

TEAM 6 – MOON TO MARS EXPLORATION SYSTEMS AND HABITATION

SENIOR DESIGN OPERATIONAL READINESS REPORT

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LIST OF ABBREVIATIONS

X-HAB	Moon to Mars eXploration Systems and Habitation
NASA	National Aeronautics and Space Administration
MMU	Manned Maneuver Unit
ISS	International Space Station
CEVIS	Cycle Ergometer with Vibration Isolation and Stabilization System
IREDD	Interim Resistive Exercise Device
AREDD	Advanced Resistive Exercise Device
FDM	Fused Deposition Modeling
DLP	Digital Light Projection
SLS	Selective Laser Sintering
PLA	Polylactic Acid
PETG	Polyethylene Terephthalate Glycol
TPU	Thermoplastic Polyurethane
CAD	Computed Aided Design
PDR	Preliminary Design Review
CDR	Critical Design Review
LED	Light Emitting Device
FEA	Finite Element Analysis
RTC	Real-Time Clock
BLE	Bluetooth Low Energy
LCD	Liquid Crystal Display

INTRODUCTION

Life on extraterrestrial planets like the Earth's Moon and Mars have unique qualities that most humans are not used to. Lower gravity has negative effects on humans' biological systems. NASA studies show that "without Earth's gravity affecting the human body, weight-bearing bones lose on average 1% to 1.5% of mineral density per month during spaceflight" [1]. Additionally, lessened gravity affects the human heart and circulatory system. NASA comments, "the loss of blood volume, combined with atrophy of the heart and blood vessels that can occur in space, reduces the ability to regulate a drop in blood pressure that happens while standing on Earth" [2]. Blood flow plays a key role in muscle growth. Essentially, humans lose muscle mass and bone density in a lower gravity environment.

To counteract the reduction of bone density and muscle mass in a lower gravity environment, astronauts must endure resistance training, cardiovascular and bone strengthening exercises. Although these precautions do help to mitigate the loss of muscle and bone density and aid adequate cardiovascular health, astronauts continue to face issues upon returning to Earth. Some of these issues include difficulty walking or standing, lightheadedness, fainting, balance, coordination, and visual impairments like blurred vision.

However, lower gravity changes the paradigm of mobility, especially in a habitat. Habitational systems are put on the Moon and Mars which include life support, environmental control, radiation protection, exercise and health maintenance, and other factors needed to keep the crew safe, healthy, and productive on long deep space missions. Instead of walking or using a staircase to increase elevation; astronauts can move in different ways such as climbing, swinging, pole transportation, jumping, and other modes around the habitat. These mobility modes allow for a more natural way to diminish the loss of muscle and bone density and maintain cardiovascular health.

The objective of this project is to design elements in a habitat on the Earth's Moon or Mars that consist of these mobility modes for a crew to use while navigating their daily routines within the habitat. This can be used to reduce the loss of muscle and bone density, maintain cardiovascular health, allow for a quicker way to traverse about the habitat, and introduce fun activities into everyday routines.

DESIGN SPECIFICATIONS

The team will come up with a solution that creates novel ways of mobility around the habitat. NASA has stated that habitat designs for Lunar and Martian favor structures with small footprint and use of elevation for living, work, and activity spaces. The provided pictures of the habitats given in the solicitation are shown below in Figures 2-1 and 2-2:

Figure 2-1: Kahn Yates- Phase 3: Level 1 of NASA's 3D-Printed Habitat Challenge [3]

Figure 2-2: MARSHA - Vertical Martian Future [4]

These visuals provide the team knowledge in which, instead of focusing on horizontal movement, the team needs to focus on vertical movement. The team is now having to consider vertical forces and design elements in the habitat that will fit vertically to accommodate the new mobility modalities.

Aspects of Lower Gravity

The weight of a person on the Moon is 16.5% and on Mars 34% of his/her weight on Earth. Lower gravity allows for more weight included in the space suits because the equivalent weight is significantly lower. Two famously known suits were used in the Apollo missions: the Apollo suit and the Shuttle suit. The Apollo suit was designed specifically for low gravity of the Moon, prioritizing lightweight mobility, while the Shuttle suit was designed for zero gravity and focused on longer duration missions. In the Apollo missions, the average weight of the astronaut was 175 pounds; while the Apollo suit weighed approximately 180 pounds, and the shuttle suit weighed approximately 310 pounds [5]. Table 2-1 shows the equivalent weights of the astronaut in each suit on the Moon and Mars:

Table 2-1: Weights Converted to Planetary Gravity

Suit	Apollo	Shuttle
Earth	355 pounds	485 pounds
Moon	58.575 pounds	80.025 pounds
Mars	113.90 pounds	164.90 pounds

Taking these new weights from Table 2-1 into account, the factor of safety can be used to determine the amount of weight that could be supported. As the design specifications have yet to be fully stated from NASA, having a factor of safety is important to reach the most effective and safest method of achieving the end goal. The factors of safety will differ between the Moon and Mars. Therefore, the material used should be focused on the more considerable gravity value and weight on Mars so that the factor of safety is well beyond the threshold for the lower levels of gravity on the Moon. Tables 2-2 and 2-3 show the supported weight with various factors of safety values in both suits.

Table 2-2: Supported Weight Value for Factor of Safety (Apollo Suit)

Factor of Safety	2	2.5	3
Moon	117.15 pounds	146.44 pounds	175.73 pounds
Mars	227.80 pounds	284.75 pounds	341.70 pounds

Table 2-3: Supported Weight Value for Factor of Safety (Shuttle Suit)

Factor of Safety	2	2.5	3
Moon	160.05 pounds	200.06 pounds	240.08 pounds
Mars	329.80 pounds	412.25 pounds	494.70 pounds

As seen in the factors of safety from Table 2-2 and 2-3, the lighter iterations of the suit lead to a significantly lower value of support weight needed to achieve certain factors of safety.

If the design was directed toward the weights determined through the analysis of the Apollo Suit, then the factor of safety would be well above what is needed. While in this analysis the suits included the weight of the life support systems, the habitat will have these built in.

Health

The crew's health is a vital part of any mission's success. However, due to differences in gravity, the human body reacts differently and essentially deteriorates over time. Based upon research conducted by the Baylor College of Medicine, space negatively impacts the skeletal, muscular, and cardiovascular systems [6]. All the research done for these three systems leads to the same conclusion: they all deteriorate due to the lack of work done in a lower gravity environment. After some long stints in space, many astronauts, upon their return to Earth, have

significant trouble when trying to exit the spacecraft and walk.

There is already equipment and a workout regimen for astronauts in space to counteract these effects. The current equipment available is an Advanced Resistive Exercise Device (a resistance band weightlifting apparatus), a treadmill (T2), and the Cycle Ergometer with Vibration Isolation and Stabilization System (a wheelless bike). Based on previous astronauts' experiences using this equipment, the best results come from high-load, low-volume workouts.

To increase the effectiveness of staving off these effects, a device that increases mobility and increases the natural levels of work done by the user would be beneficial. While this seems partially counter-intuitive for a device on Earth, because of the lower levels of gravity, there are ways in which increased mobility also increases the fitness levels of the user. To achieve this, the device must either contain a mechanical device, suit modification to counteract the gravitational effects, or entirely focus on the increased mobility and pair this with an updated workout regimen.

Entertainment

The objective is to create a fun way to traverse the habitat while providing the crew with entertainment and exercise as they move throughout the day. The set of bullet points below restate all the constraints needed to be considered:

- Vertical habitat structures
- Focus on vertical movement, vertical forces
- Aspects of lower gravity
- Increase crew's health with mobility during long space explorations in lower gravity environments
- Incorporate an entertaining/fun mobility solution

BACKGROUND

Assumptions

To properly set up the problem, some assumptions were made:

- Gravity on the Moon and Mars are about 16.5% and 34% of Earth's gravity
- Habitats will be designed vertically to take advantage of low gravity environments
- No spacesuits will be needed inside habitats
- Physical fitness requirements for an Astronaut are based off the 95th percentile male
- Specialized materials may be useful
- Materials may be manufactured in the habitat (3D printing, biomaterials, etc.)

Analysis

Manufacturing of PDMS or other 3D printable, microfluid, or biomaterials may have the capability to be manufactured using equipment and materials brought into space and installed in the habitat. Materials like PDMS, GeckSkin, and Hoowaki micro-surfaces will be explored to be used in friction-based solutions to horizontal and vertical movement inside the habitats. These will be explained in further detail in the later portion of the background.

Functional Decomposition

The main functions the team is focusing on is the direction of movement the solution will experience, the solution being compatible within the canvas habitat, and incorporates exercise for the crew. Stated above, the goal is to design an innovative solution that takes advantage of the lower gravity and will be compatible with the habitat and the crew. Meaning that the final solution will make moving around the habitat easier, not harder. The solution will be compatible within the habitat, not destructing any elements within and favors elevation. Lastly, the solution will incorporate exercise when moving around the habitat, this will retain bone density and bone mass.

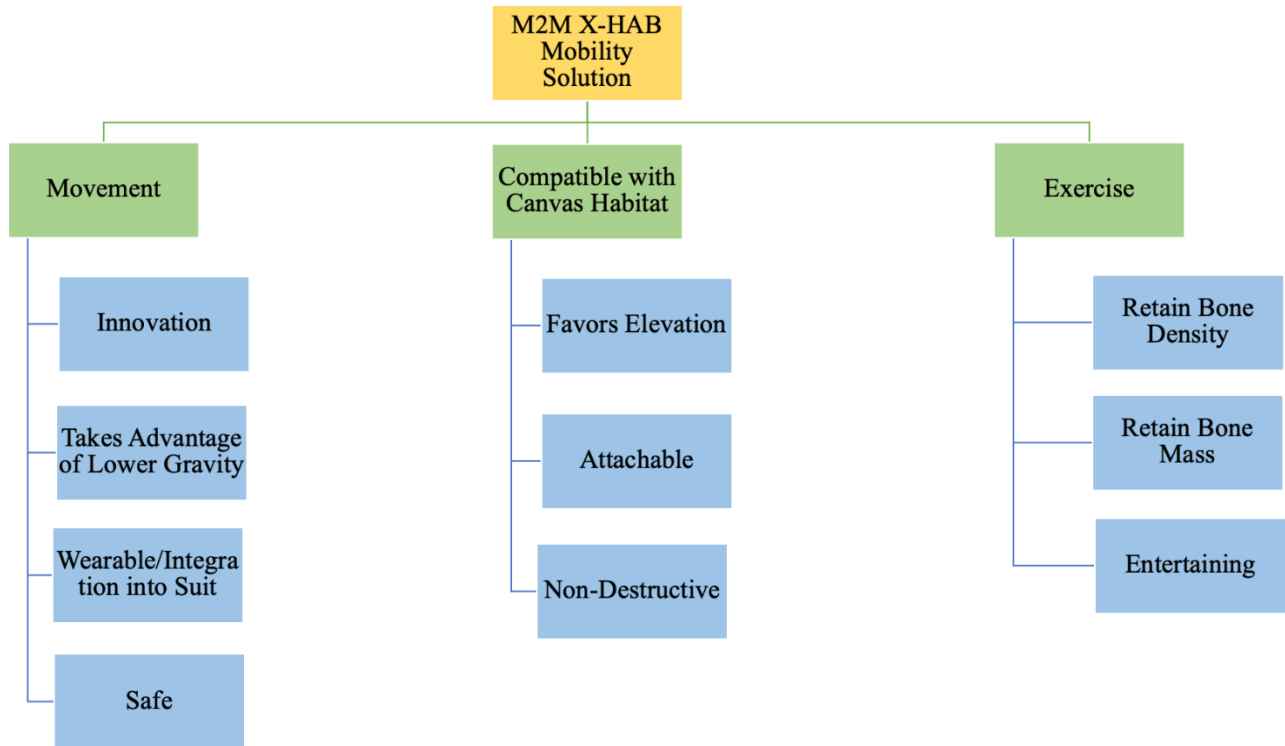


Figure 3-1: Functional Decomposition

Previous Solutions

Based on some preliminary research, there has not been much effort dedicated to finding potential solutions for a mobility element within the habitats. Astronauts move in the ISS by simply grabbing on to equipment or walls to propel themselves forward. The only thing that allowed crew members to move in space is the Manned Maneuver Unit (MMU), but this is a suit used to maneuver outside of a space station to repair satellites. The MMU used gaseous nitrogen to propel forward and could potentially pose some dangerous threats while inside the ISS.

Mars/Moon Gravity Field/Health Metrics

Adjusting to the change of gravitational fields from the Earth to the Moon and Mars can have a major effect on the human body. Affects can contain spatial orientation, space motion sickness, hand/head eye coordination, and balance. Throughout many missions to space, NASA

has observed the loss of mineral density of the astronauts' bones by 1% to 1.5% per month of spaceflight. Due to the microgravity of space, the fluids in the body tend to shift upwards towards the head causing pressure to build up that could negatively impact their vision. These health threats are closely monitored every day. Solutions such as compression cuffs are worn on the legs to keep the blood in the lower extremities, MRI scans help monitor muscle density loss, and crew members perform periodic fitness self-evaluations. New solutions were in the works by NASA for bone density loss, such as a bisphosphonate medication. In addition, potassium citrate is one of the few medicines being researched and tested to help combat psychological effects but does have side effects that could put crew members in danger. Back pain was recorded by some astronauts during spaceflight, monitored by spinal cord ultrasounds. Another way health is monitored closely is through crew members producing urine, which is significant because urine gives key details into a person's health. This allows researchers to calculate the risk that a crew member could be at risk for nephrolithiasis (kidney stones) by analyzing the different levels of substances, making changes to their diet, or providing them with a different exercise regimen. Nephrolithiasis is a major concern due to microgravity causing bone loss and dehydration to crew members [8].

Physical Fitness in Space

Exercise is one of the main ways that NASA combats the problem of muscle/bone density loss. As space exploration continued to advance, so did the exercise technology with it. Scientists and engineers first created the Cycle Ergometer with Vibration Isolation and Stabilization System (CEVIS) which is a stationary bike that uses friction controlled by a computer to create the proper resistance while pedaling. This computer also monitors the heart rate, cycling speed, time elapsed, and exercise program. Figure 3-2 below is a picture of an astronaut using the CEVIS.



Figure 3-2: Crew Member Using CEVIS

During the same time as the CEVIS there was a stationary treadmill called T2 that NASA developed to allow crew members to run distances required of them. After extensive research into the problem of muscle loss, NASA realized in 1996 that the use of stationary treadmills and bikes were not going to be sufficient to prevent or solve the issue at hand. NASA knew they needed to come up with an innovative idea to apply resistance workout programs. This project was required to be completed before the first crew was sent to the International Space Station (ISS) for long term space exploration. NASA Johnson Space Center's Life Sciences and engineering teams created the Interim Resistive Exercise Device (IRED). The IRED is a very complex mechanism that configures 18 different ways to use your lower and upper body in a workout with up to 300 pounds of resistivity. Once connected to a pulley, it allowed the crew members to load up for squats which put loads on to the major parts of the bodies that loss muscle due to the microgravity. The

IRED was the first of its kind and installed into the ISS in 2000s and was used all the way up to 2009 when there was a more innovative and improved mechanism. In Figure 3-3 below, the astronaut is using the IRED to do a resistive deadlift. To do a squat or other exercises, there is an attachment of shoulder pads that the crew members put on and attach to the resistivity load [9].



Figure 3-3: IRED Resistive Deadlift

After years of furthering the research into the project, a new and improved mechanical machine was created called the Advanced Resistive Exercise Device (ARED). This device was tested and made after the IRED was sent to the ISS and was officially installed in 2009 to be part of the ISS. The ARED had the same concept as the IRED with a couple differences.

Although the ARED continues to use the idea of resistive weight training, the resistive force is generated by two vacuum cylinders. On one side of the cylinder is a vacuum and the other is

atmospheric air, so when the piston pulls it creates a bunch of pressure and force. By adjusting a crank on the machine, it adjusts the lever arms to change the amount of resistance that is being applied. Figure 3-4 below shows the main components that provide resistance and stability [10].

