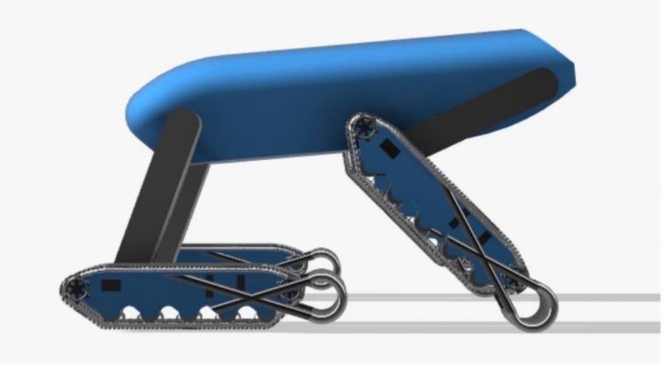
Morphing Tank-to-Leg Modality for Exploratory Lunar Vehicles

University of Connecticut



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1.0 Summary

To date, no autonomous rover has explored the lunar south pole due to the locomotive challenges posed by highly porous and fluffy regolith, steep crater walls, and the icy regolith patches. Traditional wheeled modalities that have been used in past lunar applications cannot traverse such extreme terrain, which is sure to be encountered when searching for water-ice. This year's NASA BIG Idea Challenge is to conceptualize, develop, and test an alternate modality to be used on such terrain.

The proposed Adaptive Morphing and Balanced Exploratory Rover (A.M.B.E.R.), modality aims to overcome these environmental obstacles by utilizing a morphing modality design with integrated leg, tank, and hybrid modes of travel. A.M.B.E.R.'s design consists of four continuous chain-link treads that can extend into legs via two joints. On terrain with gradual gradients, the modality will run in tank mode such that all four chainmail tracks operate as traditional treads, with the advantage of being lighter weight, more energy efficient, and can traverse uneven, loose, and icy regolith. For rocky sloped surfaces, the modality adopts quadruped mode where it has the potential to more effectively climb up and down elevations.

At the conclusion of this project, this team will deliver an integrated leg and tread mechanical designs/prototypes that is tested against traversing lunar regolith slopes of 36 degrees and traction on icy and non-icy lunar regolith. The prototype will be programmed to perform the morphing motions.

To assess the effectiveness of these modes of travel, the following tests are proposed. A miniature slope lab (MSL) will be built and filled with non-silica sand to assess the prototype's basic movement and slope climbing capabilities at different angles of incline. The MSL will also be filled with large rocks to judge the modality's effectiveness on rugged terrain that more accurately mimics the lunar surface. A drawbar pull test will be used to measure traction in various environments. The test will be run on the flat MSL slope to establish a baseline for the prototype before moving on to room temperature lunar simulant soil in an enclosed container and icy lunar simulant soil in a chest freezer. Performance will be evaluated at low-pressure vacuum chamber at a National Technical Systems lab, and cryochambers at Caveman Cryotherapy. A single leg that is more resilient to vacuum and cryogenic conditions than our prototype will be built to conduct those verifications.

Through these methods, the team can lend credence that the modality performs well in diverse lunar conditions and would significantly benefit future moon missions. A.M.B.E.R has the potential benefit of having a lunar exploration vehicle that is resilient and adaptable to a wide range of harsh and unpredictable conditions on the moon could be the solution necessary to enable exploration of the vast lunar landscape where no human, nor machine, has gone before. Performing tests both quantitative and qualitative in these environments will allow for greater understanding of the prototype's functionality as well as its durability in environmental conditions similar to what will be found at the lunar south pole.

2.0 Progress from Phase 1

2.1 Finalized parts list, requested quotes, located distributors, and received parts

During weeks 1-4, the team compiled a comprehensive parts list based on the Open Dynamics Robot Initiative (ODRI). Due to massive supply shortages as well as our funds being dispersed late (by week 4), we were unable to acquire many of the parts that were critical to the ODRI's function. After exhaustively searching and directly contacting ODRI contributors, we concluded that these key components necessary for the ODRI design could not be acquired, so we adapted the design to use components that were most available at the time. As a result, the most critical tools, materials, supplies, and spares were received by week 8 (with 100+ tools and components received). Ordering has now reached a sustainable pace and will occur as necessary.

