to map nearby surroundings. By rotating quickly, it's able to update this map according to changes in the environment. The LiDAR currently works along a 1D plane, but can be placed at an angle slightly down to improve its navigation ability. In future designs, trigonometry could be used to interpolate the 1D plane into a 3D plane, further improving the Fengaribot's mapping capabilities.

The updated design improves upon the previous iteration of the design with (1) a second method of data collection through the deployment of dandelion sensors, (2) an improved communication range within the swarm network due to the use of a proprietary communication protocol from Espressif systems including node hopping and (3) a more robust design to emphasize protection of electronics and stability. Sketches of the process of redesigning the hatch and wiring mechanism are shown in figures [5 and 6].

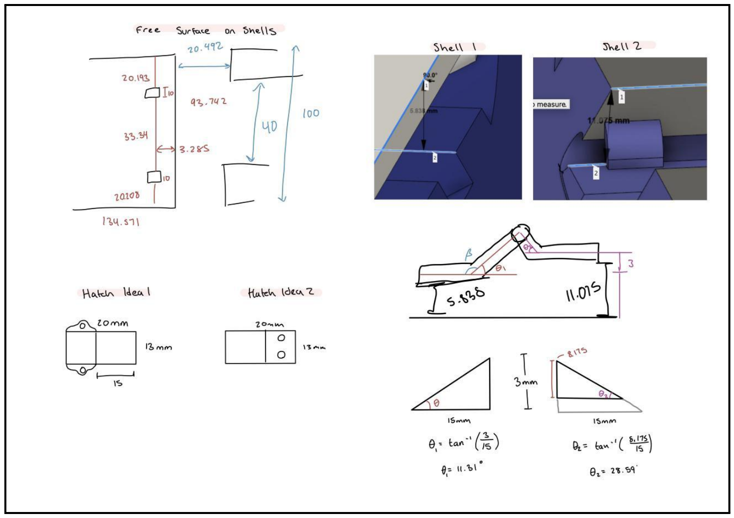


Figure 5: Sketch of Potential Hatches for Shell Connections

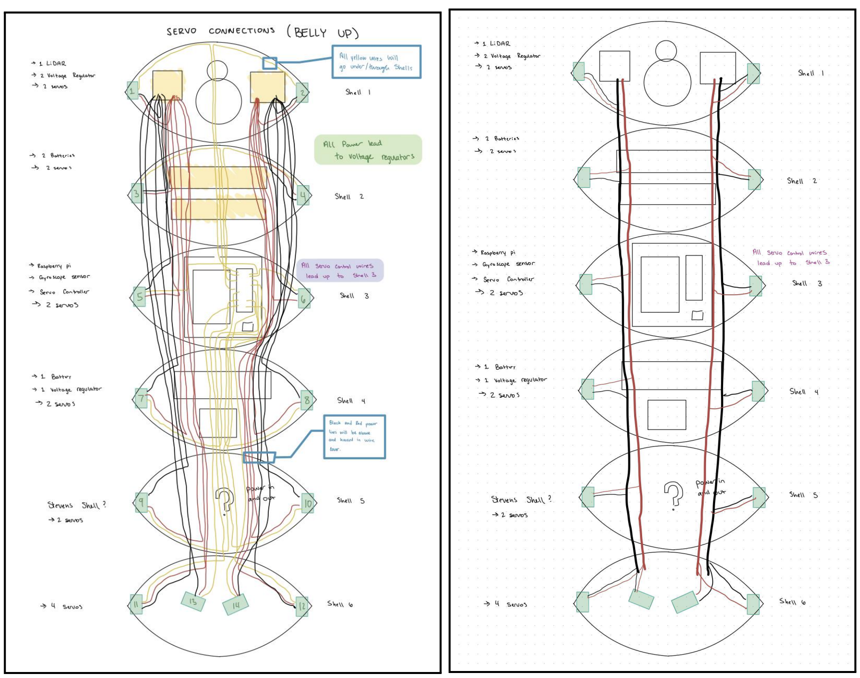


Figure 6: Sketch of Connection of Servo Wires where left was old design, and right is the improved design (yellow lines not included on right)

The Fengaribot is split into six equal segments that contain the components and sensors based on what best suits each location. The shells were redesigned to better accommodate the new dandelion dispersion mechanism and better balance the robot to avoid it falling on its side, while still being able to fit into a ball as in the previous design. The first segment contains the LiDAR and the second segment houses two batteries, as was the case last year. The other segments have been modified to better fit the new dispersion sensor. The third segment contains the microcomputer, Inertial Mass Unit (IMU), and the servo controller, allowing the servo controller to be easily connected to the microcomputer. The fourth segment contains the voltage regulator. The fifth segment contains the new dandelion sensors and their dispersal mechanism. Each of the first five segments has two servos, while segment six houses the last four. The cable routing system exists on each shell to guide the winch mechanism and was modified this year to allow for better cable organization.