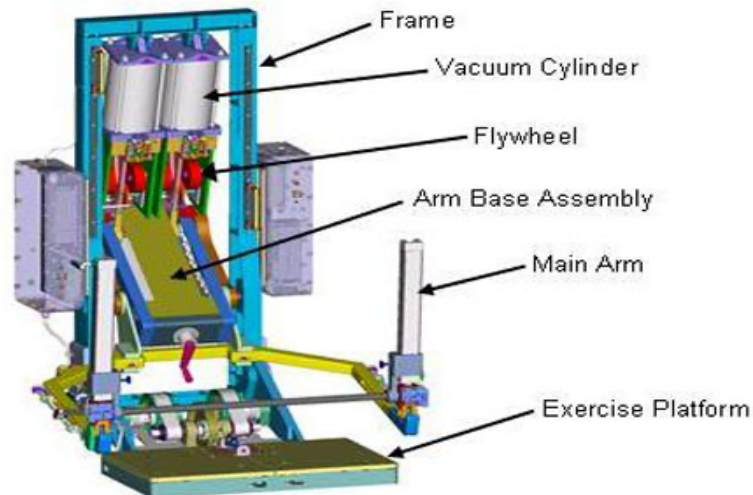


Figure 3-4: Main Components of ARED

Another important aspect of the machine is the flywheel that creates enough inertial force that it simulates lifting free-weights in a 1-G environment like Earth. The ARED is also connected to a computer that helps monitor the crew members heart rate during the workout, time elapsed, and the number of reps/sets that the astronauts have left in their program. These are just some of the improvements from the IRED to the ARED. The ARED has a higher capability to do different exercises, up to 30, at a resistance weight of up to 600 pounds which is double that of the IRED. The platform as seen in the figure above, rotates about a pivoting point along with the silver bar in which as the crew member lifts on the silver bar the platform rotates down. This allows the crew members to not need a harness due to the weightlessness as compared to the IRED having attachments for certain exercises. Through NASA's studies, they did a comparison between the ARED and IRED as shown in Table 3-1 below [11].

Table 3-1: Comparison Chart from NASA Study

	ARED	IRED
Maximum Bar Exercise Load	272 kgf (600 lbf)	136 kgf (300 lbf)
Maximum Bar Exercise Stroke	76.2 cm (30 in)	127 cm (50 in) at low loads 56 cm (22 in) at high load
Maximum Cable Exercise Load	68 kgf (150 lbf)	68 kgf (150 lbf)
Maximum Cable Exercise Stroke	183 cm (72 in)	127 cm (50 in) at low loads 56 cm (22 in) at high load
1-g Free-Weight Inertial Component	Yes	No
Force Profile	Nearly constant throughout stroke	Linearly increasing during stroke

The duration of this equipment was tested here on Earth for high intensity short work outs versus low intensity long workouts and the results show that it would last about 15 years at a time before the stresses on the different aspects would cause a safety concern. This proved to last a longer time than the IRED meaning longer space flights could be achieved for Moon and Mars exploration. Figure 3-5 gives a simple diagram and visual for the movement of the ARED during a squatting motion.

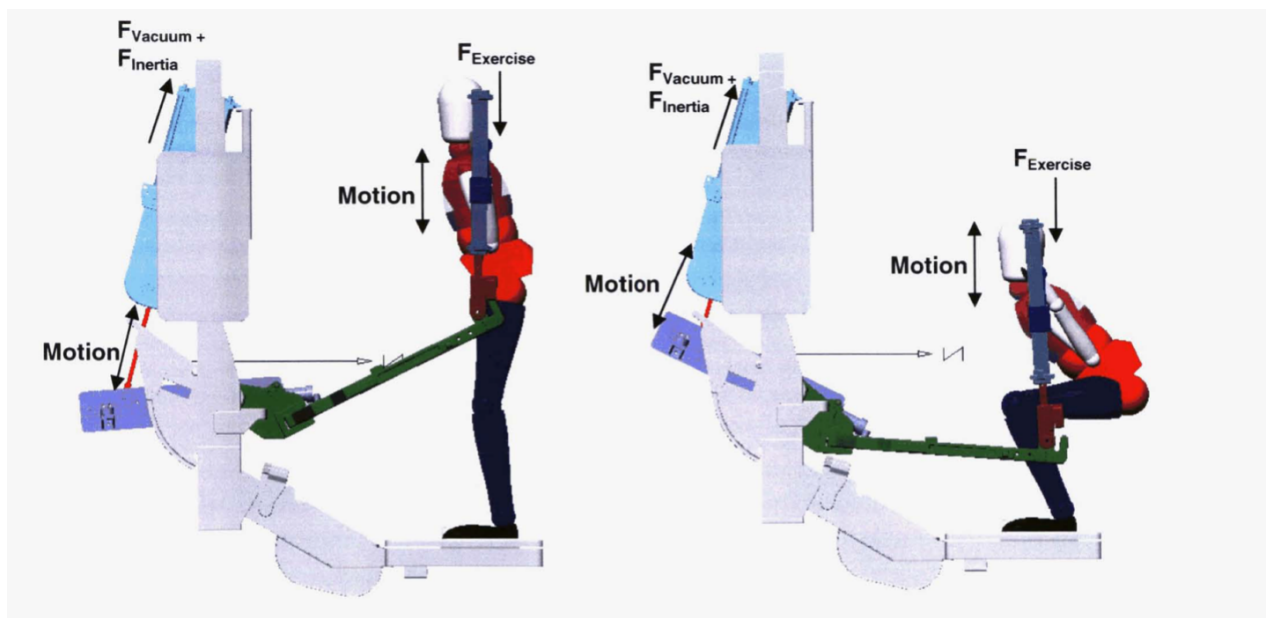


Figure 3-5: ARED Squatting Motion

These crew members workout 2-3 hours a day in space to try and counteract the problem

at hand. This is why it is important that the team creates a more efficient way to move in the habitat while also creating an environment where it's a workout, so the astronauts can do more and experience more enjoyment in these long space flights.

X-Hab Project

With NASA taking the lead in the project to go further into the solar system and do more intensive research, it has been their mission and vision to one day send a crew to Mars. The age of space exploration is here, and now even commercial space exploration is emerging [12]. The idea of sending tourists up to space is gaining traction. With all these ideas behind space exploration, NASA has this concept of creating habitats to live for a long period of time or even permanently on the Moon and Mars. NASA's vision is to even one day in the future build cities on the Moon and Mars using the microgravity fields to their advantage going higher and higher. This idea sparked an innovative challenge and competition that NASA held in 2015 called the 3- D Printed Habitat Challenge. This challenge was composed of multiple teams that went through multiple phases of design with the goal for three teams to be chosen to move onto phase 3. This phase was the final phase where they had to build the habitat virtually using a 3-D modeling software. As shown in Figures 2-1 and 2-2, the winning team's habitat design ideas are being incorporated into the current planning process.

These designs were chosen to get pushed through to phase 3 level 4 where they will be 3D printed and tested under extreme heats and stresses that can occur with space travel. This project is not just a theoretical problem but is being propelled forward by the young minds of today. With NASA's vision of space exploration for the future, this is just a start into the innovative challenges that are to come.

Previous X-Hab Habitat Design – University of Maryland

The university of Maryland also participated in the X-Hab challenge in 2022 and published their layout of what a deployable habitat would look like once all the infrastructure is installed [13]. A CAD drawing of this habitat can be seen in Figure 3-8.

Figure 3-8: Previous Hab Design

The report theorized that the core of the Hab would need to be the most essential parts like the life support equipment, water reclamation and crew quarters. A diagram of this can be seen in Figure 3-9.

Figure 3-9: Hab Core Design

This information and thought process is important to consider during the design process. Many of the assumptions and literature that was used can be very useful or even incorporated directly into the design.

Materials Background

One company that the team found was Hoowaki – a manufacturer of patented textured high friction micro-surfaces [14]. Instead of these surfaces having specific material properties, they are manufactured mechanical solutions to friction. The “micro-surfaces” are manufactured by press fitting steel sheets to have a pattern of microscopic half cylinder like structures on the surface that are surprisingly effective at increasing friction. These surfaces are great at gripping on to materials that usually are very difficult to adhere to like plastics, fabrics and even skin. Since they are manufactured textures and not adhesives, these surfaces are far less destructive to the materials that they attach to. The downside is that the strength of these surfaces may not be high enough for the loads incurred, and since they are proprietary, they would be difficult to acquire and test, and also expensive.

More solutions are Gecko-like adhesives and materials [15]. There are two types, adhesives, and Van der Waals. Adhesives are more widely available; however, they are not suitable for this type of application. Van der Waals forces are what Geckos use in real life in order to hang off of the side of surfaces and climb vertical and near vertical angles. Products like GeckSkin utilize these same forces, which are one directional scales called spatulae that utilize Van der Waals forces between the surface and spatulae molecules. These products show some promising developments; however, they are only effective on very smooth flat surfaces like glass, and they are not necessarily strong enough to support the weight necessary for this application. Weak shearing forces are all that are required to break the Van der Waals forces bond, so this makes them difficult

to use effectively. Also, since they are one directional, any shear in another direction is enough to decrease the strength and detach.

Another method the team found was magnetorheological elastomers, or a flexible injectable molded synthetic silicone composite polymer. A common one is PDMS, which is very common and used in lots of research and products due to it being cheap and easy to manufacture. There are many types of these materials that can be made by anything from molding to 3D printing. In this application, these molds can be injected with magnetic microparticles, and when a current is induced into the material, it can change shape [16, 17]. This shape can be controlled enough to make specific shapes. One benefit is that these materials can be manufactured and repaired using equipment that could be sent up with the astronauts and installed in the habitat. Some of these materials are cheap to make but suffer from that aspect as they are not long lasting in nature [18].

SYSTEM DESIGN REVIEW

Design Concepts

Launching Mechanism

When thinking of modes to possibly increase mobility most modern minds tend to make jokes about the use of a grappling gun like Batman or shooting webs like Spiderman. On Earth, these sound farfetched because of gravitational forces. This project is designed for other planets where gravity is much less than that of Earth. Since the gravity on these other planets is so low, the components of the grappling hook concept (the chord, winch, contact force, launching speed, etc.) do not need to be as robust because the forces within them will not be as strong. The designs of the potential habitats on the Moon and Mars all share one common theme, the habitat would focus on vertical development. Taking advantage of this vertical development, a grappling hook style design is beneficial. It could essentially act as a personal elevator allowing for efficient vertical movement within habitat. The user will also have the option of using this concept to swing around the habitat for horizontal movement.

As the astronaut uses this concept, they will engage multiple muscle groups. They will need to use their arms to raise the launcher and control the recoil from it, their legs to carry the equipment around with them, and their core for stabilization while in flight. This muscle engagement, paired with their scheduled exercise, will help maintain their bone density and muscle mass while away from Earth. Additionally, this new method of transportation would provide the astronauts with a new form of entertainment.

For this new form of movement, the habitat will need to have elements within it that make it more convenient and streamlined. Targets will be used for the astronauts to aim and launch at. These targets will be strategically placed around the habitat to maximize efficiency when using this mechanism to move around the habitat. These targets will also be made from materials that

will increase the contact force between them and the projectile, while also being replaceable. Some examples of this could be the use of a magnetic projectile and steel targets or the use of an adhesive projectile and a high friction target. Additionally, the use of targets helps with mitigating damage to other parts of the structure and injury. Along with targets, there will be sensors to assess the performance and health of the users. The targets will be able to track the user's accuracy and consistency, and the users will be wearing health and fitness tracker accessories daily to maintain their fitness levels.

For this concept, there are multiple possible designs. One design could be a fully arm mounted launcher that houses the spool of line, the projectile, the winch, batteries, and launching mechanism. For this design, the user will aim their arm at the target inside the habitat, activate the launching mechanism to launch the projectile towards the target, and then turn the winch on to start taking up line to pull themselves upwards once the projectile has made solid contact with the target. Another potential design could be a harness with the spool, winch, batteries, and holster mounted to it with a muzzle-loaded, handheld launching device. This design works the same way, but instead of aiming their arm at the target, the user will aim the handheld launcher at the target. The battery pack powers the winch in both designs. For this project, the team has chosen to go for the first type of design and models of the launcher and projectile can be seen in Figures 4-1 and 4-2, respectively.

Figure 4-1: Launcher Model [19]

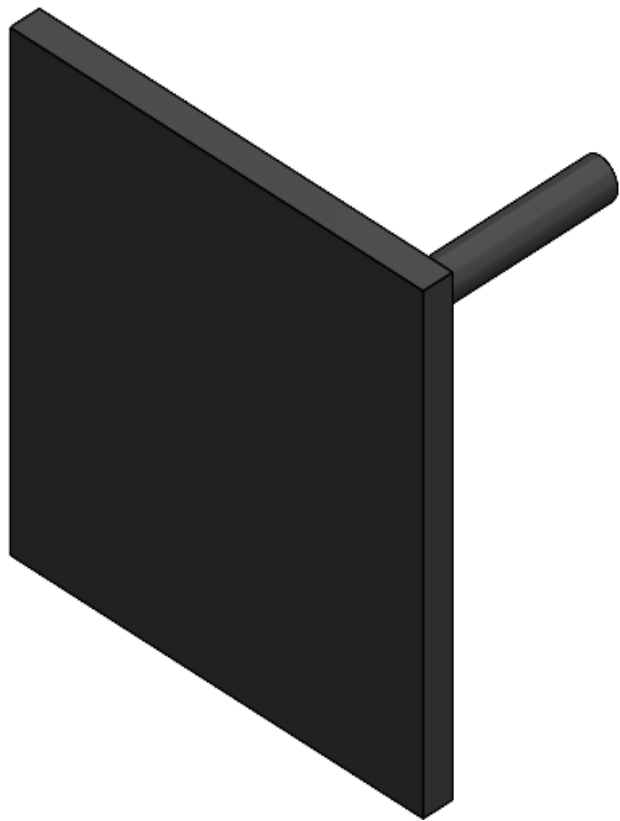


Figure 4-2: Projectile Model

When looking at the functional decomposition of the problem in the background section of this report, this concept satisfies all the lowest level functions. This means that it is a viable solution to the problem at hand. To compare this concept to the others, a decision matrix was formed. The performance of each design is compared based on the total weighted score they received. This decision matrix and comparison can be found in the next section of the report.

Electromagnetic Grips

The electromagnetic hands are a relatively simple way to traverse vertically and possibly horizontal throughout the habitat. A model of this design concept can be seen in Figure 4-3. The advantages of this design are that it is relatively lightweight and simple to build. This device will also help astronauts to stay fit on Mars and the Moon since they will have to pull themselves up a wall using the magnets. Some downsides are that the interior of the habitat will need to be made of a magnetic surface so that the magnets will attach. This can easily increase weight to of launch shuttles, lowering feasibility. Another downside is power consumption. There would need to be large batteries to use this device properly which can increase weight and will require charging.



Figure 4-3: Electromagnetic Grips

This design was broken into each component to determine feasibility. These components consist of the magnet, grips, wiring, and battery. For the magnet, it would need to be relatively small, lightweight, and able to hold the astronaut's weight. It will also need to have low power

consumption and heat generation. Taking these into consideration, the magnet was narrowed down to a solenoid electromagnet and a flat-pole electromagnet. These magnets are relatively similar, differing in their coil configuration, and can be seen below in Figures 4-4 and 4-5, respectively.



Figure 4-4: Solenoid Electromagnet [20]



Figure 4-5: Flat-Pole Electromagnet [21]

The grips would need to be high-strength and lightweight. They also need to not deform under high loads and be relatively easy to 3-D print. Using these, the material used to 3-D print the grips was narrowed down to carbon fiber reinforced nylon, polycarbonate, and ABS. Carbon fiber reinforced nylon is high-strength, is lightweight, and it won't deform under high loads. The only issue with this material is that there is a 3-D printing challenge due to its abrasive nature. Polycarbonate is impact resistant and can support high loads. This material can become brittle at low temperatures and poses 3-D printing challenges due to its high viscosity and tendency to warp. ABS can withstand moderate loads which can be increased in the design of the grips. The downside of this material is that it can warp dramatically during the cooling process and emits toxic fumes while printing.