2.2 Demonstrated software stack functionality and development of simulated environment and hardware implementation

During weeks 5-6, the programming team configured and demonstrated that the software stack (Docker, Rust, and ROS) was usable for the project. Docker abstracted the build/compilation process and significantly reduced successive setup times for team members. Weeks 7-9 were spent learning and teaching less experienced members about our system and quadruped control, as well as configuring our computing setup.

During weeks 11-12, the programming team was split into two; one group is focusing on physical implementation, and the other is developing a simulation environment using Gazebo-ROS to evaluate and visualize our control systems.

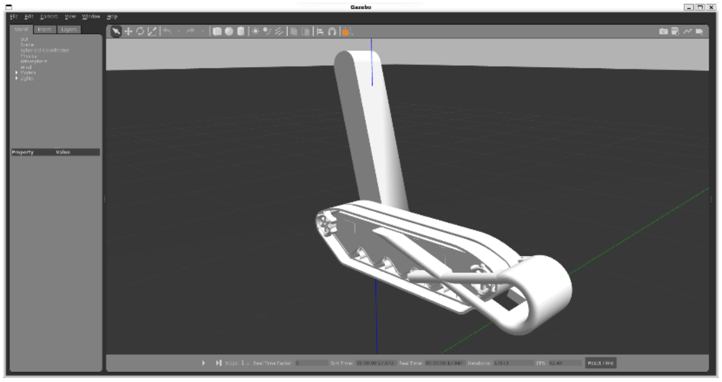


Figure 1: Fixed leg test stand, Figure 2: Leg model in the Gazebo-ROS environment

The physical system team has built a leg test stand as seen in Figure 1 to use for testing multiple degrees of freedom. The team is working towards modifying the leg test stand to allow the leg to move, giving us the ability to test basic walking motions, folding and unfolding, as well as active suspension. Once these functions for one leg are achieved, programming it for all the legs can be done. Additionally, the team built a motor/encoder bench for configuring and testing motor feedback control, shown in Figure 3. The next step is to support daisy-chaining the motor controllers so that all twelve motors can be controlled simultaneously. Once these plans for both teams have been accomplished, the goal is to combine them by daisy chaining all the motors and test the walking and active suspension with the full prototype.

The simulation team has been constructing a model of the rover in the Gazebo-ROS environment. The team is working to create an accurate simulation of the rover to test code for the control systems to evaluate the code's performance on a simulated model before testing on the physical rover. So far, the team has designed and tested the leg of the model, consisting of two arm segments and a joint connecting them (see Figure 2). The model is constructed using the Unified Robot Description Format (URDF) specification, which allows for linking separate objects together for physics simulations with ease. Nevertheless, the team had faced difficulty in positioning different meshes with differing proportions, size, and rotational offset. After completion of the model, the team will move on to testing controlling the model and fine-tuning physical properties, including mass and inertia, to increase the accuracy of the simulation.