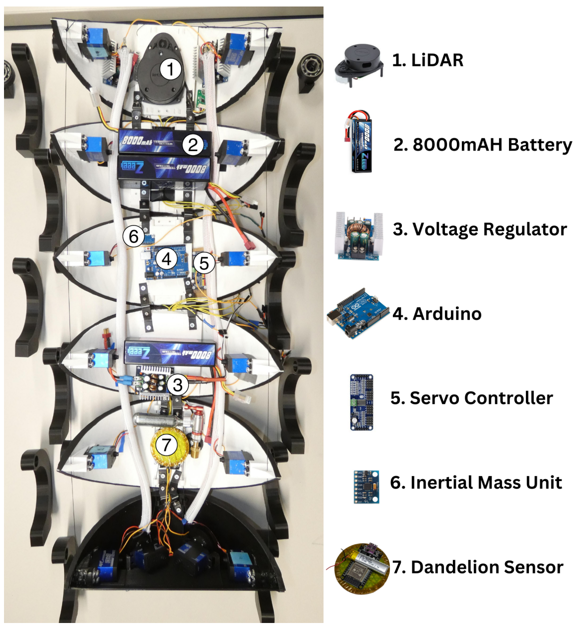
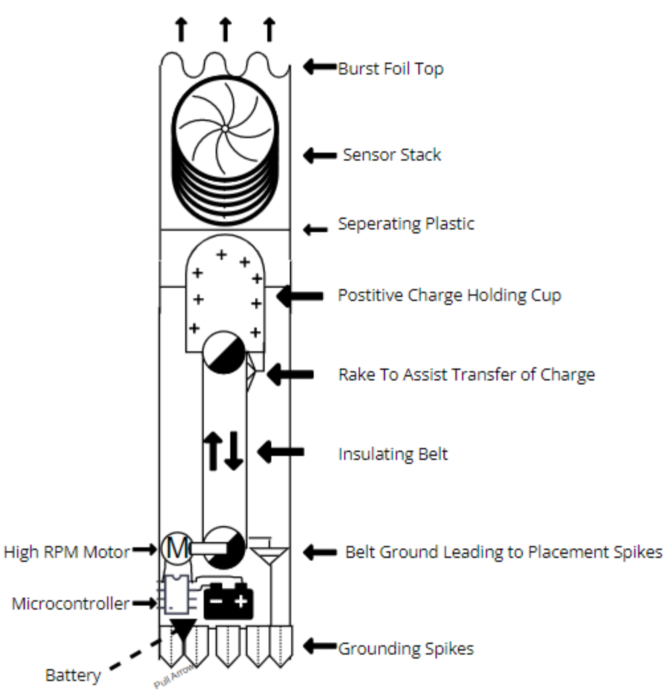


Figure 7: Labeled Components of Fengaribot

The project features a rapid deployment sensor network dispersion unit attached to the underside of the robot. This system uses stored cold gas as a propellant and is capable of launching a stack of up to 10 wifi capable sensor packages radially around the dispersion site. This segment will cover the description and function of both the launching mechanism and the individual sensor packages. First, I will discuss the description and function of the dandelion based bio - inspired sensor packages. From here on in, they will be referred to as dandelions. Each dandelion consists of a 2.5 inch diameter kapton based flexible PCB affixed to a 3d printed stiffener to allow for them to be pushed by the cold gas launcher. Each dandelion is required to have a battery capable of maintaining 3.5V DC, a esp32-3c microcontroller, and a desired sensor for a given survey. For the battery, the team decided on a 500mAh LiPo battery with a nominal value of 3.7V DC. These meet the required power requirements and voltage requirements as well as allowing for a variable lifetime based on the sampling speed needed by the sensors for missions. This can range from 5 hours to 10 days depending on the energy needs of the sensor and idle time. This estimate is based on the low power protocols of the chosen microcontroller. The team decided to use an esp 32-3C module as it comes with many desirable features, and has many common communication protocols including: UART, I2C, LoRa, WiFi, Bluetooth low energy, and the proprietary esp-now WiFi based protocol. These allow for both a wide arrange of sensor compatibility and the option of long range data transmissions of over 200m. This is well beyond the range than expected from the launching mechanism. This long range communication allows for us to set up nodes that can have different functions that all get sent back to the Fengari bot for later analysis. These sensor nodes are meant to be modular and allow for reconfiguration for each required test. For instance, if there was a mission to determine if an area had a specific gas deposit these dandelions would be able to be equipped with gas sensors that would denote the existence of these deposits. Once the data is analyzed these dandelions can be retrieved by a human operator and recharged for later use.

The launcher system uses 16 grams of stored CO_2 gas. This expands to over 9L of volume in under a second. This creates a large thrust that is capable of propelling our sensor dandelions an estimated 120m away from the bot on the moon. This is an estimate based on expected thrust and weight of the sensors. This is due to a local missile ban ordinance that does not allow for us to test our concept without a permit from our local government. In lieu of this permit, the team has done a conceptual test that demonstrated the capabilities of these sensors while placing manually at the predicted distance expected from launch. These results are discussed later in the technical performance measurement section. For future design considerations the team expects the CO_2 canister to be placed near the heat sinks of the voltage converters during launch to carry heat away from the system. This method of heat transfer is preferable due to the fact that there is no convection on the lunar surface, and conduction would only allow the heat to be transferred back into other portions of the bot. This leaves either radiation, or the active expulsion of heat using the stored cold gas of the launcher. The below figure shows our original charge based design and our new cold gas design.

The Fengharibot has twelve legs, which are able to rotate independently with separate servos. The legs were redesigned to be thicker and longer and have stronger axles. Holders were created for the bearings to make them more efficiently placed. These upgrades allow for stronger legs that allow the robot to better traverse the surface.