The batteries need to have a high energy density, long life cycle, and lightweight design. Taking this into account, a lithium-ion battery was chosen due to it having all these aspects. The wiring would need to be relatively simple, impact resistant, and low heat generation. Due to the chosen magnets, the wiring may be complex, and the size of the batteries may cause heat generation in the wires. This will most likely require simple circuitry from the batteries to the magnets and the push-button switch.

Mechanical Elevator

Given the unique shape and structure of habitats, vertical movement becomes a crucial aspect in the day to day lives of astronauts. In environments where space is limited, the ability to navigate between levels of the habitat is essential. When most people think of vertical transportation, elevators are one of the first things that come to mind. They provide a quick, straightforward way to travel between floors in most large buildings today. While it is impractical to replicate the conventional elevators used on Earth, a mechanical elevator could be designed to

meet the needs of astronauts in Lunar or Martian environments.

The mechanical elevator would operate similarly to a cage platform system that a window washer would use; however, rather than being automatically controlled, it would be man operated. Figures 4-6 and 4-7 give a visual of the concept. It would have a sturdy platform equipped with handrails to ensure safety during use. It would be designed to not only transport the astronauts but also any cargo, making it versatile for various tasks within the habitat. The mechanism for raising and lowering the platform uses a pulley system, which is both simple and effective. The pulley would include a ratcheting mechanism that prevents downward movement while the platform is being raised, ensuring that the astronauts can safely ascend without the risk of sudden drops.

Figure 4-6: Window Washer Cage System [22]

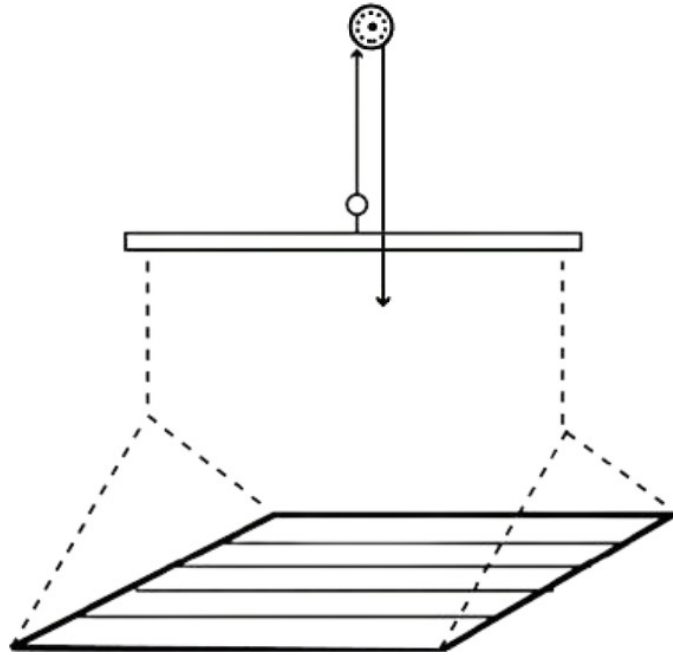


Figure 4-7: Simplified Mechanical Elevator Design

The complexity of the pulley system could be adjusted to optimize the effort needed to lift different loads. On the Moon and Mars, gravity is significantly lower than on Earth, which makes it to where astronauts can easily handle their own weight along with the weight of the platform and any additional cargo. Therefore, a simple pulley would be sufficient to fulfill the operational requirements of the elevator. The system would not only enhance functionality, but it would also promote physical activity amongst the astronauts.

The force needed to operate the elevator would provide an exercise opportunity, turning the act of moving between levels into a beneficial workout. By including adjustable resistance settings on the pulley, astronauts can modify their workout to make it more or less challenging depending on their fitness goals and daily routines. This feature would not only contribute to their physical well-being, but it would also serve as an engaging way to stay active in an otherwise confined environment.

Customizable Rock-Climbing Wall

The prompt can be answered with numerous futuristic and “superhero-like” ideas, yet the

team also wanted to look at more realistic approaches to the problem. One of the team’s leading concepts is to create a rearrangeable or customizable rock wall. Although this concept does not reinvent the wheel, a seemingly simple design may be the best answer to the prompt. A rock wall would allow for an entertaining, health focused, and replicable design.

Rock climbing, specifically indoor climbing, is a fun hobby that is becoming increasingly popular in the United States. Figure 4-8 gives an idea of the steady growth of rock climbers over the past 6 years. As of 2023, there are more than 600 climbing gyms in America alone [23].

People are willing to pay a monthly gym fee to be able to enjoy climbing throughout the year.

Climbing itself has a fan base behind it that helps promote a sense of community and

competitiveness. Being a relatively newer hobby, indoor climbing itself has become an enjoyable activity with a low bar for entry that can even act to socialize.

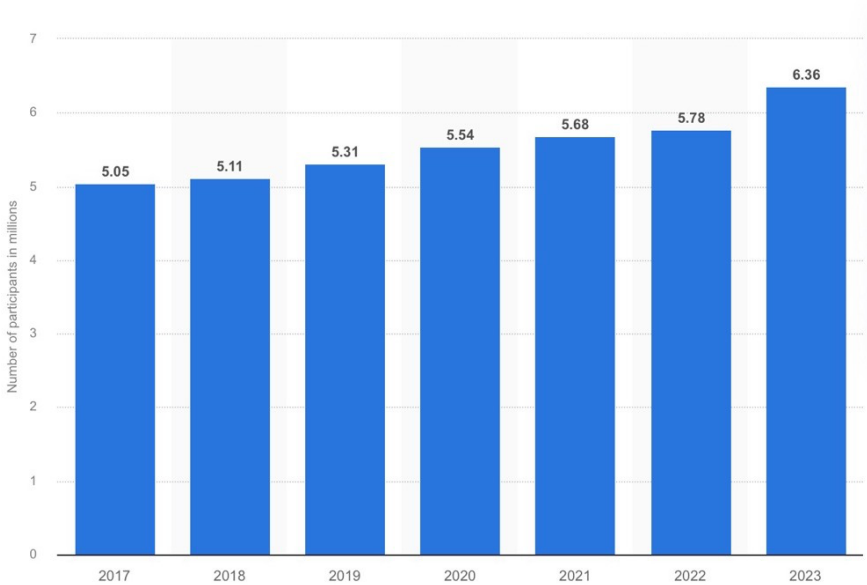


Figure 4-8: Estimated Number of Rock Climbers Over the Last Six Years [24]

Although a rearrangeable rock wall is an amusing idea with several strong points, the idea itself is only as good as it answers the prompt. This idea answers the first section well by leaving a relatively small footprint while still allowing vertical movement. The wall itself could be made as minimal or complex as necessary. As for utilizing the different gravities, this idea would allow

for a wall design that could never be made with Earth’s gravity. For example, the grabbing and stepping points along the wall could be further apart. This concept is explained more in the next section of the prompt by utilizing a unique mode of mobility throughout the habitat. This concept’s initial vision only includes simple rock pieces, but the wall could be adjusted to allow for even more ways to traverse vertically. As for muscle retention and entertainment factor, rock climbing is a full body workout that is commonly enjoyed [25]. A strong advantage of the rock wall is that the workout would be, simply put, fun. Finally, this design could be used to assess performance for the whole crew by promoting a fun, competitive element like a “climb timer.” After assessing its background and analyzing it against the prompt, the rock wall makes a compelling contender amongst the other ideas.

It is important to analyze the feasibility of the idea after answering the prompt with it. The rocks along the wall would realistically be made using 3D printing. This would allow for ease of completely unique designs for grabbing points along the wall. Figures 4-9 and 4-10 give a glimpse of what the concept would look like, if selected.

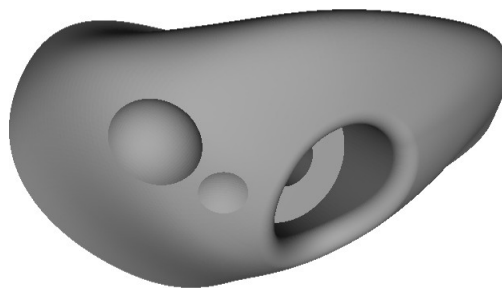


Figure 4-9: Example Rock [26]



Figure 4-10: Assembled Rock Wall [27]

Some of the other ideas can be used as inspiration as to how the rocks can be secured to the wall and later rearranged. A high friction material, similar to the gecko hand concept, could be used to attach the rocks, but they could be brought loose unintentionally while climbing. Using electromagnets is another viable option that would allow the rocks to be arranged in various ways without hurting the rocks or the wall. Lastly, the wall could have multiple points that rocks, or other attachments could be secured to. This would include bolting or screwing down the rocks. This would probably not be ideal for continual reorganization. If this design is chosen, the team will continue to come up with solutions for the continual layout change of the rock-climbing wall while still being sturdy.

Decision Matrix

Table 4-1 is the decision matrix used to select the best option to further develop, using criteria derived from the design requirements. The five criteria that were chosen are the total mass of the design, how safe it is, how durable the design is, how much using it impacts fitness, how much it enhances mobility, and how entertaining it is to use. The designs evaluated were launching stick hand, electromagnetic hands, mechanical elevator, and customizable rock-climbing wall. Each criterion was assigned a weight, based on how important it is to the

customer. Each design was assigned a score from 0 to 10, with 10 being the best. Each individual score was multiplied by its weight, then those values were summed to determine the best design.

Table 4-1: Decision Matrix

Criteria	Weighting	Launching Sticky Hand	Electromagnetic Hands	Mechanical Elevator	Customizable Rock-Climbing Wall
Safety	Go/NoGo	NoGo	Go	Go	Go
Mass	0.25	3	2.5	2	5
Durability	0.2	5	5	7	7.5
Fitness	0.2	2	8	7	8
Cost	0.15	6	5	7	8
Mobility	0.15	7	5	5	5
Entertainment	0.05	8	6	4	7
Total Weighted Score		4.5	5.03	5.3	6.65

Factors Chosen

Safety

Safety was chosen as a criterion also because of its importance in space travel. The astronauts will be living in a habitat module for an extended period of time, and it is imperative nothing injure them or the habitat itself. This is why it is a Go/NoGo category, as any option with a NoGo rating will not be considered further. This criterion considers the design's intended use, and any accidents that may occur through regular use.

Mass

Mass was chosen as a requirement because of its importance in space travel. Every gram sent up out of Earth's gravity well takes a large amount of energy and increases costs dramatically. This is why its weight is 0.25. In addition, for three of the designs, an astronaut will have to wear it. Four the fourth, they will have to be placed by hand. A high mass would make using it cumbersome and overly fatiguing, and an astronaut may bypass it entirely. This criterion also considers any additions to the habitat that may need to be added.

Durability

Durability was chosen as a requirement because of how often the design will need to be used. The astronauts will need to use the design to move around the habitat multiple times per day, sometimes multiple times per hour. Astronauts constantly have tasks that need to be accomplished. It is important the design be robust and unlikely to break from regular use. This is why its weight is 0.2.

Fitness

Fitness was chosen as a criterion because of how important it is in space. Astronauts will experience profound bone and muscle density loss during their tenure in the habitat. This is mitigated by regular exercise, but every extra bit of athletic activity will benefit the astronauts greatly. This is why its weight is 0.2.

Cost

Cost was chosen as a criterion because of its impact on the mission as a whole. If the cost of the design is very high, it will not be considered. This is why it has a weight of 0.15.

Mobility

Mobility was chosen as a requirement because that is what the design is ultimately trying to accomplish, in addition to fitness. Moving around in a low gravity environment will be challenging for the astronauts. The design should help them in this endeavor. Being able to move around quickly and effectively during everyday tasks and emergencies is important. This is why its weight is 0.15. The habitat will make use of vertical space, more so than buildings on Earth, because of the reduced gravity. How well the design can help astronauts travel vertically, as well as horizontally, was considered.

Entertainment

Entertainment was chosen as a criterion because of its importance on crew morale. Having fun while on a prolonged mission is critical, especially when that mission takes place in cramped quarters. High morale will improve teamwork and productivity. This is why its weight is 0.05. Also, the astronauts will use the design more if it is fun, aiding in their mobility and fitness.

Decision Matrix Results

Based on the results from the decision matrix, the customizable rock-climbing wall is the preferred design. It has the highest total weighted score of 6.775. The launching sticky hand design has almost no fitness aspect, and it would be heavy and inconvenient for astronauts to use. Plus, firing a projectile of any sort in a habitat on the Moon or Mars would not be conducive to a safe environment. The electromagnetic hand design necessitates a wall or wall inserts made from steel, or another magnetic metal, giving it a high total mass. The mechanical elevator design can only move vertically, only works out the upper body, and would have a high mass. The

customizable rock-climbing wall design does not have a high mass, as it is just several, light, individual pieces. It provides a high fitness level for astronauts, and it is modular, making it more entertaining to change and use. It is also able to provide horizontal motion to astronauts. For the above reasons, the customizable rock-climbing wall design has been chosen to be further developed.

Combined Design

To give the astronauts a choice, the mechanical elevator will be developed with the customizable rock wall. This combined design will feature a unique elevator shaft in the habitat with rock handholds on the inner surfaces and bosun chairs on each outer surface. Both the bosun chair and the rock wall allow the user to travel vertically in the habitat and require the astronauts to engage their muscles. The rock wall handholds will be mounted on the inner surfaces of the walls to give the climbers the ability to jump from wall to wall. The bosun chairs will be on the outer surfaces of the walls to reduce the risk of tangling with other bosun chairs, and to make it easier to help users if they get stuck during ascent/descent. In this combined design, climbing the rock wall is the main method that the astronauts will use to maintain their fitness levels as it will be engaging and challenging to climb the walls. The bosun chairs aren't as physically demanding to use, so they will not maintain fitness levels as well, but they act as a secondary method for the user to get to different floors of the habitat. The astronauts will now have the option to use a harder or easier method to travel vertically within the habitat depending on how they feel.

For this project, the design must take advantage of the lower gravity environment, maintain the astronaut's physical health, be able to be used vertically, be entertaining, and be safe. The rock wall meets these needs by having innovative handholds that allow for unique movement on the Moon and Mars. Also, rock climbing is an activity that people do both for fun and exercise. Lastly, the rock wall will have an auto belay system, the users will wear harnesses, and the base of the wall

will be padded for safety. The bosun chair will still require the user to use their muscles to pull themselves up but will not require as much energy in the lower gravity environment. It will also make use of a harness and padding at the base of the wall for safety.

The rock wall is a flat, vertical surface with a color-coded system that distinguishes the different climbing routes based on difficulty. Beginner routes are often marked by bright colors and have handholds close together so that an easy ascending climb is safe and convenient for a novice to manage. Intermediate routes are colored differently and require greater strength and coordination; there are fewer handholds and feature more intricate sequences. The most challenging routes feature even less handholds that are more complex and therefore harder to grip. Even though different paths have different levels of difficulty, they all keep the climbers completely physically engaged. Astronauts may also enjoy free play, which is climbing in any direction on any route as the climber sees fit. The result of which fosters spontaneity in exploration and enjoyment. Thus, the climbing wall is a very versatile design choice as it implements a method of physical training, fosters creativity and motivation, and creates friendly competition for occupants in the habitat.

There will be multiple different handhold attachments for the rock wall. There will be 3D printed rock pieces similar to the kind found on rock walls on Earth but various other handholds like ropes, wedges, salmon bars, and more will also be incorporated. These unique combinations of handholds will provide a novel rock-climbing experience for the astronauts. Each wall of the elevator shaft will have handholds covering the surface which will create multiple possible routes of varying difficulty. The easier routes will not maintain the astronaut's fitness as well as the more challenging ones, but they will allow the astronaut to scale the wall faster if needed. There will also be force sensors incorporated into some of the handholds which will measure the force exerted onto them. The force exerted at any point during the mission can be compared to the force exerted at the

beginning of the mission to see if the climber's muscles have become weaker, stronger, or remained the same. A timer, point system, and score board will be used in the rock wall design to increase entertainment and to motivate the users to break their records. To use the rock wall, the astronaut will clip their harness to the auto belay system, start the timer, begin climbing, stop the timer once they reach their desired floor, and then unclip themselves from the auto belay system. They will then input their time along with the route difficulty into the rock wall software system and a score will be generated. The score, time, route difficulty, and name of the astronaut will then be displayed onto the scoreboard.