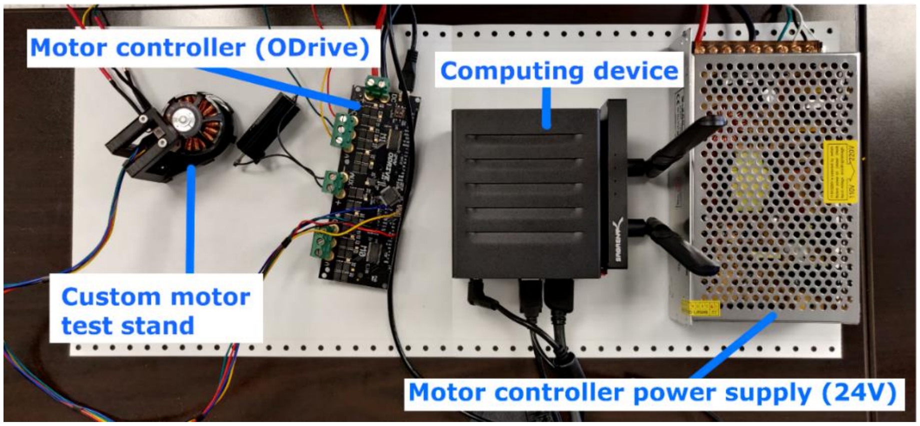


Figure 3: Motor feedback control test setup

2.3 Developed testing procedures alongside start of the MSL construction

The testing team developed a standard operating procedure (SOP) for the drawbar pull test to determine the net thrust the modality's tires produce with respect to different circumstances. Factors such as sinkage, decreased efficiency, and reduced locomotion will be observed. An SOP was created for the load bearing capacity test as well to determine the amount of load the modality will be able to manage. The MSL design has been finalized, the components have been ordered, and it will be built in June.

2.4 Refined project management and systems engineering methodologies

A comprehensive systems engineering plan has been developed following the process described by Space Mission Analysis and Design. During weeks 10-11 the system objectives, function tree, measures of performance and effectiveness, requirements, and risk analysis were advanced. These charts can be viewed in the supplemental material Project Objectives and Function Tree.

The team significantly streamlined the project management methodology by using Kanban and Scrum for managing tasks during phase 1. As our team continues into phase 2, we will finalize our verification matrix and any additional systems engineering material.

Figure 4: Scrum Board Weeks 11-12

2.5 Launched recruitment campaign and expanded team

During week 1, the team distributed applications to the University of Connecticut engineering departments in search of more members. Three team members filtered the responses, interviewed applicants, and invited ten new members during week 3. The team gained additional expertise in programming, electrical engineering, and mechanical engineering.

2.6 Organized outreach opportunities and built connections with NASA, industry, and past teams

The team made an additional industry connection with Peer Robotics, a local robotics company, and contacted authors from the ODRI source. This team is still looking to expand to companies that specialize with quadrupeds specifically.

During weeks 6-8, the team organized the BIG Idea Challenge symposium at the 2022 ASCE Earth and Space Conference in Denver, CO from April 25 - 28. Five members of the team attended and presented our concept alongside a past winner and three other past participating teams from Colorado School of Mines, Michigan Technological University, and Missouri University of Science and Technology. We are now in close contact with previous years' teams in attendance and have already received impactful feedback and mentorship related to management, systems engineering, and the competition.

2.7 Designed and assembled first iteration of chainmail tread

The chainmail sub-team focused on developing a chainmail tread for the lower leg module. Our first iteration of the chainmail design shown in Figures 5 and 6 depicts what the tread will be composed of. Using 3D printed sprockets and fasteners we were able to attach the chainmail in a secure way. Figure 5 emphasizes what the fasteners look like and how they are securely attached to the chainmail using washers and screws. Each fastener is placed at a specific distance apart to catch the sprocket as the tread rotates around during travel. Figure 6 depicts the sprocket design and how the chainmail wraps around the gear.