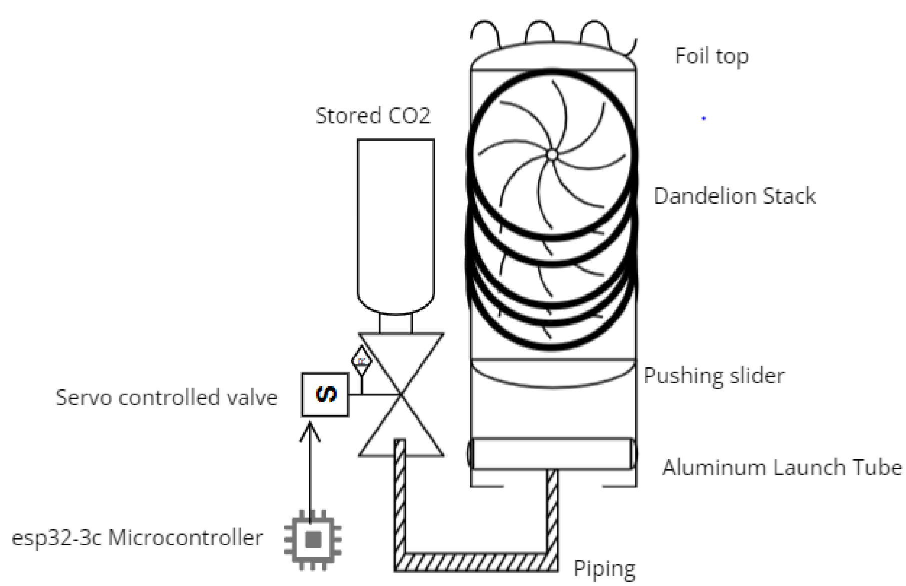


Figure 8: Old dispersion device design (Left) vs new Design (Right)

2.2 Schedule of Work

The following Gantt chart describes the preliminary schedule with tasks assigned for the projects. Teams were divided between the mechanical, electrical, and programming design systems. Secondary teams were assigned for different components of research, testing, and prototype development. The mechanical division focused on the fabrication and design of the robot's main body, placement and the locomotion system, as well as the robot's rolling mechanism. The electrical division was responsible for implementing electrical design, testing the electronic components, and assembling the sensors. The programming team specialized in coding various systems–including raspberry pi, mapping and navigation systems. Combined, the three teams worked on assembling the three main systems together.

Table 1: Primary estimated schedule of Events.

Estimated Schedule of Events			
Event	Number of days	Start Date	End Date
Fengaribot Redesign	53	12/5/2022	1/27/2023
Dandelion Launcher Design	53	12/5/2022	1/27/2023
Main Body Prototype II	18	1/30/2023	2/17/2023
Dandelion Launcher Prototypes	18	1/30/2023	2/17/2023
Main Body Testing II	11	2/20/2023	3/3/2023
Dandelion Testing	11	2/20/2023	3/3/2023
Main Body Refinement II	11	3/6/2023	3/17/2023
Dandelion Refinement	11	3/6/2023	3/17/2023
Main Body Final Design II	14	3/20/2023	4/3/2023
Dandelion Final Design	14	3/20/2023	4/3/2023
Proposal	27	9/21/2022	10/18/2022
Quiz 1	14	11/7/2022	11/21/2022
Preliminary Design Review	28	10/24/2022	11/21/2022
Funding + PDR Notification	1	12/2/2022	12/2/2022

Estimated Schedule of Events			
Purchase Parts	119	12/2/2022	3/31/2023
Team Check in + Quiz 2	25	1/23/2023	2/17/2023
Systems Engineering Paper	42	2/20/2023	4/3/2023
Poster	21	3/13/2023	4/3/2023
Project + Team Video	21	3/13/2023	4/3/2023
Quiz 3	14	3/27/2023	4/10/2023
Finalist Teams Notified	0	5/4/2023	5/4/2023
Presentations	1	5/9/2023	5/10/2023
Award Ceremony	0	5/12/2023	5/12/2023