The bosun chair is a simple but effective tool commonly used on sail boats. These chairs were used to reach areas such as the rigging masts or sides of the ship. It is essentially a sturdy seat or sling that is suspended from a rope allowing the user to raise themselves up vertically and work safely as needed. The bosun chair will be attached to a block and tackle system that will be at the top of climbing shaft on the outside surface. This block and tackle system allows the astronaut to pull themselves up and lower themselves as needed. The bottom will be a fabric-like material that will be comfortable for the astronaut to sit in as the system is used. Once in the bosun chair, the rope that is attached to multiple pulleys will feed through a friction device like that of a belay clip. This device will allow the rope to feed through one side but not allow the rope to retract back through without the astronaut making it. Pulling the slack of the rope through the belay system allows the bosun chair to be raised. The astronaut can use their feet to increase the speed of ascension, increase stability, and to reduce twisting of the rope. When descending, the astronaut will use one hand as a break hand to control the speed at which they descend. There is a mesh-like material that will surround the back and sides of the astronaut when sitting to prevent them from falling out of the chair. To exit the bosun chair, the astronaut will go to their desired floor and step onto a platform which they can stand on.

PRELIMINARY DESIGN REVIEW

Major Trades and Options

Rock Wall

3D Printing Method Comparison

There are several different types of 3D printing, and each type has a variety of materials that can be printed. The main types are fused deposition modeling, digital light projection, and selective laser sintering. All three types create objects in layers. Smaller layer heights mean a higher level of detail and print time. A 2D pattern is created; then the machine moves in the z-axis and creates another 2D pattern. This continues until a 3D object is formed.

Fused deposition modeling (FDM) is the most common type of 3D printing. A continuous strand of plastic wound around a spool, called filament, is fed into a heated nozzle which melts it into a liquid. The nozzle moves to the desired location and deposits this liquid, which solidifies, creating one's desired object. Many different types of plastics can be printed, and each of those can have various additives, such as carbon fiber, wood, metal, or different types of plastics. The amount of post processing varies depending on the individual object. Mostly, this is from removing supports. Support is necessary for any object that has steep overhangs in its geometry. Digital light projection (DPL) uses a vat of resin and a screen to create objects. It is known for its capability for high detail objects. The machine lowers the build plate, what the object is built on, into a vat of resin. The vat has a clear bottom, which allows a screen to project ultraviolet light into the resin. This cures the resin from a liquid to a solid. There are several types of resin available to use; some resins can even be flexible or heat resistant. Printing time for SLS printers is only dependent on the tallest object. The screen can light a small portion or the entire build plate, and it will take the same amount of time. However, resin and its fumes are toxic to touch or breathe. Personal protective equipment, such as gloves and masks, is required. Resin prints also require much post processing. Supports are necessary to hold the object to the build plate and will have to be removed. They must

be washed in a vat of isopropyl alcohol, then dried, and then cured with more ultraviolet light. The build area of these printers is small when compared to their FDM counterparts. Both FDM and DPL printers are desktop machines, including the resin post processing machine. Selective laser sintering (SLS) uses a laser to melt powder together to form a layer, then places a layer of powder over the previous one and repeats the process. SLS printers can print different types of plastics and metals. However, these prints require even more post processing than resin prints. First, the print must be put in a reclaiming machine to remove all excess powder. Next, the print must be blasted with a high-pressure blast medium. Usually, this is air for plastic and sand for metal. Each step in the printing process requires a large machine. Managing the powder can create safety hazards. A respirator is necessary when working with SLS printers. No support is required during the printing process, as the extra powder provides the support. It is also impossible to print objects that are hollow, one must add holes in the bottom to drain the extra powder. These objects can be completely solid, but this is costly in powder and time. Based on the above information, FDM is the best option for printing the rocks for the rock wall. It is the easiest to print with, has little post processing, and will not be impacted by the lower gravity as much [29].

3D Printing Material Comparison

Several different types of filaments exist that FDM machines can take advantage of. Polylactic acid (PLA) is the most common of these filaments. It is the easiest material to print, has high dimensional accuracy, and is resistant to bending. Unfortunately, the material is very brittle. Polyethylene terephthalate glycol (PETG) is the second most common filament to print with. PETG is more difficult to print, but it is stronger and less brittle than PLA. PETG and PLA cost the same, around twenty dollars per kilogram, but the price varies depending on the brand. Thermoplastic polyurethane (TPU) is another popular filament. It is known for its flexibility and high layer adhesion, but a higher durometer variant can be used to create very tough parts with

lower flexibility and high fatigue resistance. TPU is even more difficult to print than PETG, mostly due to how hygroscopic it is. This filament must be kept in a temperature and humidity-controlled box at all times. Otherwise, it absorbs the water in the air and will ruin the print when the water boils to steam as the filament leaves the nozzle. TPU is about twice as expensive as PLA. All non-plastic additives will require a harder nozzle than the typical brass nozzle, as it will wear it down. Several materials are available, such as hardened steel, ruby, or diamond tipped. A larger nozzle diameter is all but necessary to prevent clogs. Using other plastics as additives is an easier way to achieve a stronger material. One example is a combination of PLA and TPU filament. This combines the mechanical properties of both, creating a plastic that is strong, easy to print, and has excellent layer adhesion. It is about twenty-five percent more expensive than basic PLA. All materials have strengths and weaknesses when choosing the optimal material for printing the climbing rocks [29]. PLA is a proven material for creating rocks for climbing, as seen in Figure 5-1. Even considering that this example used two different types of PLA, as shown in Figure 5-2, the rock did not have any layer adhesion issues when supporting a person's weight [28].



Figure 5-1: PLA Climbing Handhold



Figure 5-2: Climbing Handhold with Two Types of PLA

3D Printing Infill and Perimeter Comparison

Infill relates to the pattern and density of the interior of the object that also supports the top surface. Almost every FDM printed object is mostly hollow. The average value of the infill density is fifteen percent. There are both 2D and 3D patterns available to do this. For both 2D and 3D patterns, as the infill density increases, so does the strength of the part. It also increases the print time and material used. Some 2D examples include grid, triangular, and honeycomb. These are made by repeating a 2D shape, layer after layer. Some 3D pattern examples include gyroid, 3D honeycomb, and lightning. These patterns are different layer by layer, forming a 3D shape on the inside of the object. Gyroid and 3D honeycomb are the best patterns to use for climbing rocks. This is because 3D patterns support in all directions without large differences, unlike 2D patterns. Perimeters are how many times the 3D printer creates the walls of the object before starting on infill. Typically, using more perimeters makes the part stronger and increases print time. Various perimeter options will be tested to find the best balance of strength and cost [29].

Texture and Grip Considerations

After determining the material to 3D print the rocks, the team considered the texture and grip of the rocks. One of the initial considerations was to use a gecko-like texture. This would

involve high-friction material to enable a secure grip. Although this solution appears feasible, it presents several drawbacks. One significant challenge is the method of gripping the rocks. The gecko grip operates in a specific direction. Releasing the rock would require a corresponding direction, which could restrict the climber's movement. This would need to be an important distinction made to the user. Another drawback to this method is the price. The gecko grip material is the most expensive option. The other options may be readily available, but outside sources and research is required to take advantage of a true high friction material with the properties needed. Even though the drawbacks may have been highlighted, this is a reliable way to give proper grip to the rocks. Although it works, other options may be more realistic and reasonable if it offers the same or better quality with less downsides.

The standard PLA print was discussed and seems to be a decent option. It would not require any extra steps and has proven to, at least, work. However, the team desired to explore other options to further ensure the security of the climber. Another option that was found during research was "fuzzy skin" for 3D printing. Similar to its name, the fuzzy skin would create a unique texture and grip, as seen in Figure 5-3. It is available to create using on-campus resources. The cost in time and material would be very similar to the print without the texture. The main factor that the team needed to consider was which option got the job done well and with safety at the forefront.

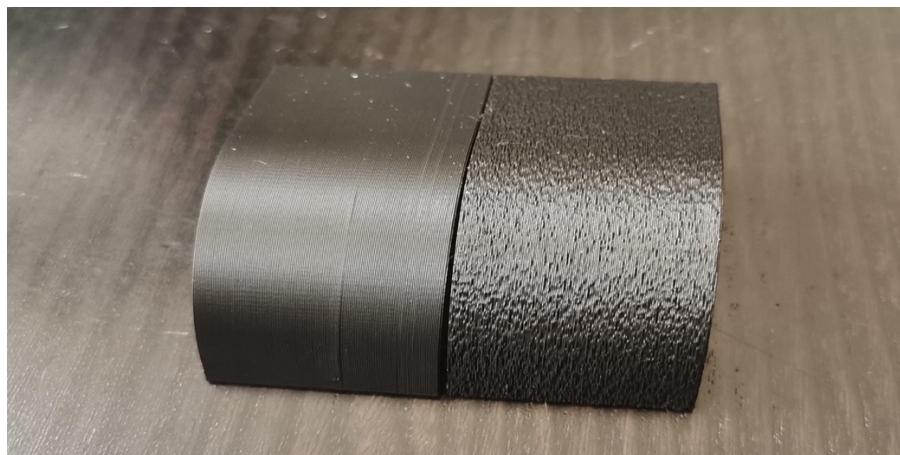


Figure 5-3: Standard and Fuzzy Skin 3D Print Comparison

After considering the different options and weighing their respective strengths and weaknesses, the team determined that the fuzzy skin texture is the best option for creating the custom rocks. One main advantage of this option is that it allows for ease of access to prototyping. Using the software and printers available, the team felt confident in their ability to create, test, and execute properly without making compromises.

Wall Material

When analyzing the rock wall assembly, there are many different design decisions that can be made. The most obvious decision is the material of the wall itself. A common material that is used for home climbing walls is plywood. While this material is cheap, readily available, and lightweight, it is highly flammable, can splinter, is not radiation resistant, and can warp and rot when exposed to moisture. Another common material used for climbing walls is acrylic. This material is often used for pool side climbing walls. It is slightly heavier than plywood, but water has no effect on it, it doesn't splinter, has a higher combustion temperature, and it can be made with lead suspended throughout it which makes it radiation resistant. It is also transparent, which will add to the entertainment factor of the wall because the astronauts will be able to see when other astronauts are climbing. When considering the qualities of these two materials, acrylic is the better choice.

Handhold Attachment

Another big decision to consider is the method used to attach the handholds to the wall. Traditionally, handholds are attached to the wall using t-nuts, bolts, and washers. When coming up with different ways to attach the handholds to the wall, the team decided that a quick-release method that is integrated into the handhold itself could be a viable option. After researching more, it was determined that 3D printing an extrusion from the handhold that would screw into the wall would introduce waste when printing and increase the time to print. It would also be a weaker

connection since the 3D print material is weaker than the hardware material. Additionally, the weight savings from not using hardware would be marginal. So, after considering these points, it was determined that using the traditional hardware to mount the handholds is the better option.

Hardware

When choosing hardware, the bolts and washers do not have much of an effect on performance if different types are used. They all do essentially the same thing with minor differences in size, shape, or material. The nuts, on the other hand, do play a big role in performance. There are two types of nuts that can be used for the rock wall: t-nuts and rivet nuts. Both accomplish the same goal but have different methods of installation. Once the hole for the bolt has been drilled, the t-nuts can either be hammered into the back of the wall or it can be pulled into the back of the wall by screwing the bolt in. These two methods ensure that the teeth on the nut get good purchase into the wall to prevent it from spinning when screwing the bolt in. The teeth on the t-nuts could cause the acrylic wall to crack or chip. For rivet nuts, the rivet nut is inserted into the bolt hole and a tool is used to compress the barrel of the nut which causes it to pinch the wall. The barrel of the nut pinching the wall prevents it from spinning when screwing the bolt in. The downside to rivet nuts is that the barrel of it protrudes from the wall. Figures 5-4 and 5-5 show the operation of t-nuts and rivet nuts, respectively. When considering these two options, the rivet nuts are the better of the two because the installation will not damage the wall.

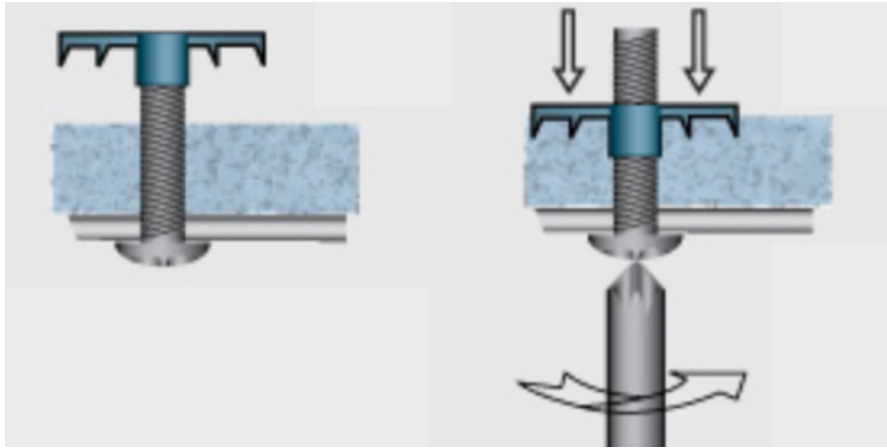


Figure 5-4: T-Nut Operation [30]

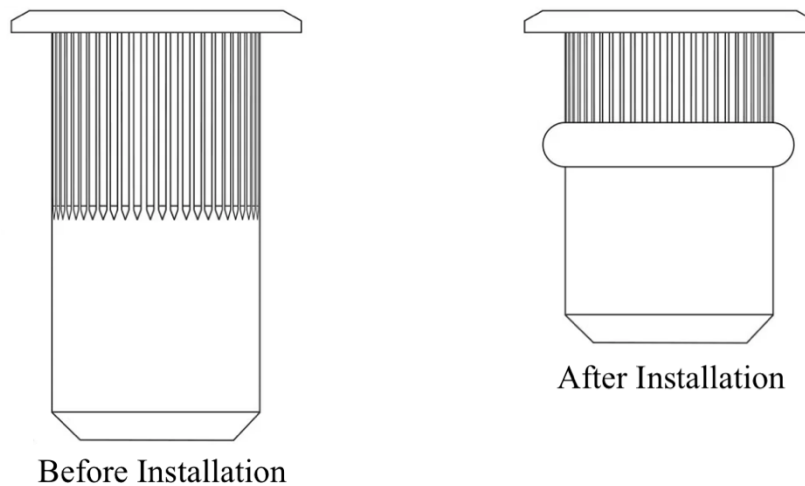


Figure 5-5: Rivet Nut Operation [31]

Bosun Chair

Bosun Chair vs Vertical Bike

When deciding between the vertical bicycle and the bosun chair, several factors were taken into consideration: weight, reparability, and using a chain versus a rope. The vertical bicycle consists of a bike frame, sliders, and a chain. The bike frame is welded to the sliders, and the sliders are connected to the guide rails. The chain is then used to move the bike vertically while the sliders and guide rails stabilize the movement. A typical bosun chair consists of a wooden plank, fabric, rope, a clip, sliders, and a pulley system. The wooden plank acts as the seat, the fabric as the

harness, the clip as way to maintain lift, and the rope as a connector and way to lift the chair. The sliders are connected to the guide rails to stabilize the movement of the chair. Both designs incorporate some form of guide rails and slider that direct the mechanism from the bottom floor to the ceiling, therefore, these parts of the design are not considered for this analysis.

Weight

The weight analysis was done based on the average weights of the components of each design. First, the bosun chair’s main component is the wooden plank. Based on chairs that are currently on the market, this component weighs approximately 6lbs. Next, the weight of the fabric was estimated using standard climbing harnesses which weigh between 12 and 17 ounces. Ultra lightweight harnesses can weigh as little as 3 ounces. For the rope, a 2/5” diameter by 64’ climbing rope was used to estimate a weight of 3.7lb. The clip that is intended to be used in this design weighs 175g. Finally, a pulley that can hold a minimum of 300lb weighs 2.05lb. There will be three pulleys incorporated into the pulley system. The vertical bike’s main component is the bike frame. A typical bike frame weighs between 15 and 18lb. For the chain, a 3/16” stainless steel chain with similar strength to the rope of the bosun chair was used for the estimation of 0.38lb per foot. A minimum of 60’ of chain would be needed for a 30’ building. The greatest weights were summarized and summed together in Table 5-1 below.