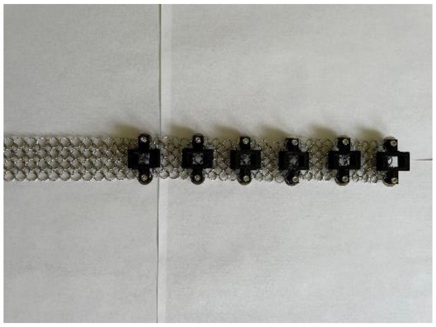


Figure 5 Fasteners and chainmail

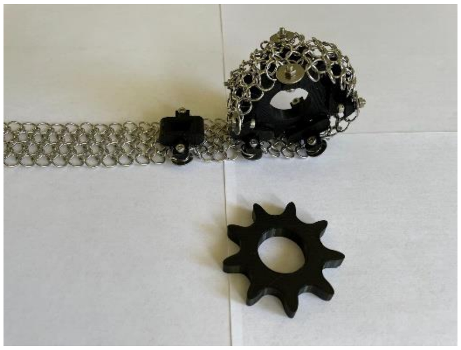


Figure 6 Sprocket and chainmail

2.8 Designed lower leg module

The first prototype of the design is based on the ODRI model. To get a reference for scale and function, the team printed and constructed a majority of the ODRI as seen in Figure 7. The team concluded that the ODRI model has an unusable lower leg module due to its size and capability for our use case. In weeks 9-11, the design team took these constraints and defined parameters such as gear size, tension, and tread length into account to create a design that would be compatible with the current model and is scalable. After various design changes and CAD model iterations, the design sub-team finished a 3D printable iteration of the lower leg module. Figures 8 and 9 show the final design of the lower leg module without the chainmail tread attached. At the start of phase 2, the team plans to build the custom design for the lower leg which will be more rugged and capable of bearing more load than the legs of the ODRI model. The team is also iterating through chainmail designs, such as one that is comprised of lightweight links, but instead of a hinge, uses chainmail as the connection for the links. This has a higher potential for ease of manufacturing and reduced risk of the sprocket coming loose since the mounting point will not be as insecurely mounted with a screw and a washer. Once the chainmail is finalized, it will be integrated with the lower leg design mentioned above and evaluated in the MSL.

Figure 7 ODRI made by team

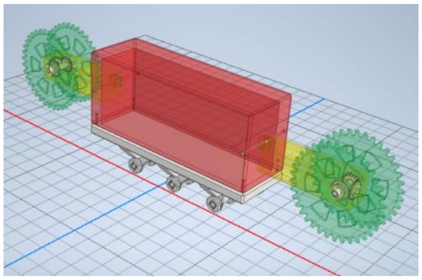


Figure 8 Lower leg design – orthographic view

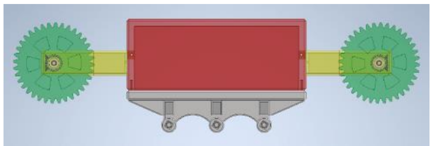


Figure 9 Lower leg design – side view

Additionally, electrical motors were selected based on the required tractive effort for the lunar and the starting torque required for lifting load. A trade-off relation between torque and angular velocity was considered in the motor selection and was monitored for the normal motion to be compared with modality's simulation and minimize the relative differences.

2.9 Designed inner gear transmission for lower leg module

To ensure the functionality of the tread motion it is imperative that the motor in the lower legs remains protected and the axis of rotation of the sprockets remains perpendicular to the motion of the modality. The design sub-team addresses this by placing the motor in a protective casing in the center of the lower leg and transferring its rotational motion to a perpendicular axis through the transmission near the sprockets (as seen in Figure 11).

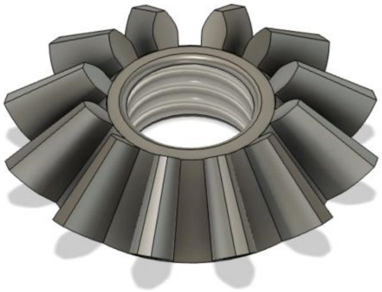


Figure 10 CAD Bevel Gear design

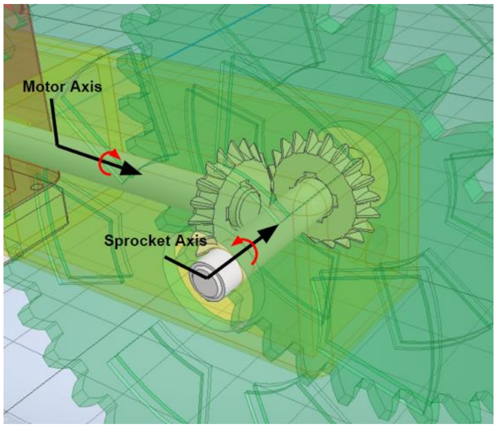


Figure 11 CAD Transmission in appendage

2.10 Learning and modifications

As the project progressed from an idea to tangible work, there were several aspects that ended up being changed. The original plan consisted of a modality that morphed from a tank to leg using computer vision. The use of computer vision and AI will not be pursued due to time constraints and since the project focused more so on the modality rather than the mode of changing it. The team chose to focus on the aspects of the project that were more closely related to the end goal.