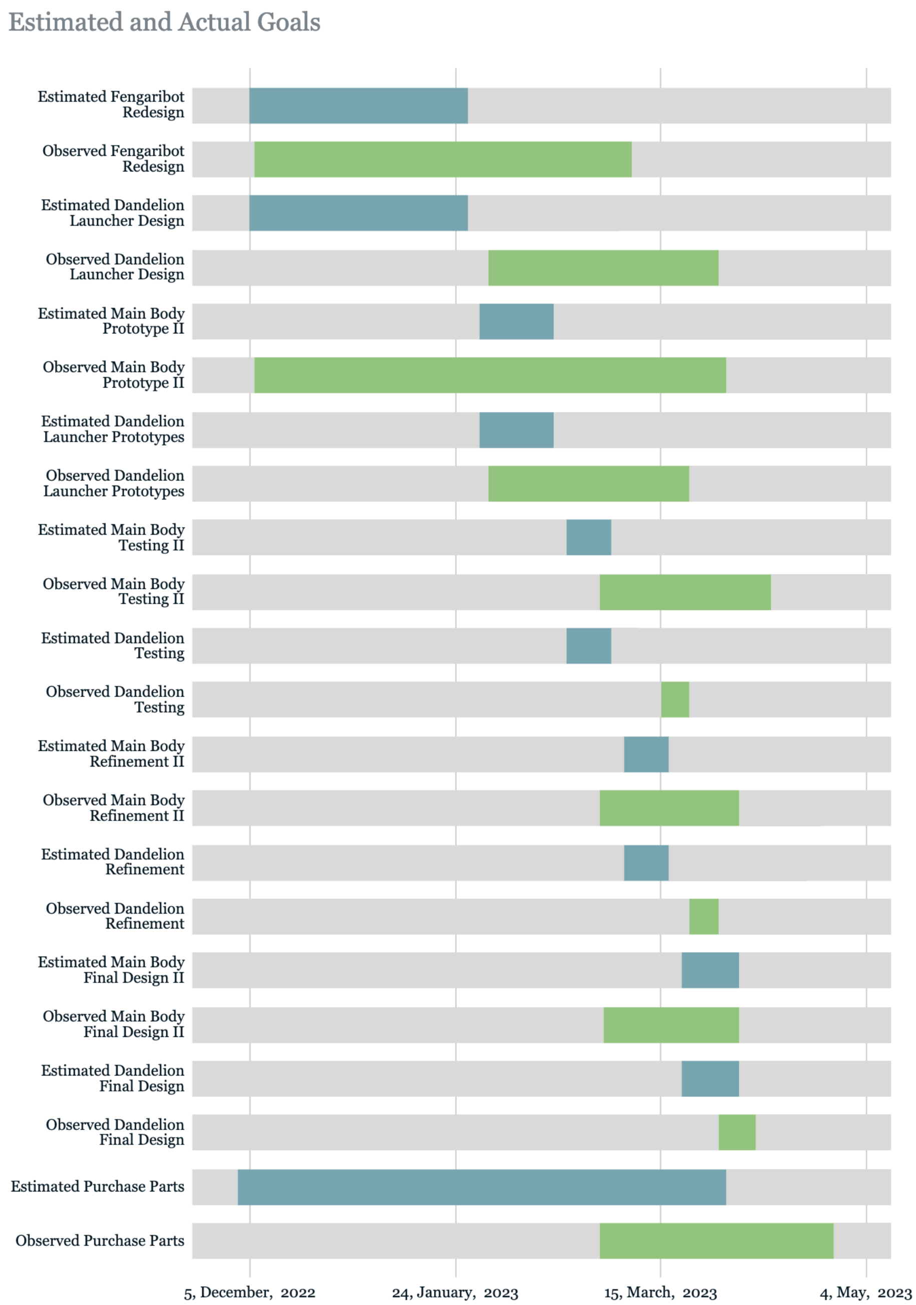


Figure 9. Gantt chart of estimated and actual goals timeline; Blue indicates the estimated schedule, where green indicates the actual timeline.

As seen in Fig. 9, the expected and actual schedules the team followed is indicated. Some unforeseen delays were encountered by the team during the design phase due to complexity in the designs, as well as shipping delays which interfered with the assembly process. Despite these circumstances, the Rolling Miners II were able to complete the deliverables successfully in a timely manner, as well as complete the assembly of the Fengaribot.

2.3 Budget

As a continuing project, some parts were able to be reused. The expected total budget cost is shown in Table 1. The total cost of materials amounted to $526.62 as shown in Table 2, resulting in $1,473.38 of remaining funds.

Electronics	
LiDAR	$500
Microcomputer	$100
IMU	$50
Servos/Motors	$300
Batteries	$100
Misc. Electronics	$100
Total	$1150

Budget for Materials	
PLA filament	$200
Misc. Materials	$100
Van de Graff belts	$50
Metal Components	$100
CO_2 Tank	$200
Total	$650

Miscellaneous	
Incidentals	$200

Total	**$2000**

Table 1. Expected budget for electronics, materials, and miscellaneous items.

Electronics	
Smaller solar panels	$20.97
Flexible Solar panel	$29.97
Step Down Module	
Adjustable DC	$18.99
Battery	$186.27

Budget for Materials	
Bike inflator	$27.96
UNF 3/8 gas cart	$29.99
Schrader to 1/4 npt	
Insulation	$12.99
Hinge	$17.40
Bearings	$111.26
Cord protector wire loom cable	

Miscellaneous	
Screws, velcros, powertools	$70.82

Total	$526.62

Table 2. Actual budget for electronics, materials, and miscellaneous items.

The actual budget of components needed for the Fengaribot was underestimated.

3 Systems Engineering

3.1 Concept of Operations

The Rolling Miners II is a continuation of the NASA MINDS 2021-2022 design project with improvements in design quality and addition of a denalion sensor suite and dispersion system. Recalling the Rolling Miners iteration of the Fengaribot, a bio-inspired model of a pillbug provided great advantage in the lack of atmosphere on the Moon. Any propeller based system should be deemed nearly impossible, hence a need for versatile ground transport. The mechanical team have previously designed the Fengaribot to traverse in two states: a walking state and a rolled state. The different mobility options provide an advantage to traverse both the harsh lunar surfaces and down steep craters. The Fengaribot's low center of gravity and symmetrical frame will give a less likely probability of falling to its side and – unlike a rover with treads – can recover itself if it ever did find itself in this situation. The ball form can be utilized in conserving power by taking advantage of lunar gravity to roll down a crater and other inclines. The robust shell design in conjunction with the Fengaribot in its rolled configuration can protect any internal sensitive components from the harsh moon environment; in the instance where a Fengaribot is damaged, it can rely on its swarm to retrieve it.