Table 5-1: Estimated Weight Analysis

Bosun Chair		Vertical Bike	
Component	Weight (lb)	Component	Weight (lb)
Wooden Plank	6	Bike Frame	18
Fabric	1.1	Chain	22.8
Rope	3.7	-	-
Clip	0.4	-	-
Pulley	6.2	-	-
Total	17.4	Total	40.8

From the table, the components of the vertical bike are heavier than those of the bosun chair.

Repairability

When evaluating repairability, the most important factor is how straightforward it is to fix a broken component. The bosun chair, although it has numerous working parts that could potentially fail, features a design with simpler connections compared to the vertical bike. These connections allow for quicker and less complicated repairs. Additionally, its components are extremely lightweight, making it far easier to transport and store spare parts in the challenging environments of the Moon and Mars, where minimizing weight is critical.

On the other hand, the vertical bike's frame is constructed from welded metal bars, which are further connected to a chain and bolted to sliders. This construction creates a much more complex system to repair. Reaching a broken part often requires complete disassembly of the entire design, significantly increasing repair time and effort. Furthermore, the welded frame introduces a serious drawback: if one of the welded bars fails, repairing or replacing it in a remote setting would be exceptionally challenging, requiring advanced tools and techniques that may not be readily available in space.

Considering these factors, the bosun chair stands out as a significantly more practical option for reparability in space. Its straightforward design, lightweight components, and ease of maintenance make it a far better choice for environments where simplicity and efficiency are paramount.

Chain vs. Rope

When comparing ropes and chains for this system, both offer unique advantages and safety considerations, particularly in the extreme environments of the Moon and Mars. Chains are durable and resistant to wear but are heavier and susceptible to derailment from gears due to misalignment,

slack, or debris interference. They have predictable failure modes, typically deforming or breaking at links, which makes inspections straightforward. However, chains require lubrication, which can attract fine lunar or Martian dust, leading to jamming and accelerated wear. Chains are also susceptible to fatigue over time due to repeated loading and unloading, which can reduce their longevity, especially under high-stress conditions. Additionally, the extreme temperature swings on the Moon and Mars can cause thermal expansion or contraction in chains, potentially affecting tension and alignment. Proper maintenance, including alignment checks, tension adjustment, and cleaning, is critical to mitigate these risks.

In contrast, ropes are lighter and more flexible, ideal for low-gravity environments. Synthetic ropes, while significantly lighter than metal chains, are prone to abrasion, fraying, and degradation from extreme UV radiation and temperature fluctuations, which are more severe on the Moon and Mars. Unlike chains, ropes are less affected by thermal expansion but may stiffen or become brittle under prolonged exposure to low temperatures, compromising their flexibility and durability. Ropes are also vulnerable to cumulative damage from micro-abrasions, which can reduce their lifespan and make regular inspection essential. Dust accumulation can accelerate wear on ropes, particularly where they may rub against edges. Ropes also risk snapping and recoiling under tension, posing safety concerns. While chains benefit from protective guards and tensioning systems, ropes require abrasion-resistant materials and frequent inspections to ensure reliability in these harsh conditions. So, after considering these design choices, the bosun chair that uses ropes is a better option than the vertical bike that uses chains due to the weight savings and ease of repairability.

Bosun Chair Material

When designing the seat for the bosun chair, instead of going the traditional route of a wood or metal seat, a fabric trade study was conducted. The best fabrics for holding a lot of weight while

also conforming to the shape for comfortability are typically those that combine high tensile strength, durability, and flexibility. This allows the load to be distributed evenly and maintain structural integrity under stress. Some of the common materials used in bosun chairs today are nylon webbing, polyester webbing, and canvas. Nylon has a high abrasion resistance while the fibers have a slight elasticity which allows them to conform to shapes. Nylon is used in hammocks, tarps, and straps which shows its ability to provide comfort and conform to the shape of the astronaut. Polyester is resistant to stretching and shrinking which is why it is widely used in industrial applications like slings or straps. Polyester is also UV-resistant which could be an important factor with being in space. Considering the weight of each of these materials, there isn't much of a weight difference that should matter in the grand scheme of the entire weight, but nylon seems to be the lightest with polyester being the next option. However, the cheapest of the materials is polyester with nylon close behind. Both materials are easily accessible, and after considering the characteristics of each, polyester has been chosen to be the material of the chair.

Interface with Habitat Design Solutions

The center shaft is the habitat's primary vertical system. It is designed to address mobility and fitness needs in a low-gravity environment. It features climbing walls on all sides and a bosun chair pulley system, which provides astronauts with flexible options for ascending and descending. The climbing walls incorporate modular handholds made of lightweight, durable materials such as 3D-printed PLA or PETG, arranged to create multiple routes of varying difficulty. Sensors embedded in the handholds track force application, which enables health and performance monitoring. The bosun chair system uses a block-and-tackle pulley setup, which optimizes for low-gravity operation to reduce astronaut fatigue while still promoting physical engagement. The shaft's central location minimizes travel time to key areas of the habitat to ensure an efficient and functional component of the design.

A floor plan around the shaft must be designed to enable use of this combined design concept. There will be holes in the floor adjacent to each outer surface of the climbing shaft so the bosun chairs can be used efficiently. Padded flooring surrounds each level of the shaft to lessen the risk of injury from falls. The design utilizes radial symmetry, and the main operational spaces, like the living area, workspace, and storage are equidistant from the shaft to increase convenience. Each floor has clearly defined access points to the shaft for both climbing and bosun chair entry, avoiding clusters and ensuring that all astronauts can access the system together at the same time. The integration of the shaft into the layout also optimizes the use of vertical space, which is in high demand for more compact domiciles, as this is a key attribute for more compact living spaces. This floor plan can be seen below in Figure 5-6.

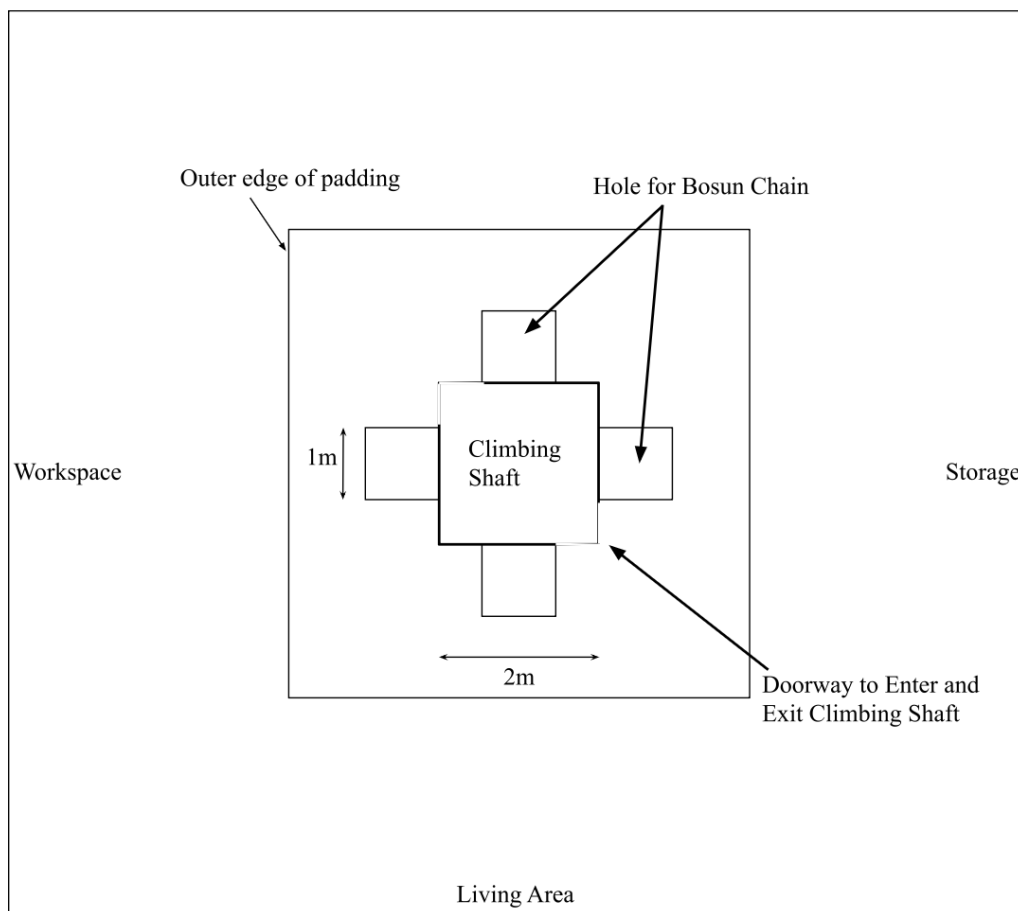


Figure 5-6: Climbing Wall and Bosun Chair Floor Plan

When further considering the safety of the user, the team drew inspiration from a traditional rock wall that utilized an auto belay system. This system allows any of the residents of the habitat to traverse the rock wall without needing someone else to spot them. The auto belay will be attached to the ceiling, allowing for full traversal of the rock wall up to the top floor. There will be four total auto belays so there will be one for each member of the habitat which will let all of the astronauts climb at the same time if they want or need to. Another safety measure taken from a standard rock wall is the padded flooring. Padded flooring will be used in both sections of the design, not only the rock wall. This allows for safe ascents and descents on both the rock wall and the Bosun chair.

Structural supports are optimized to provide the stability and safety of the central shaft and of its surrounding parts. Vertical beams are present at the base and middle parts of the shaft and tie it to the floor and ceiling consecutively by preventing it from bending or moving constantly due to usage. Acrylic walls (strength, transparency, low mass) are further reinforced with rivets nuts to clamp climbing handholds tightly without causing weakness or wear. Cross-bracing and strategic stiffening at points of maximum loading increase rigidity, especially at the locations of potential load variation, such as access points. When combined with a padded floor base, these features give rise to a strong, compliant framework that can withstand the dynamic loading forces encountered during climbing and pulley exertion under a low-gravity environment.

Climbing Wall and Bosun Chair Specifications

When designing the rock wall, there needs to be adequate climbing space and enough handholds to decrease repetitiveness. When analyzing rock climbing towers on Earth, most of the climbing surfaces are between 2 and 4 meters wide. This amount of climbing area allows the climber to move horizontally on each surface and not be confined to just climbing vertically. To save weight, climbing walls that are 2 meters wide have been chosen for the final design. Four of

them will be used to create the climbing shaft which will ultimately give the climbers access to 8 meters of lateral climbing space. These walls will span the entire height of the habitat which is assumed to be 10 meters tall so the total climbable surface area will be 80 square meters. There will be four auto belay systems in total, one for each climbing wall, so all the inhabitants will be able to climb simultaneously. According to various rock-climbing resources, a good rule of thumb is to have approximately 3 handholds per square meter per route [32]. To give the climbers multiple routes when in the habitat, there will be 9 handholds per square meter for the final design. This means that there will be 3 different routes per rock wall, and a total of 12 different routes for the whole rock-climbing shaft. All of which will include the unique handholds mentioned above and will be of varying difficulties. Since some of the unique handholds, like the salmon bar, take up more space than a typical handhold, and there are door cutouts on each wall, the total number of handholds used for the climbing shaft will be around 650.

The team's bosun chair design is not the same as a traditional bosun chair. When looking at traditional bosun chairs, the bottom material that the user sits on can be made of wood, metal, and or a fabric like material. Also, the ropes that go around the bottom of the seat all come up at around forty-five degrees and meet up at one point of a d-ring like structure as seen in Figure 5-7 below.



Figure 5-7: Traditional Bosun Chair

By running an optimization program in MATLAB that showed the best way to distribute the force, the chair design would be best if the angles that the ropes went up were at ninety degrees. The design will have four ropes attached to a metal plate at the top keeping the ropes at ninety degrees. The bottom of the bosun chair will be a soft compressible fabric material that conforms to the body of the astronaut. Attached to the top of this metal plate are two more ropes that will lead to a d-ring that is attached to the rope that goes to the pulleys. To give the astronauts a mechanical advantage, there will be two to three pulleys which will cut the amount of weight they must pull for up to three levels. The rope will hang from the pulleys and have enough length to reach where the astronaut can pull on it. As the rope is pulled by the astronaut through the pulleys, the bosun chair will ascend as seen in Figure 5-8 below.

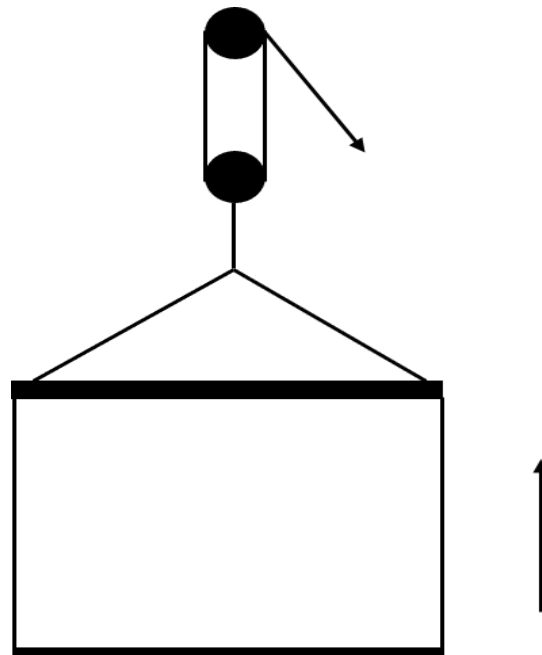


Figure 5-8: Bosun Chair Basic ConOps

One of the main safety concerns is making sure the astronaut does not fall off or out of the bosun chair especially when at a great height because that could be catastrophic. The traditional bosun chair above shows a harness like strap that keeps the user in, but the team has decided to put a mesh like netting or material around the four ropes to secure the astronaut on their back, right,

and left side. This mesh material will allow for a little movement but ultimately will catch the astronaut if they lean too far one way or another. Considering the possibility of the astronaut falling forwards, the chair will have a rope that extends in front of the astronaut and clips in the other side making sure the astronaut is safely secured from all sides.

Another safety concern for the bosun chair is the twisting of the chair throughout the climbing process. To counteract this concern two ropes will be added to the sides of the chair and attached to the wall through a system of sliders and clips. As to not restrict efficient movement these ropes will have some slack but not enough as to allow for much rotation. If more rotation is needed to exit the chair one side or the other can be unclipped allowing the user to turn towards the platform and exit the chair.

A model of the full assembly of the combined rock wall and bosun chair design can be seen below in Figure 5-9. The models of the individual components of the design can be found in Appendix B.

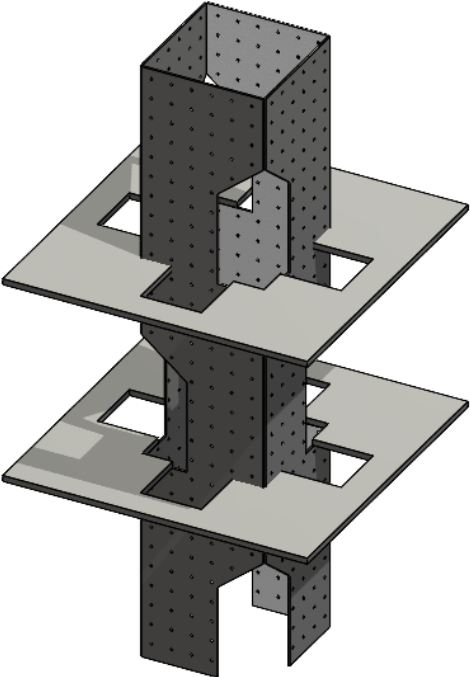


Figure 5-9: Combined Design Model

Potential Safety Issues and Component Test Plan

With a complex solution, there are bound to be potential safety issues that could be caused. The component test plan will outline a strategic approach for testing individual components in isolation, verifying their functionality, behavior, and interactions within their defined boundaries. The goal for testing these components is to prevent failure and the user can move around the habitat unharmed. Table 5-2 shows preliminary test plans for each component. Once a preliminary test plan is assembled, a lead will develop strategy documents and an official test plan. Testers will develop test scenarios and test cases.