For testing the rover and modality, one aspect that was initially planned but not executed was the use of the OptiTrack system. This was abandoned because of the opportunity to test our rover at Glenn Research Center, where there is an OptiTrack system. Also, testing on a shake table will not take place due to time and it is not a focus of the prompt.

The ODRI open-source design components were not used as much as expected early on. Electronic component changes and module design changes resulted in recreation of various parts that make up the modality. The design change was a result of supply chain issues, parameter changes that were necessary for modality success, and compatibility with already existing components.

2.11 Work remaining

The work remaining is to complete the build of a prototype while designing the components to ensure it is most effective as well as to program it to move as the morphing modality. Testing of the capabilities will be done as described in the Verification Matrix and as seen in the Timeline in Section 4.0.

2.12 Schedule risks and mitigation plans

During the COVID-19 pandemic, supply chain issues have been noticed globally. Where some essential items for the project may have taken a week to arrive, the estimated delivery times have now been pushed to several months. Mitigating a global supply change shortage is accomplished by organizing a timeline and list of what parts are needed, when they have needed them, and how long it will take for them to arrive. A list started being compiled prior to phase 1 and continues to be updated.

The successful programming of a quadruped is a complicated task. There is a great amount of knowledge to be gained to do this. The team is using online resources as well as industry personnel resources to continue and complete this portion of the project.

The team intends to do testing at Glenn Research Center from August 22-25. This depends on having a fully functioning prototype by this time. There are five team members working on this project during the summer to ensure this happens. This also depends on the availability of the facility. If VIPER or other projects require testing during this time, the team will need to select other dates.

2.13 Ability assessment

This team is confident about completing this project as proposed due to the skills and cooperation present among the team. The team is organized into specific departments based on the skillset of each individual: programming, mechanics, and testing. Programming members have coding experience and background knowledge to pursue development of the morphing functions of the modality. Mechanic members have experience with building hardware and electronics and are working to determine the best, innovative options. Testing members have knowledge and experience about what tests must be performed to determine the capabilities of the modality. Collaboration among different departments is done by virtue of weekly team meetings and communication on Discord and Microsoft Teams. Along with skill and collaboration, the team is volunteering their time by doing this project and are very enthusiastic in wanting to make it a success.

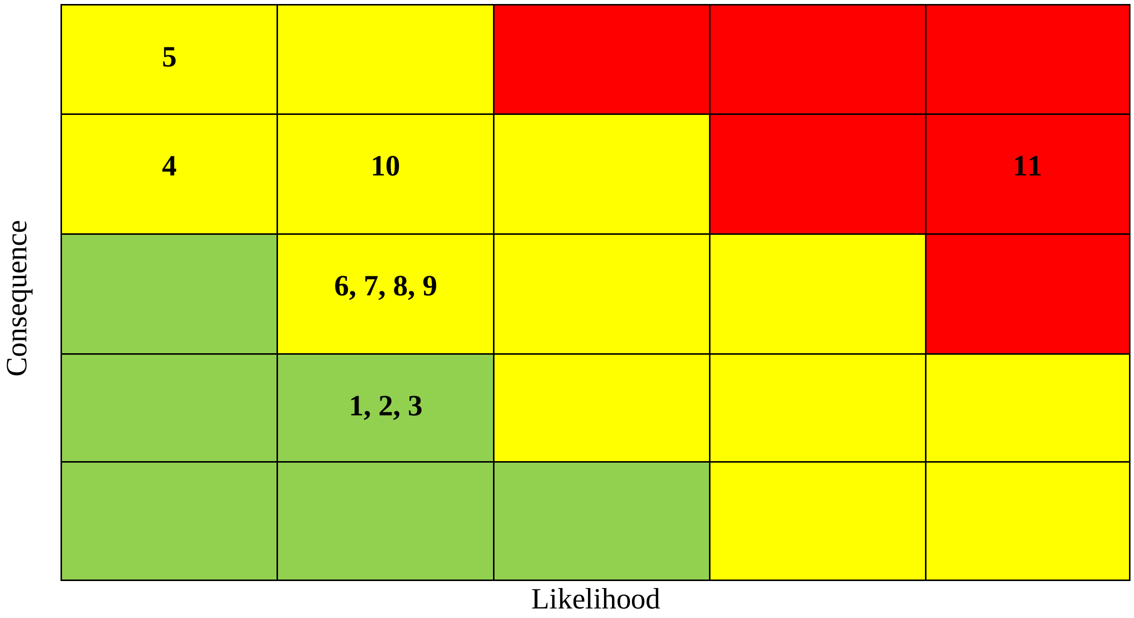
We have set ourselves up for success in phase 2 by purchasing and receiving necessary components and equipment, defined clear deliverables, and determined methods to assess those deliverables. A timeline has been created and followed throughout Phase 1 and through Phase 2. Further, a list of all objectives of the project are taken note of and all requirements that remain to be done and a brief explanation of how it will be conducted in the supplemental documentation Verification Matrix.