- *Figure 10: Shows the bioinspiration between the pill bugs curling up mechanism and the fengaribot, along with the fengaribot rolled and unrolled*

The Fengari bot has two continuous servo motors on shell 6 (Figure 7) that contain a winch mechanism. These two winch systems work together to activate the four nylon cords that are directed throughout the rest of the shells to pull the Fengaribot into a ball. Two of the nylon cords are along the "spine" of the robot, while the other two are along the lower-corners of the shell (when in standing position). In shortening the length of the cords – with the winch motors spinning in the clockwise direction – the shells are concentrated together to form a ball. In loosening the cords by spinning the servo motors counterclockwise, the Fengaribot can return to its walking state. The winch works in a similar way to how an actual pill bug curls up in which it has stronger stomach muscles that contract its body inward to close, and relax to open. The fengari bot will walk on 12 legs which gives significant stability. Each side has six legs that move in succession; as it rotates one leg to the other side, the next leg will follow thereafter, and repeat for each leg allowing it to propel itself forward. The rotation of legs of each shell will be the same, and will mimic the movement of a pillbug . The legs can individually move via 360 degree high torque servo motors, and–similar to a machine with treads– the Fengaribot will also turn by rotating about its center (if observed from the top view).

- *Figure 11: Shows the loops used to keep nylon cords in place on the spine (in red) and the bottom of shell*

The additional bio-inspired design feature is based upon the wind dispersal method for dandelion reproduction. The dandelion-sensors launching mechanism will utilize a CO_2 gas launcher to propel multiple sensors from the bot in various directions to assist in surveying a larger boundary region. This feature will aid in data collection without requiring additional movement from the bot itself. The dandelion sensors are modular with different sensors for a multitude of different surveying missions, especially since the sensors could be launched away from the robot while carrying data or collect various data samples of a wider area that one traditional rover may not typically be capable of collecting.

As for the Electronics of the fengari bot it will have five subsystems which are: winch mechanism, leg movement, sensor suite, onboard computer, and power system. The winch subsystem which allows the Fengaribot to pull on interior cables to roll the bot into a ball. The leg movement system will allow the bot to traverse lunar regolith more easily. The sensor suite consists of the LiDAR, the IMU sensor, and the dandelion sensors. The LiDAR will be used to navigate and map its environment by using laser triangulation. The IMU sensor will be able to tell the orientation and the angle of the bot with lunar gravity as a reference.

3.2 System Hierarchy

The fengaribot is composed of three subsystems; the mechanical, electrical, and the computer systems. The mechanical team focuses on the locomotion and integrity of the body design. This version of the fengaribot had a redesign focus, especially in updating the design flaws that were made apparent in its previous iteration. The internal components were reorganized to evenly distribute weight, which was made challenging where the team needed a dedicated shell for the new dandelion sensor launching mechanism. A better hinge solution was created to remove the previously large gaps between the shells when in a ball form, which is ideal when needing to properly protect the internal electronics. The locomotion had improvements in the legs to better support the Fengaribots weight, and implemented bearing holders for both additional support as well as frictionless rotation.

- *Figure 12: Leg form old design vs New Design*

The team focused all electrical aspects in the organization of wires, increased power supply, and more in depth research into voltage regulators. For the wire organization, it was necessary to avoid tangles and remove the previously complicated power system as there were multiple safety concerns that were overlooked on the previous iteration. The previous design also had power insufficiencies that were upgraded by obtaining higher capacitance and voltage batteries along with an additional third battery. The team further investigated voltage step down regulators when connected to the seven continuous servos in a parallel configuration. The servo controller was outdated, hence it was proposed to use an arduino as servo controller in which a Raspberry pi could read and write commands. Overall, allowing us to combine the LiDAR and IMU system, which are better compatible with the Raspberry PI, to the simple controls of an arduino board.

The software aspect of the robot is integrated together by the code from the arduino. The arduino is the brain of the system that controls the robots movement, rolling up function, and sensor package. The sensor package consists of LiDAR for navigation and mapping, IMU for ground orientation determination, and communication with the dandelion surveying package. The code also interconnects with the mechanical aspects by communicating with the servos to tell them to move so that the robot walks and curls up.

3.3 Interfaces

To achieve proper functionality of the various design features, several interfaces need to be capable of successfully working together. The key components to be interfaced include a Raspberry Pi, an Ardunio, servos, IMU, LiDAR, and launching mechanism.

A Raspberry Pi will be utilized as the Fengaribot's microprocessor, interfacing with the Arduino microprocessor to control the operation of the launching mechanism, LiDAR, and sensors. The Raspberry Pi must be capable of interfacing with the bot's rolling and locomotion mechanisms through the Arduino. Additionally, the rolling and locomotion mechanisms have servos which must interface with the Arduino board. Once the interface is established between the servos, the Arduino, and the Raspberry Pi, the team will be able to control the rotation rate of the servos for the locomotion mechanism and the rolling mechanism.

Another interface that must be established within the Fengaribot is between the Inertial Mass Unit, or IMU, and the Arduino. The IMU will be connected via wires to the Raspberry Pi's pins so that data from the IMU can be directly transferred to the microcontroller's navigation algorithm. In addition, an interface must be established between the LiDAR and microcontroller. To accomplish this interface, the LiDAR will be connected to the microcontroller via a USB 3.0 port, as this port will allow the Raspberry Pi to both power and receive input from the LiDAR. As the Raspberry Pi receives the LiDAR's input, the input will be directly fed to the Raspberry Pi's navigation algorithm. The Fengaribots will utilize LiDAR while navigating the lunar surface to create a 3D map of its surrounding terrain. To ensure the bot remains aware of its position and allow for any necessary self adjustment after rolling, the bot will utilize an accelerometer and gyroscope system. These features will also allow for unexplored terrain to be more thoroughly documented and obstacles, such as large rocks or steep slopes, to be avoided.