Table 5-2: Preliminary Component Test Plan

Components	Component Test Plan
Wall	<ul style="list-style-type: none"> • FEA
Rocks	<ul style="list-style-type: none"> • Material of rocks will be tested with tensile compression testing • Force implemented at realistic angles • Vary infill percentages and shapes
Pulley System	<ul style="list-style-type: none"> • Setting up different pulley systems with varying pulleys • Applying a known weight • Measuring weights • Calculating mechanical advantage
Bosun Chair	<ul style="list-style-type: none"> • Visual inspection of seat, suspension lines, safety lines, hardware (carabiners, D-rings) of wear, damage, corrosion • Functionality check- test of ascent/descent and locking mechanism under load • Anchor point assessment • Suspension line check • Safety regulations and guidelines followed

NASA will give the team specific requirements about the habitat after the CDR presentation. From there the team can continue with a requirement analysis, modify test planning/specifications, and test implementation. All tests will be recorded and documented. Once the test is verified and passed, the test will come to completion. Table 5-3 expresses potential safety issues with each component.

Table 5-3: Potential Safety Issues

Potential Safety Components	Specific Safety Issue
Wall	<ul style="list-style-type: none">• Wall material cracking
Rocks	<ul style="list-style-type: none">• Handholds cracking• Handholds rotating
Pulley System	<ul style="list-style-type: none">• Auto belay failure• Auto belay tangling• Rope failure (fray/break)
Bosun Chair	<ul style="list-style-type: none">• User falling through harness• Harness failure• Twisting• Stuck mid-air
Other	<ul style="list-style-type: none">• User falling off wall• Rope burn• Blisters from pulling on rope• Head collision on ceiling• Missing step when dismounting from chair or wall

Risk Management

The team has done FEA analysis for all components listed above. This concept will have required routine inspections. All equipment will be checked visually before each use and worn equipment will be repaired or replaced. FEA analysis of the selected plexiglass wall material shows how much force the wall can handle before failure and prevent the wall from potential cracks. Different rock handholds will be printed using different infill percentages and shapes to prevent failure from of the applied forces. Testing different rock handholds will give the team knowledge of the lifecycle of the rocks before needing to be reprinted and replaced. To prevent rock rotation, every week the crew will check t-nuts and bolts behind the wall to ensure all hardware remains secured. Pulley systems will be present for both the rock wall and bosun chairs, the team selected auto belays that can withstand the weight of an astronaut with their suit plus any cargo that is needed to be moved across the habitat. To prevent rope tangling, the crew will visually check to make sure the rope is not tangled before use. Other safety features such as carabiners prevent

rotation in rope movement. The rope will also be checked visually before each use to prevent a possibly of breakage during use. Auto belays and a harness will prevent the user from falling off the wall. A padded mat will be at the base of the wall in case of incident. The crew will wear high grip gloves to prevent from rope burn and increase grasp on rock wall elements. Before use of this design, the crew will be fully trained. This prepares the crew of the surroundings of the full design and prevent issues such as head collisions on the ceiling or misstep when dismounting. Table 5-3 expressed the issues the team is expecting to see; however, the team understands other issues may become present. Other issues that may occur will have to be approach based on the situation. All identified issues will be tracked and reported during component testing.

Preliminary Design Concept

In summary, a combined design that includes a climbing wall and a mechanical elevator, in the form of a bosun chair, is the best solution to this complex problem. This solution will not only help increase their physical activity and therefore decrease bone density and muscle mass loss, but it will also promote friendly competition in the habitat which will decrease boredom and increase motivation among the inhabitants. It also allows for a unique and novel climbing experience by taking advantage of the low gravity environment to create climbing hold combinations that aren't possible on Earth. Through various trade studies, the materials of each component of this combined design have been chosen, and the specifics of each component, like thickness of the wall, infill percentage of each handhold, etc. will be optimized by following each component test plan. Finally, all potential risks that have been brought up, and any additional risks that arise, will be minimized by following the component test plans and risk management plans.

Feedback

The team presented the current PDR design to NASA on December 4th, 2024. The

comparison of the three vertical mobility techniques—elevator, bosun chair, and the bike-based "vycle"—was well received, with enthusiasm for the vycle concept. If weight was not a consideration, the “vycle” (short for vertical bike) idea would have been a new creative idea. From the PDR design, the team included trade studies of how many rock walls are going to be put in the habitat, location of the four-rock wall structure, and if the rocks are going to be placed inside or outside of the central shaft structure. Originally, the decision to have four walls in the PDR design was to ensure that each crew member had their own wall. Each member would have their own wall and have two different options (rock wall or bosun chair) to move up the habitat. This would ensure safety within the crew. With the structure being a four-wall central shaft, the structure would be equidistant from everything in the habitat. And if the team decided for the rocks to be on the inside of the four-wall central shaft, then the crew would have the ability to jump from wall to wall on the inside of the shaft. However, incorporating four auto belay systems for each wall would need more consideration and risk management. Also, having a central shaft with four walls and four bosun chairs would be heavy, take up a lot of usable space in the habitat and block line of sight in the habitat. Blocking the line of sight in the habitat would make the habitat feel much smaller increasing mental ware.

NASA favored the fuzzy skin material for the exterior surface of the 3D printed rocks because of the desirable properties such as grip and durability. The team included visuals of the gyroid structure as it appears in prints, along with a description of the gyroid’s internal structure and its functional advantages, such as strength-to-weight optimization and flexibility. The team plans to do crush tests, method used to evaluate the resistance of a material compressive forces until significant deformation/failure, and profilometry scans, method to determine surface profile or topography of an object, for multiple 3D printed rocks. Furthermore, the Critical Design section will include these key assessments to evaluate material integrity and surface characteristics in

greater detail.

On the software side, a health detection system is being considered, with the innovative idea of embedding it into wearable technology – potentially in a piece of clothing or through a concept similar to a Fitbit. A Fitbit would reintegrate the heart monitoring system into the Critical Design Review, as it remains a valuable feature for tracking physical exertion. Additionally, a programmable scoring system is being proposed that incorporates a start/stop timer and difficulty modifiers based on levels. For instance, a Level 4 rock wall could feature a 1.25x score multiplier, adding a competitive edge to the system and motivating users to challenge themselves.

CRITICAL DESIGN REVIEW

Critical Design Concept

Incorporating as many concerns from the Preliminary Design Review as possible, the team developed a new design that they believe offered significant improvements. This design consisted of two rock walls and two bosun chairs.

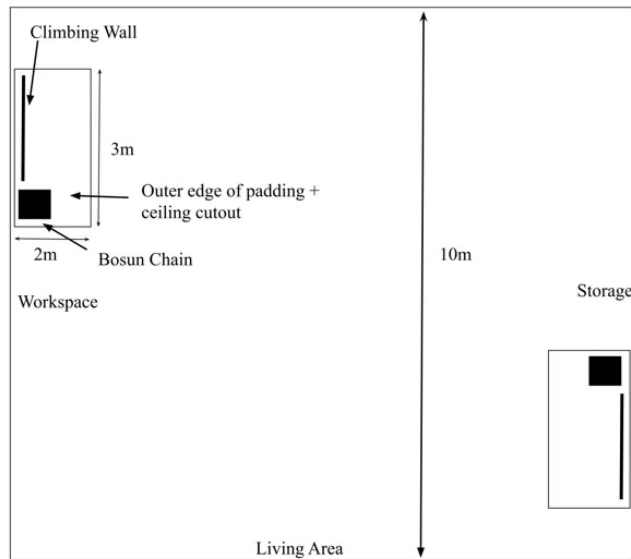


Figure 6-1: Revised Habitat Layout

As shown in the Figure 6-1, the rock wall is now flat against the wall of the habitat with the bosun chair just to the side of it. Additionally, the two structures are placed on opposite walls of the habitat. This design opens up the central area, allowing astronauts to see across the habitat while preserving more usable space. While maintaining the accessibility value of the previous design, it also increases safety by eliminating the risk caused by having multiple auto-belay systems in close proximity. One concern that was that each astronaut would no longer have access to both a wall and bosun chair at any given time. Since there are four modes of transportation (two walls and two chairs), each astronaut would always have a way to ascend and descend, though the available method might not be their preferred choice. The team came to the conclusion that the reduction in weight and safety risks outweighed this potential minor inconvenience.

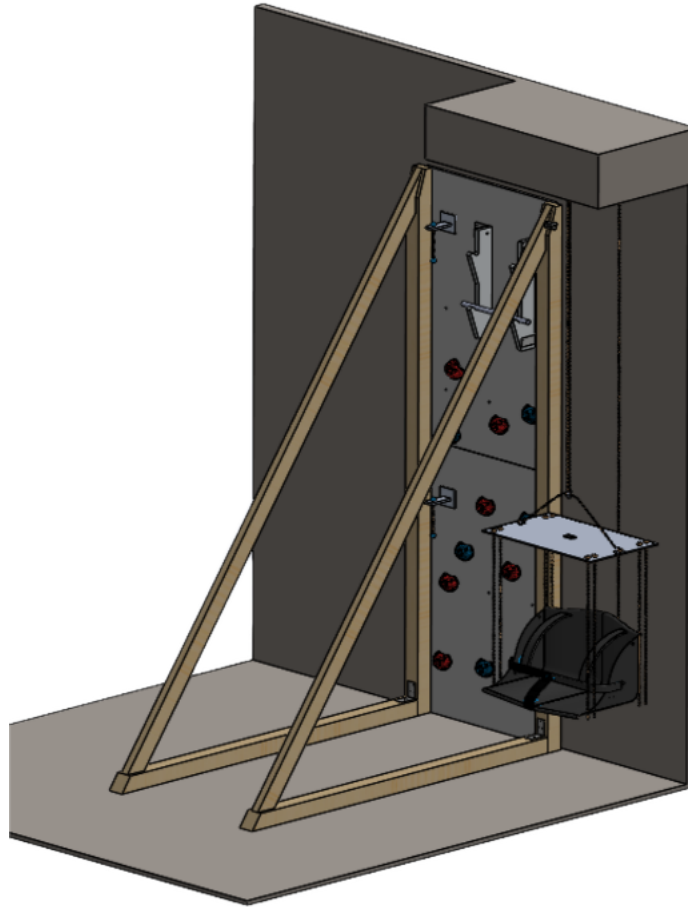


Figure 6-2: Final CAD Design

Rock Wall Revisions

Since the wall is no longer part of the shaft structure, the team designed supports as seen in the figure above that would keep it from falling over. Figure 6-3 shows that supports consist of a triangular truss shape places on either side of the wall.

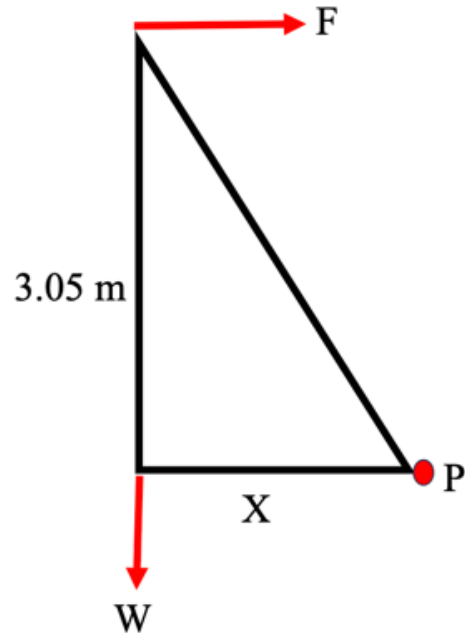


Figure 6-3: Supports Diagram and Calculations

Calculation 1 shows the momentum equation to determine the horizontal length (X) of the truss.

(1)

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Another difference from the previous design is the variability of paths. Rather than constantly having to rearrange rocks, the team investigated different ways to customize routes. This design incorporates different colored rocks that determine different paths. Each color would be dedicated to a certain path that has a predetermined difficulty. These rocks would be secured to the wall using standard bolts. Each rock is also equipped with a light. The system can randomly generate a path and light up the rocks that make up that path, guiding the user visually.

Bosun Chair Revisions

The team has received a carbon fiber chair as a gift from another team and now considering using it as the seating component for the bosun chair. Originally, the plan was to construct a simple wooden plank seat with a padded cushion, but this unexpected gift presents a new opportunity and a few new challenges as well. The carbon fiber chair has several key advantages over the original wooden design. First, its material is both lightweight and extremely strong, which is ideal for supporting the user while suspended. Carbon fiber is known for its high impact resistance and durability, meaning it is unlikely to crack or deform under load, which enhances safety. Its ergonomic, molded shape also provides a more comfortable seating experience compared to a flat wooden plank, reducing strain during use. Additionally, because the chair is a single molded piece, there are no joints or fasteners that might weaken over time. Although our chair was molded, carbon fiber can also be 3D printed in space. This could be printed in space, like the rocks, making it easily repairable and the replacement materials would be easily storable. There is also potential for research to be done to figure out how the current particles on the Moon and Mars could be used to print this material. Another advantage is aesthetic: the chair has a professional and clean look, which may benefit the project in presentations or evaluations. It also saves the team build time and materials, since the chair is ready-made and doesn't require sanding, cutting, or finishing like wood would have. However, there are some downsides. The shape of the carbon fiber chair might not integrate perfectly with the existing rigging design, which was tailored for a flat plank. The team may need to engineer custom attachment points or reinforcement areas to secure the chair safely. Carbon fiber can also be slippery, especially if smooth, so the team might need to add grip tape or padding to prevent the user from sliding. Additionally, although strong, carbon fiber can be prone to stress cracking if drilled improperly, so any modifications must be done with care. In

comparison, the original wooden seat concept had the advantage of simplicity and full customizability. It could be easily drilled, cut, and adjusted for rigging, and padding could be added exactly where needed. However, wood is heavier and may not have matched the durability or comfort level of the carbon fiber chair in the long run. Overall, the carbon fiber chair offers a durable and ergonomic alternative to the wooden seat, but it will require thoughtful adaptation to ensure compatibility with the bosun chair rig. With the proper modifications, it has the potential to elevate both the safety and user experience of the project.

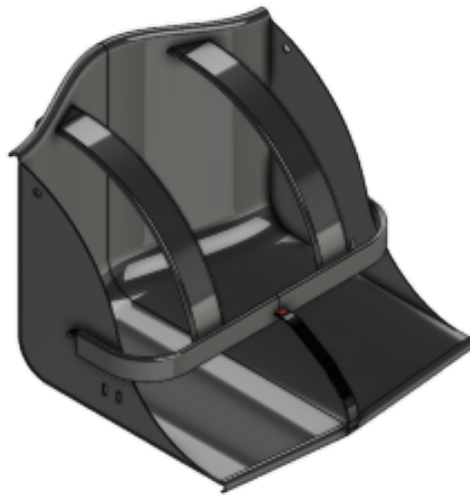


Figure 6-4: Bosun Chair CAD Model

Force Sensors

One of the key components that will be used to measure the astronaut's health will be force sensors. These can either be embedded into rocks on the climbing wall to measure dynamic climbing forces, or they can be a separate system used to measure other dynamic forces like vertical jumping. The force exerted by a human when jumping is approximately five times their body weight. To accurately measure force data in this range, the Piezotronics PCB 208C04 force sensor was chosen, and it can be seen below in Figure 6-5.



Figure 6-5: Piezotronics PCB 208C04 Force Sensor

This sensor can measure forces up to 1000 pounds which is a little more than the forces that are being expected in this project. Before being sent into space, the astronauts can collect data using these force sensors on Earth to generate a baseline number for their jumping/climbing forces to compare future data to. The force data that is collected when the astronauts are in space will be analyzed and compared to the Earth data to see how their physical fitness is changing. If the force data is lower, that could mean that they are losing muscle mass and need to train more. If the force data is higher or the same, that means that they are maintaining their muscle mass and need to continue doing what they are doing. To collect the data, the force sensors will be connected to the data acquisition system of choice. The DAQ that was chosen for this project is the MCC USB-202 DAQ and it can be seen in Figure 6-6 below.