2.14 Safety plan

This team primarily works in a lab space where there is little to no possibility of bodily harm due to the environment. Safety precautions are taken as needed. When using power tools, building test environments from wood, or working with moving components, team members wear protective eye equipment. When handling LHS-1 simulant soil, members will wear lab coats and respirators. The soil itself will be in an enclosed container and in a large fume hood to further mitigate the risk of exposure. Besides this, the team practices situational awareness when working to always understand what is happening around them. Also, due to covid-19, all team members wear masks when indoors.

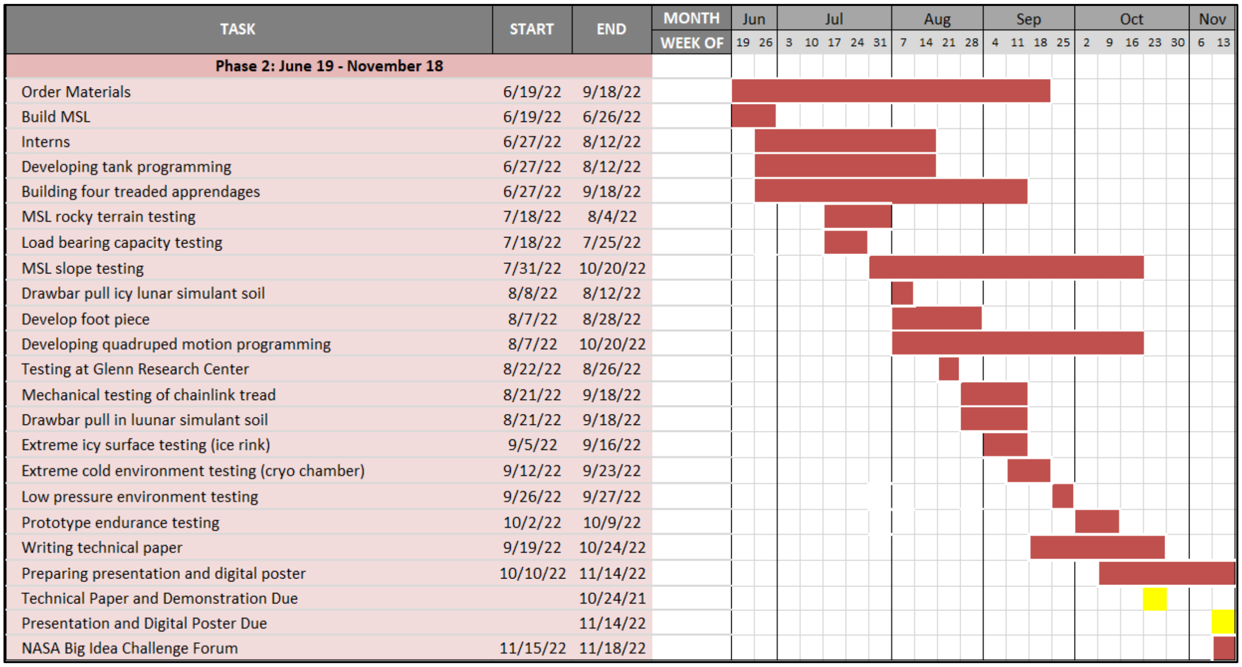
3.0 Risk Matrix

Risk	Mitigation	Likelihood	Consequence	Score	Rank
Covid - 19	Wear masks and social distance	2	2	4	1
Accident on flat icy surface	Situational awareness	2	2	4	2
Maintaining compactness of leg	Resize motors/gears	2	2	4	3
Exposure to carcinogenic lunar simulant soil	Wear respirators when handling	1	4	4	4
Electronics/ circuitry failure	Continued attention to electrical design	1	5	5	5
Machined parts delayed	Order parts ASAP, Finalize dimensions	2	3	6	6
Internal gears/motors cannot manage load	Improve design / material	2	3	6	7
Equipment breaking	Inspect all equipment before and after use	2	3	6	8
Break prototype	Situational awareness	2	3	6	9
Chainmail tread does not rotate properly	Fine tuning, Alternative tread design	2	4	8	10
Shipping delays	Check lead times for purchase and order early	5	4	20	11



5				
4	**10**			**11**
	6, 7, 8, 9			
	1, 2, 3			

4.0 Updated Schedule/Timeline of Tasks and Deliverables



TASK	START	END
Phase 2: June 19 - November 18		
Order Materials	6/19/22	9/18/22
Build MSL	6/19/22	6/26/22
Interns	6/27/22	8/12/22
Developing tank programming	6/27/22	8/12/22
Building four treaded apprendages	6/27/22	9/18/22
MSL rocky terrain testing	7/18/22	8/4/22
Load bearing capacity testing	7/18/22	7/25/22
MSL slope testing	7/31/22	10/20/22
Drawbar pull icy lunar simulant soil	8/8/22	8/12/22
Develop foot piece	8/7/22	8/28/22
Developing quadruped motion programming	8/7/22	10/20/22