An additional critical interface within the Fengaribot is between the dandelion-sensor launching mechanism and the microcontroller.

Communication between individual Fengaribots within a swarm is another key interface of the bot's computer system. As inter-communication between bots in a swarm is critical for improving task efficiency and achieving mission success, each bot must be able to communicate with each other. The Fengaribots will be able to utilize antennas to achieve short range communication. These antennas will then send information such as the robot's functionality, current planned path, and current anticipated destination. The other bots within the swarm could then use this information to better plan the paths they either take or avoid.

3.4 Requirements

The Fengaribot shall be able to carry scientific equipment across the moon; it shall be able to curl up and roll, roving the lunar terrain. In its stretched out form, it shall be able to disperse a swarm of dandelion sensors that assist in surveying larger territories on the moon that the robot cannot while stationary. The LiDAR will be able to navigate a 3D map of its surrounding environment and will be capable of avoiding obstacles. The robot shall be capable of machine learning for navigation and transport to the required destination. It shall be able to mark locations on the moon for where it will work, and shall be capable of fall recovery through the use of leg control. The robot shall be capable of absorbing solar energy and recharge via doing so. The robot shall be able to decide the necessity of rolling downhill to conserve energy. The legs shall be able to compact itself by folding without interference of other legs and maintain the distribution of weight. The robot shall be capable of autonomous operations in environments that lack accessibility for GPS navigation. It shall be able to disperse swarm communication to expand navigation potential. The robot shall be capable of unrolling from the conglobation state and be capable of walking with precision. The robot shall weigh less than 25 kilograms per unit and have parameters no longer than 100 × 140 × 100 centimeters when rolled for transport. The robot will be stored in its folded position with the legs interlocked on its sides. The Inertial Measurement Unit (IMU) shall be capable of mobile detection when rolling, and detecting slopes of the terrain. The robot shall be capable of individual and swarm operation and shall withstand the environmental conditions for a minimum of three years. The robot shall be capable of resisting damage due to solar radiation and resistance to lunar regolith. The computer shall be able to survive radiation. The robot shall be capable of operating in extreme temperatures ranging from -170°to 140°C.

3.5 Technical Performance Measurement

The performance of the navigation algorithm is a very important technical performance measurement. This is based on several sensors that can be equipped to the Fengaribot. In our current case the team is using a lidar to take a general look ahead of the robot to identify larger obstacles that may be in the way such as a sheer cliff or larger rock in front of the robot. This system is good at identifying general directions that obstacles may be. The team is also using several single direction LiDAR sensors in order to find particular distances in important directions such as directly in front of the robot, or below its shells to determine clearance from the ground. These parameters can eventually be used to guide the robot autonomously. The current project scope does not include this capability.

The team conducted several experiments with our sensor nodes that allowed for us to determine the efficacy of multiple node data acquisition. In this particular experiment the team had 3 separate nodes. One forced response node that was given semi regular impulses of CO_2 gas and a mist of water is applied near the sensor. This shows that the 2 nodes measurements simultaneously and successfully stored each data set. In this case each sensor node was equipped with a mg-811 CO_2 sensor as well as a bme280 environmental sensor capable of temperature and humidity. The data was then sent to the central node that was equipped with an sd card storage module and would wait idly until a data point was taken. As each sensor node read a measurement it was sent line by line to its own data file on the data collection node. The data was then later analyzed using a matlab program. In this particular test there was an error with the idle node as there was a calibration error with the gas sensor.

The nodes were placed across the New Mexico Tech athletic field. Each sensor node is roughly 160 ft apart, this is well within its operational range. The forced response node was in a recently watered portion of the field and can be seen with a lower average temp and significantly higher humidity. The locations are as follows.

For future work, the team can use the New Mexico Tech LunaBotics arena that mimics the lunar environment. The arena is designed for lunar testing, with dirt that is similar to the regolith on the moon along with lunar obstacles. This area will be valuable in testing to determine whether our design is capable of traversing the moon, and to adjust it accordingly. The team can directly test it in the obstacle-filled region and observe the Fengaribots limits. The team also has access to a drone cage that can be used in early testing for the sensor deployment.