Figure 6-6: MCC USB-202 DAQ

This DAQ was chosen because it can be powered by a laptop and can directly interface with the force sensors. The cables that were chosen to connect the force sensors and the DAQ are the Piezotronics Model 002C10 and they can be seen in Figure 6-7 below.



Figure 6-7: Piezotronics Model 002C10 Cable

These cables were chosen because they have the needed connectors on the ends, and it is more than enough length for the teams' needs. Finally, the DAQ will be connected to a laptop running the needed software, like LabVIEW, to view and analyze the data. The data gathered from these xsensors can be used together with the other fitness metrics, like heart rate and time to climb the wall, to develop a better understanding of why their metrics might be changing the way they are.

Software

Arduino is a software and hardware package that can be compatible with a power supply, timing module, Bluetooth, and wearable devices like Fitbit due to its modular, open-source design and support for industry-standard communication protocols. For power supply, Arduino boards like the Uno R3 can operate on 5V from USB or use an external 7–12V DC input, with onboard regulators managing stable voltage which makes it adaptable for both portable and stationary applications. Timing modules can be created by using the software's built-in counter 'millis', and displayed on an LCD display, which Arduino IDE software supports natively through the downloadable LiquidCrystal library. This makes it simple to maintain accurate timekeeping, log sensor data with time stamps, and display any information on the LCD screen. Bluetooth modules, especially HM-10, connect via Arduino's TX and RX pins and are supported with extensive example code and libraries. These modules allow Arduino to communicate wirelessly with smartphones or other Bluetooth-enabled devices through apps like terminals that send and receive

information to the board. For wearable integration, while Fitbit is a closed platform, data from it can be accessed indirectly using Bluetooth Low Energy modules, allowing Arduino to act as a relay or companion device. This enables features like step count tracking or heart rate monitoring to be integrated into larger system. A diagram is shown below with each module being used and the plan of attack to wire each module to the Arduino.

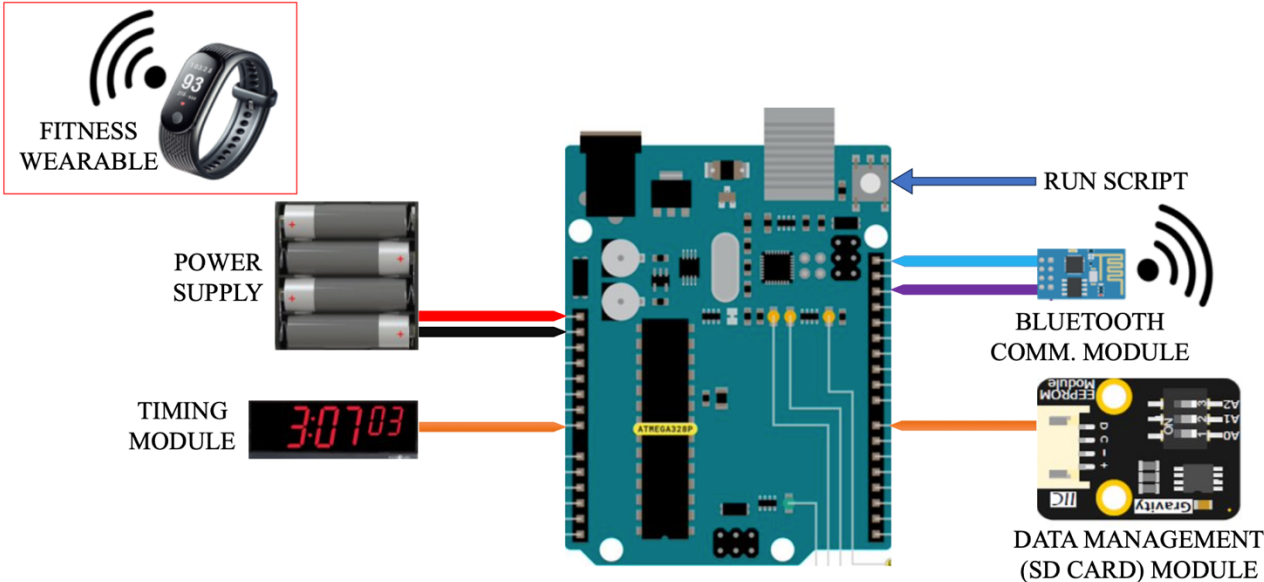


Figure 6-7: Functional Wiring Diagram

Timing Module

An LCD display is a valuable addition to timing applications using the Arduino Uno R3 due to its ability to provide clear, real-time visual feedback. For example, a common 20x4 character LCD allows users to display the current time, countdowns, or elapsed intervals which makes it ideal for stopwatch projects. When paired with a real-time clock module or timing loop through code, the LCD can continuously show accurate time information, creating a functional stopwatch. Most LCDs come with an I2C interface, which simplifies wiring by using only two data pins and frees up the Arduino's limited I/O pins for other modules like Bluetooth or sensors. Integration is straightforward thanks to widely available libraries such as LiquidCrystal_I2C, which allow easy customization of what is shown on the screen. LCDs are also power-efficient and cost-effective,

making them ideal for both portable and stationary setups. Additionally, their ability to display multiple lines of text allows developers to include status messages, prompts, or sensor data alongside timing information. Overall, the LCD provides an accessible, user-friendly, and flexible interface for time-based Arduino projects. The LCD display is what the team decided to move forward with.

Bluetooth Module

The BLE (Bluetooth Low Energy) module is a highly efficient and user-friendly option for wireless communication in Arduino-based projects, especially those focused on low-power and wearable applications. Modules like the HM-10 or the built-in BLE support in the ESP32 allow the Arduino to connect with modern smartphones, tablets, or other BLE-enabled devices with minimal energy consumption, which is essential for battery-operated systems. One of the main advantages of BLE is its ability to maintain reliable communication while using significantly less power than classic Bluetooth, making it ideal for continuous data transmission in health monitors, smartwatches, or fitness trackers. From a development perspective, BLE modules are supported by well-documented libraries and examples, and they integrate easily with the Arduino Uno. With a simple serial communication setup, developers can quickly send and receive data. BLE is also designed to be user-friendly on the end-user side, devices pair quickly and often automatically, without requiring constant manual reconnection. This seamless interaction makes BLE modules especially suitable for projects that require frequent, low-energy updates, like syncing data from a wearable device to a smartphone. Through extensive research, BLE has proven to be an easy-to-use and highly compatible module for both Arduino integration and the health monitoring aspect of the project. With the BLE, the team will be able to communicate the information to be stored in a SD card and create health profiles for everyone.

An LCD display is a valuable addition to timing applications using the Arduino Uno R3 due to its ability to provide clear, real-time visual feedback. For example, a common 20x4 character LCD allows users to display the current time, countdowns, or elapsed intervals which makes it ideal for stopwatch projects. When paired with a real-time clock module or timing loop through code, the LCD can continuously show accurate time information, creating a functional stopwatch. Most LCDs come with an I2C interface, which simplifies wiring by using only two data pins and frees up the Arduino's limited I/O pins for other modules like Bluetooth or sensors. Integration is straightforward thanks to widely available libraries such as LiquidCrystal_I2C, which allow easy customization of what is shown on the screen. LCDs are also power-efficient and cost-effective, making them ideal for both portable and stationary setups. Additionally, their ability to display multiple lines of text allows developers to include status messages, prompts, or sensor data alongside timing information. Overall, the LCD provides an accessible, user-friendly, and flexible interface for time-based Arduino projects. The LCD display is what we decided to move forward with.

Fitbit Module

The Fitbit Inspire 3 offers a range of health and fitness tracking features in a compact, lightweight, and user-friendly design, making it ideal for everyday use and wellness monitoring. One of its key benefits is its ability to continuously monitor heart rate, providing users with insights into their resting heart rate, heart rate zones during workouts, and overall cardiovascular health. The Inspire 3 also tracks steps, distance, calories burned, and active zone minutes, helping users stay accountable to daily fitness goals. In addition to physical activity, it includes tools for stress management such as guided breathing sessions and a stress score based on heart rate variability. Sleep tracking is another strong feature, offering detailed breakdowns of sleep stages, light, deep, and REM along with a sleep score to help improve sleep quality over time. The device also

monitors blood oxygen levels and skin temperature variation, providing a broader view of overall health trends. With its long battery life of up to 10 days, comfortable fit, and integration with the Fitbit app, the Inspire 3 makes health tracking accessible, consistent, and informative for users of all fitness levels. By monitoring all of these health factors, the user’s activity and fitness level and overall health can be assessed so that adjustments to their daily regimens can be made to ensure long term health. This is especially important in low-gravity environments where astronauts need to be routinely monitored to ensure bone and muscle levels remain at a healthy level.

Tying all the modules together should allow for a timing aspect to increase the competitive nature and track progress, a wearable health monitor tracking fitness metrics, a Bluetooth module to communicate that information from the Fitbit, and an SD card to store the data. Below is a block diagram of the fully integrated system.

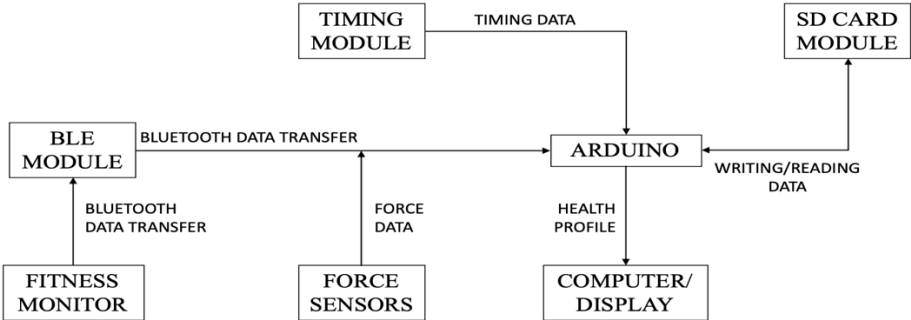


Figure 6-8: Software Block Diagram

Feedback

The team completed the Critical Design Review (CDR) design and submitted it to NASA on February 21st, 2025. The CDR incorporated major improvements over the Preliminary Design Review (PDR), specically in weight reduction and cost savings. The revised design has reduced the overall structural weight from approximately 1500 kg to 750 kg and has lowered the estimated cost from \$ to \$. Another cost-cutting effort is the donation of a carbon fiber chair by yet another senior design team.

In terms of surface design, the fuzzy skin setting has proven effective in increasing grip difficulty and realism by randomly varying the outer layer's thickness during printing. Side-by-side comparisons clearly demonstrate the increased challenge of gripping the standard print versus the fuzzy skin version. The concept of integrating dynamic lighting around rock features has also been positively received, adding an interactive and possibly functional element to the climbing environment.

OPERATIONAL READINESS REVIEW

Build

Materials

After creating a CAD model and materials plan for the project, the team made a list of materials. The main wall frame was built using 2x4 and 4x4 pieces of lumber for strength and stability, connected with wood screws and bolts. Lumber added an element of simplicity to the design due to time constraints and lack of necessary components. In space, this frame could be made from aluminum to reduce weight, or the attachments could be fully integrated into the wall to eliminate these components. For the base, the team used strong 5' x 3' x 3/8" polycarbonate panels, choosing them over acrylic because they are safer and more durable. The carbon fiber seat of the bosun chair was connected to the structure and pulley system using rope and other connectors. The materials were purchased and ordered from a variety of vendors. A summary of cost can be found below in Table 7-1.

Table 7-1: Cost Summary

	Rock Wall	Bosun Chair	Software	Miscellaneous
Cost				
Total				

A full breakdown of the materials and cost can be found in Appendix C.

Construction

The team spent several weeks building the prototype rock wall system, closely following CAD designs and project plans. Early on, the team mapped out where to place the rocks and how to set up the bosun chair support to make everything work efficiently.

In the first week, they built the base structure and framework using bolts and screws to ensure stability. Each 4x4 base support was secured through simple application of corner brackets that resisted the moment induced by any weight positioned on the wall. After the simple L shape frame the 2x4 supports were placed connecting the 4x4 at the top of the wall and the front edge of the 4x4 laying on the ground. This system ensured that if any weight was applied on the front side of the wall the supports would resist any moment forces induced in the structure. They also planned the details for rock placement and the bosun chair's support system.



Figure 7-1: Frame Assembly

During the second week, they first painted the supports for both looks and protection. Then as the supports were drying the team drilled holes in the polycarbonate panels to allow for any thermal expansion and prepare them for mounting to the wall. After the paint finished drying the full support system was assembled and the polycarbonate sheets were attached.



Figure 7-2: Initial Wall Assembly w/o Attachments

In the third week, they started 3D-printing handholds using PLA material with a 15% gyroid infill for strength and grip. To mount the bosun chair to the structure a side frame was needed as there is no habitat roof for the pulley system to attach to. The team planned and built this side structure through a system of 4x4's and corner brackets. Alongside the building of this structure the team also mounted the racing style harness to the bosun chair as well as plan the path that the supporting ropes would take around the chair.



Figure 7-3: Side Frame Assembly

By the fourth week, the team had finished the bosun chair's pulley system, making sure the rope attachments were strong and reliable. They also completed printing all the hand and foot holds.



Figure 7-4: Top Plate of Bosun Chair



Figure 7-5: Pulley System for Bosun Chair

In the fifth week, the bosun chair was fully installed, and climbing features like rope holds and alternate grips were securely attached to the wall.



Figure 7-6: Full Wall and Bosun Chair Assembly

Finally, the team created instructional and demonstration videos to teach users how to use the system safely and effectively. Throughout the entire process, keeping everything working together smoothly remained the team's top priority.

Testing

Rocks

Fuzzy Skin

The use of the fuzzy skin setting while preparing the rocks to be 3D printed adds a much-needed texture to the parts. Figure 7-1 and Figure 7-2 are a normal rock and a fuzzy skin rock, respectively. The impact that fuzzy skin has is evident. The smoothness of a normal rock makes it difficult to grip. If any handholds are not easy to grip, the crew risks injury and will be less efficient when using the wall.

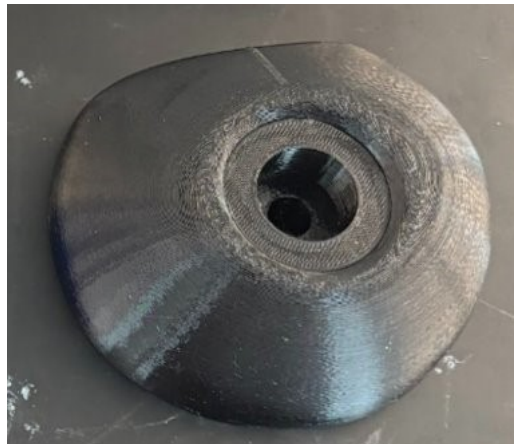


Figure 7-7: A Rock Printed with Normal Settings

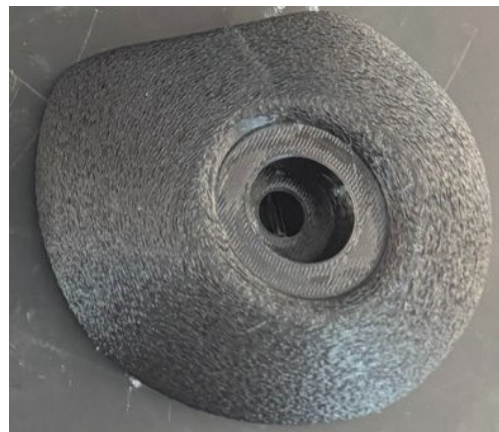


Figure 7-8: A Rock Printed with Fuzzy Skin

The exact extent of the changes to the rock's geometry can be quantified. To accomplish this task, a scanning white light interferometer was used. This metrology device is extremely accurate at measuring the topology of a surface. White light is applied to an object. Light from the

object then passes through a beam splitter and becomes a reference beam and a measurement beam. The reference beam travels along its unique path while the measurement beam travels along the surface. The beams recombine and the interferometer measures the light intensity with a specialized camera.