Testing at Glenn Research Center	8/22/22	8/26/22
Mechanical testing of chainlink tread	8/21/22	9/18/22
Drawbar pull in luunar simulant soil	8/21/22	9/18/22
Extreme icy surface testing (ice rink)	9/5/22	9/16/22
Extreme cold environment testing (cryo chamber)	9/12/22	9/23/22
Low pressure environment testing	9/26/22	9/27/22
Prototype endurance testing	10/2/22	10/9/22
Writing technical paper	9/19/22	10/24/22
Preparing presentation and digital poster	10/10/22	11/14/22
Technical Paper and Demonstration Due		10/24/21
Presentation and Digital Poster Due		11/14/22
NASA Big Idea Challenge Forum	11/15/22	11/18/22

5.0 Cost Incurred To-Date

The expenses made to date can be found in the table below. The account with which the funds were deposited did not become active until late April. Funds were used from other areas of the University to not postpone the team purchasing necessary items. Now the team's account is active, reimbursement is being made to those accounts which were used prior. Due to the length of time with which this take, the exact amount spent on shipping is not known to the team. These expenses are for the materials only.

An OptiTrack system was not purchased, and instead a PCB printer was due to the team's decision on what was more greatly needed. Other funds not spent will be directed towards the expenses associated with the custom parts, which the team has only began to have made from non – 3d printable material. Finally, only one leg will be made vacuum grade, which opens more funds due to the lessened need of vacuum grade motors. This will be used to fund two more interns to work on the project during phase 2.

Item	Total
MSL	
Wood	$677.68
Small Supplies	$170.95
Safe Sand	$1,343.25
Prototype	
Tools	$1,376.61
Tread	$112.67
Motors	$1,082.23
Raw Material and Manufacturing	$535.20
Power Supplies and Batteries	$322.13
Wires	$69.77
Mechanical Components, Fasteners, and Connectors	$365.18
Computing, Sensing, and Motor Controls	$7,347.82
Other	
Simulant soil	$3,675
Drawbar pull Equipment	$130.27
Space Mission Engineering: The New SMAD	$259.94
Voltera PCB Printer	$4,099.98
Team Shirts	$700
UConn Indirect Costs	$5,636.30
TOTAL	**$27,904.98**