- *Figure 13: LunaBotics Arena for testing, along with drone cage*

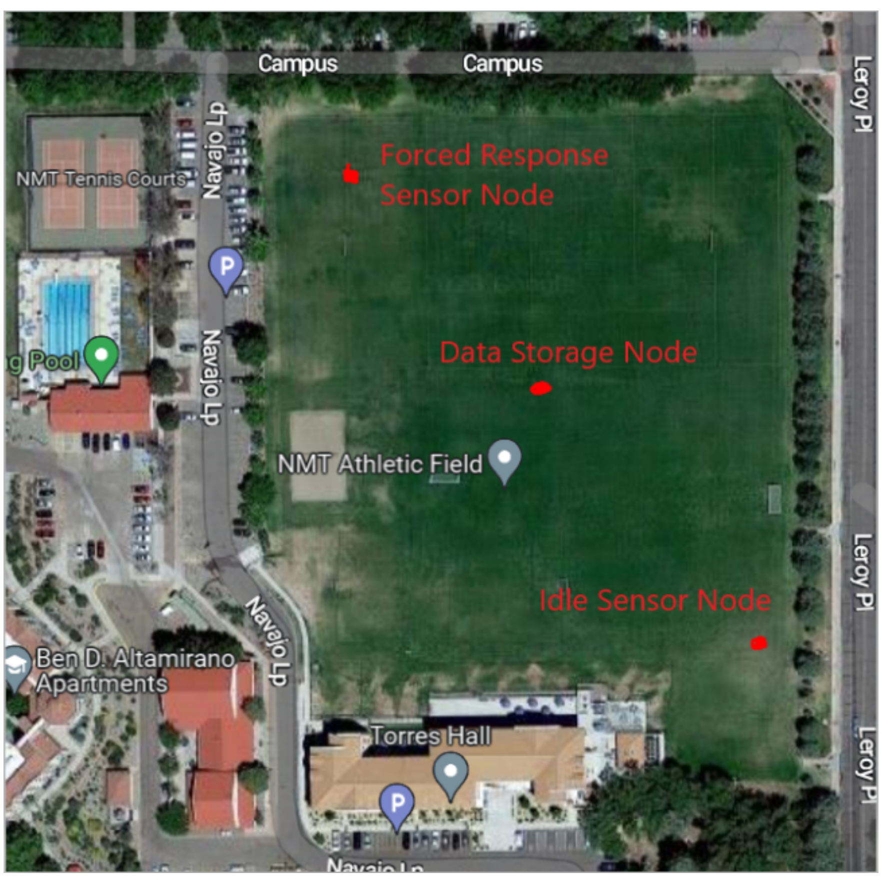
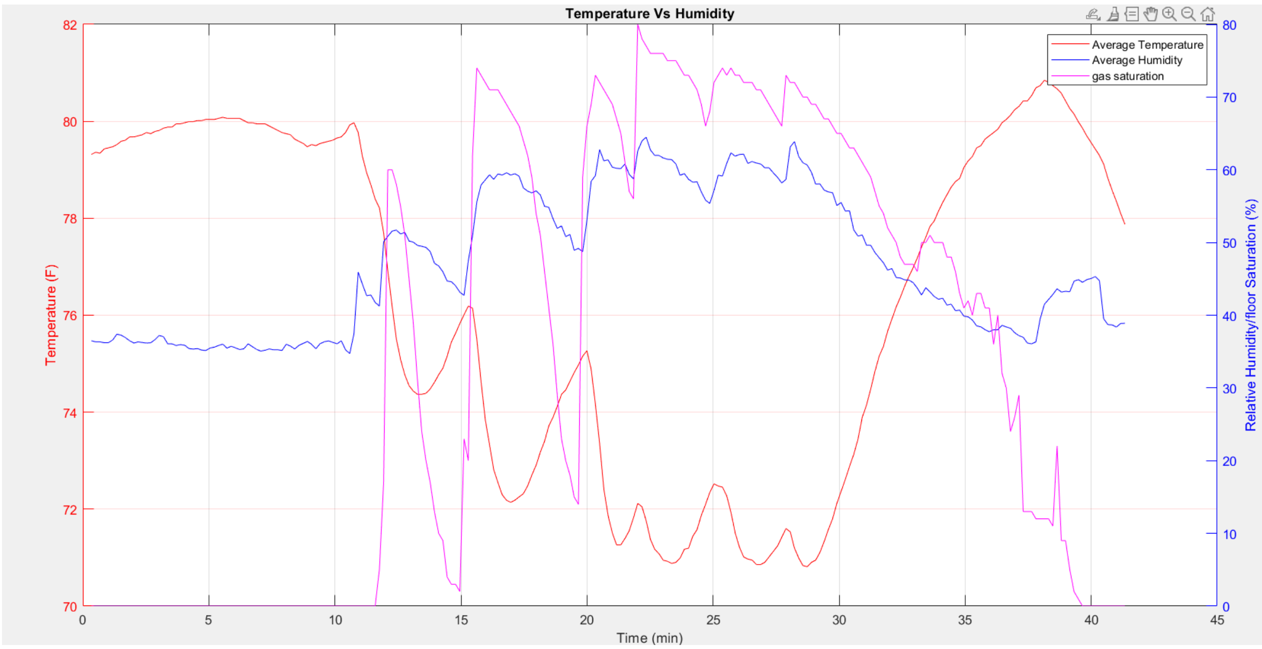
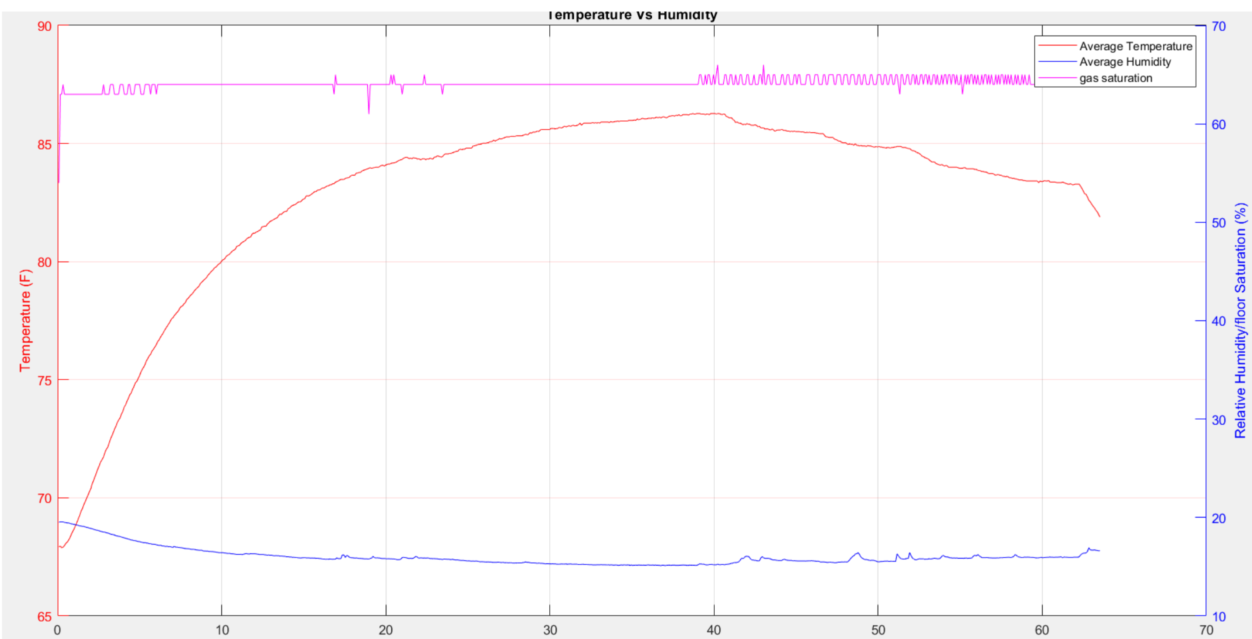


Figure 14: Location of sensor nodes across NMT athletic field



Graph 1: Forced Response Sensor node data

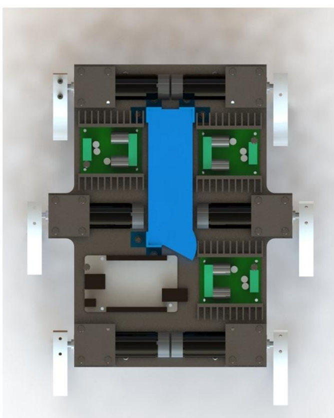


Graph 2 : Idle Sensor node data

3.6 Trade Studies

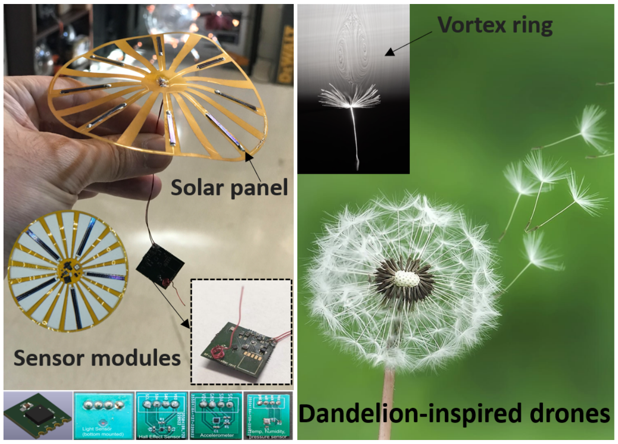
In the original leg design considered last year, the legs were intended to be double-activotation. However, this required 24 servos for 12 legs, more than could fit in the robot. The single actuation design of the legs were inspired by the locomotion systems on the Kod*Lab's RHex robot [20] and The Delf University of Technology's Zebro Light (see Fig. #) [21] robots which consist of legs that rotate in a semicircle. After walking, the legs rotate in a full circle and return the leg to the surface. This prevents the robot's legs from running into the ground. These designs require th e leg to be offset horizontally to prevent the legs from colliding. These principles were used in designing the locomotion of the legs. The design was updated this year as the legs were unable to support the weight of the robot. The axel was not strong enough, causing it to snap. The legs were updated to be thicker and longer allowing them better stability.

The leg shape of the Fengharibot is also inspired by that of the Zebro Lightbot in the updated positioning of the legs. The legs are of alternating length in order to avoid the legs from overlapping or colliding with each other.



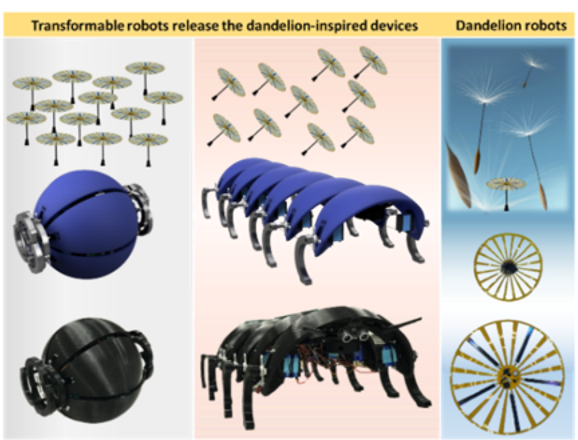
- *Figure 14: Picture of the Zebro Lite Bot*
- *Figure 15: PIcture of Fengaribot with its alternating leg axel lengths*

The dandelion sensors are micro-drones that are modeled after dandelions, allowing them to float and easily spread across a surface. Originally, the micro-drones were launched via a spring mechanism and would collect sonar, altimeter, and radio data. This design was modified to account for the lack of air in lunar conditions. Our design remains lightweight, but is launched via a propolision system that includes gas, allowing it to still reach a large area once launched. The sensors in the Fengharibot also have sensors detecting different resources, making it ideal for lunar exploration.



- *Figure 16: Picture of dandelion sensors , and there bioinspiration*

The body and electronics of the Fengaribot weigh 2.794 kg and the legs weigh 0.51792 kg. In total, the mass of the Fengaribot is 3.32 kg.



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