Compression Test

To determine the best combination of material, infill pattern, and infill density, compressive tests were performed. PLA, PETG, and TPU were the materials compared. Gyroid and 3D honeycomb were the infill patterns compared. Infill densities of 10% and 15% were compared. The same rock model was used in each test. The machine crushed the rocks by moving a flat plate down on the rock at a specified rate and measured the force and displacement. The rate used was 1 mm/min, as this was the best rate for compressive testing plastics according to the American Society for Testing and Materials [34]. The 3D honeycomb TPU prints were not tested on the advice of the student employee helping with the experiment, as the results would be very close to the already obtained values. The tests were stopped at 6 kN, because that is the most loading a rock will experience. This value was obtained based on what Dr. Zabala, the professor who runs the Biomechanical Engineering lab, said the maximum load could be [35]. Figure 7-9 shows a rock during the test, and Figure 7-10 shows the same rock after its test.



Figure 7-9: A Rock During the Compressive Test



Figure 7-10: A Rock After the Compressive Test

Software

During the software testing phase of the project, the team worked on connecting the Arduino with various modules to meet the goals of the rock wall system. This involved integrating hardware components and troubleshooting issues to make sure all parts could communicate reliably. Code was written to create a stopwatch feature that accurately measured and displayed a user's ascent time, including start, stop, and reset functions to track multiple climbing attempts. Additional code was developed to control the lighting system, which illuminated different climbing routes on the wall by activating specific light paths based on user selections or preset patterns. Fitbit data was captured by a device using Bluetooth, allowing the collection of health and activity data during a climb. All code can be found in Appendix D. To test this functionality, a Fitbit was worn during several days of activity, and the recorded data was analyzed to determine the accuracy and usefulness of the health profiles generated. This testing helped ensure the system could effectively track both climb performance and astronaut fitness over time..

Results

Rocks

Fuzzy Skin

A contour map can be produced from the results of the tests described above. This method is better than other metrology methods, such as stylus profilometry. However, one of its limiting features is that an object made with multiple materials will produce inaccurate results. The rocks that were scanned were made with the same material, so this was not an issue [33]. When viewing the height maps, the uniformity of the normal print is in stark contrast to the randomness of the fuzzy skin print, in Figures 7-11 and 7-12 respectively. The normal print's heights range from .04 mm to -.061 mm, while the fuzzy skin print's heights range from 0.14 mm to -0.18 mm. This randomness gives the rocks texture, making them better handholds.

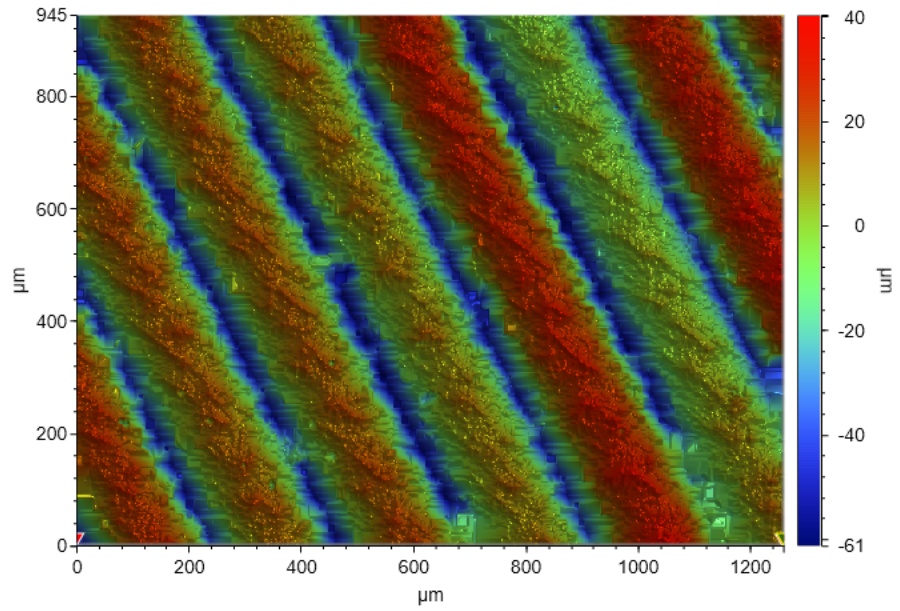


Figure 7-11: Height Map of a Normal Print

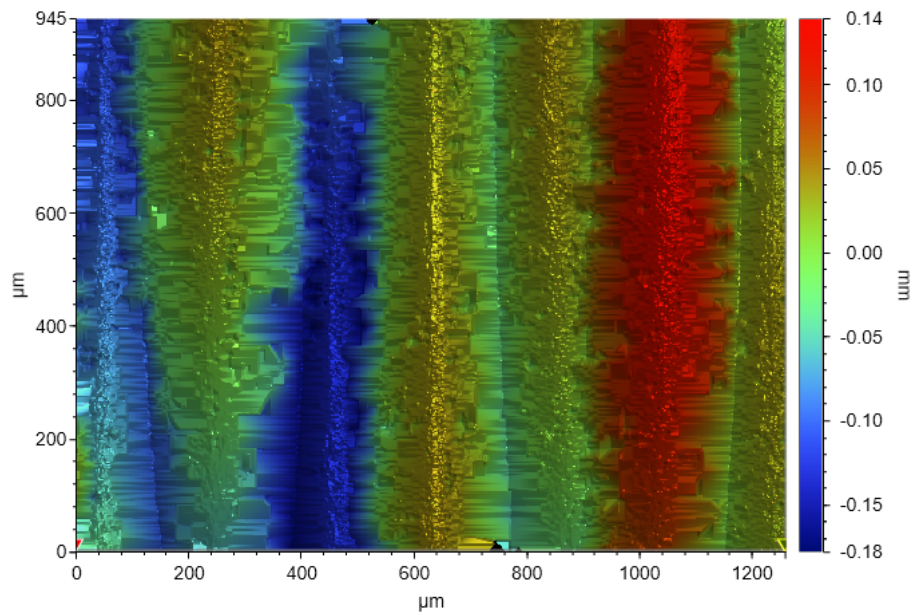


Figure 7-12: Height Map of a Fuzzy Skin Print

The difference can also be seen in a plot of the height maps. Figure 7-13 is a normal print, and Figure 7-14 is a fuzzy skin print.

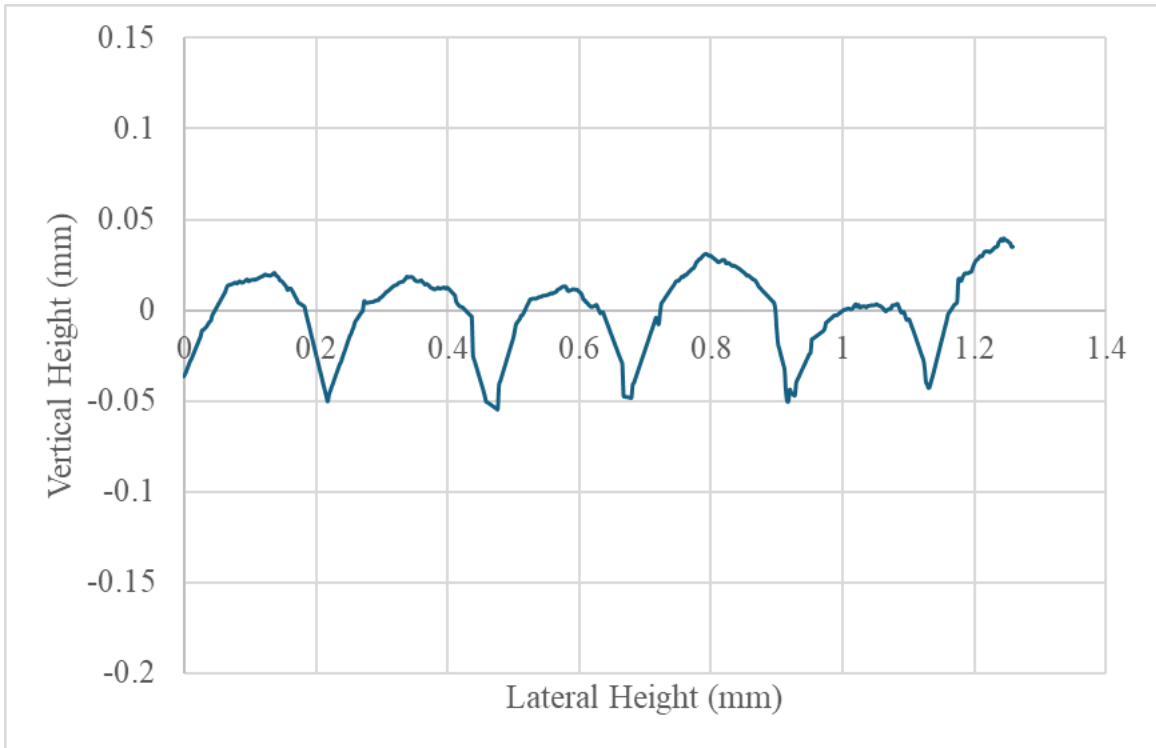


Figure 7-13: Normal Print Height Plot

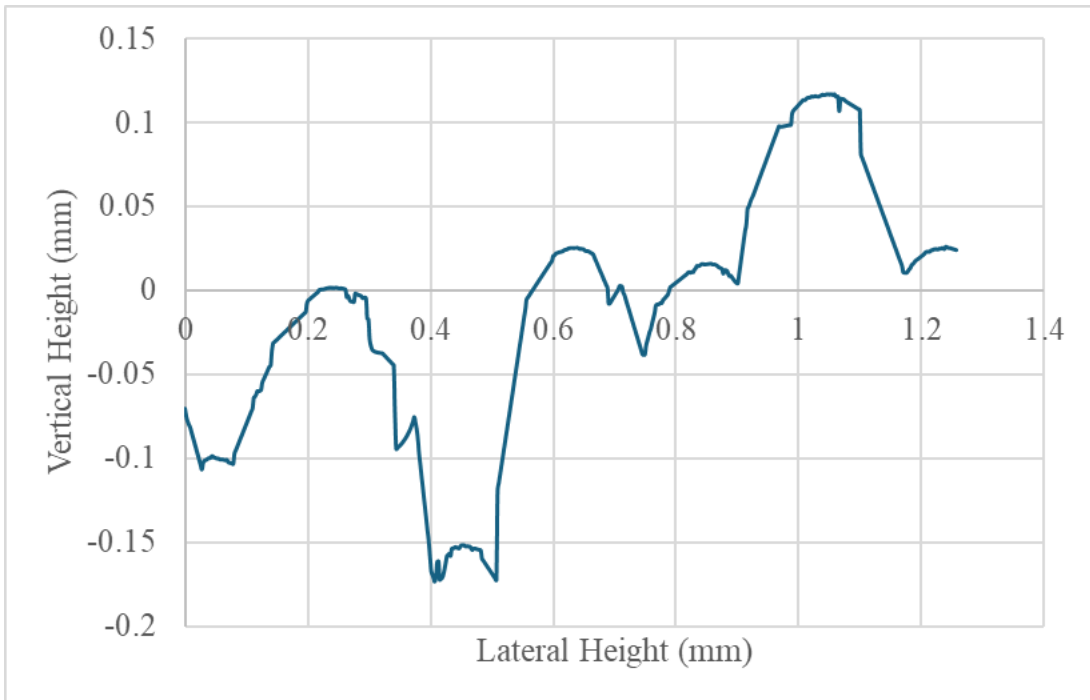


Figure 7-14: Fuzzy Skin Height Plot

Compression Test

The chosen combination for printing the rocks for the wall was PLA with 15% gyroid infill based on the results presented below. It was the most rigid, which is important for rock climbing, and supported the necessary load. TPU was ruled out as a suitable material because of how much it deformed without supporting much force. PETG would have been a viable material, but PLA proved to be more rigid. The results of the different tests can be seen below.

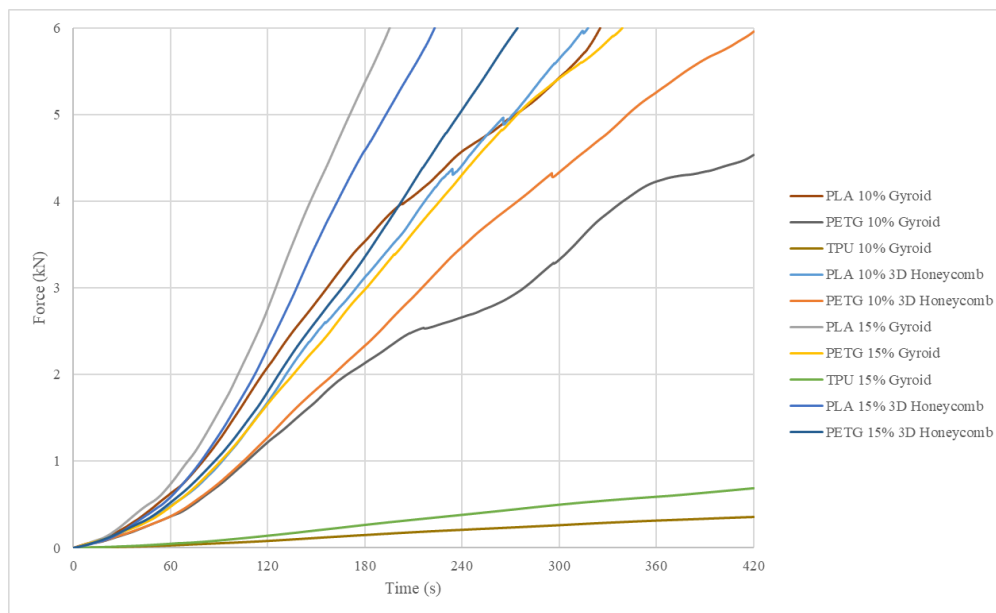


Figure 7-15: Compressive Test Results

Software

The figures below show proof of concept tests completed on a breadboard setup. The stopwatch code was able to start, stop, and reset the timer as expected (Figure 7-16). The lighting code successfully lit up a specific LED, showing that individual routes or holds on the rock wall could be highlighted (Figure 7-17). The Bluetooth code gave the Arduino Bluetooth capabilities that would allow it to connect with the Fitbit (Figure 7-18). The Fitbit was able to track and detect changes in heart rate, sleeping patterns, activity levels, energy consumption, stress, breathing rate, blood oxygen level, and body temperature.

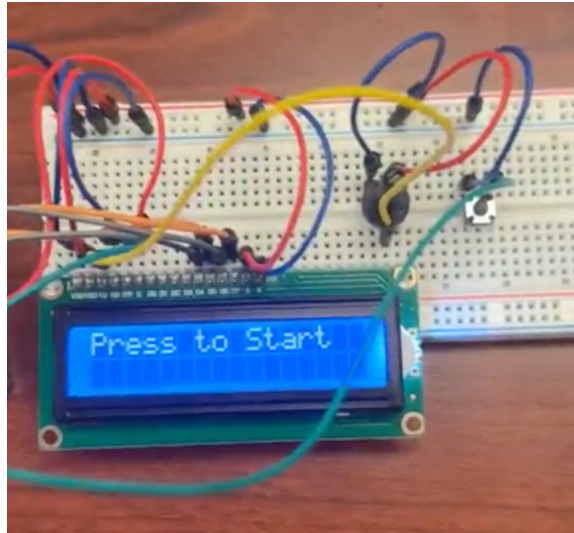


Figure 7-16: Timing Module

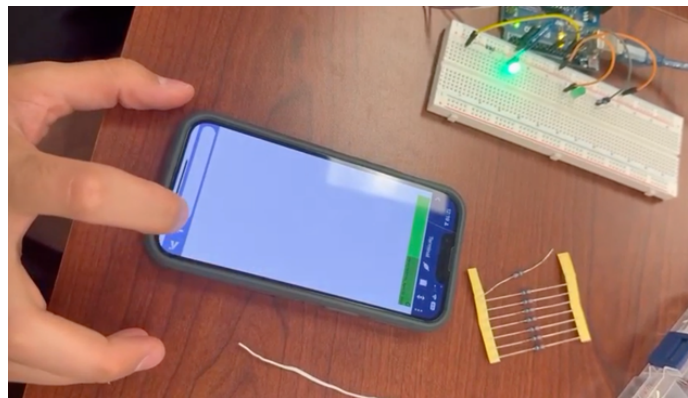


Figure 7-17: Light Responding to Command

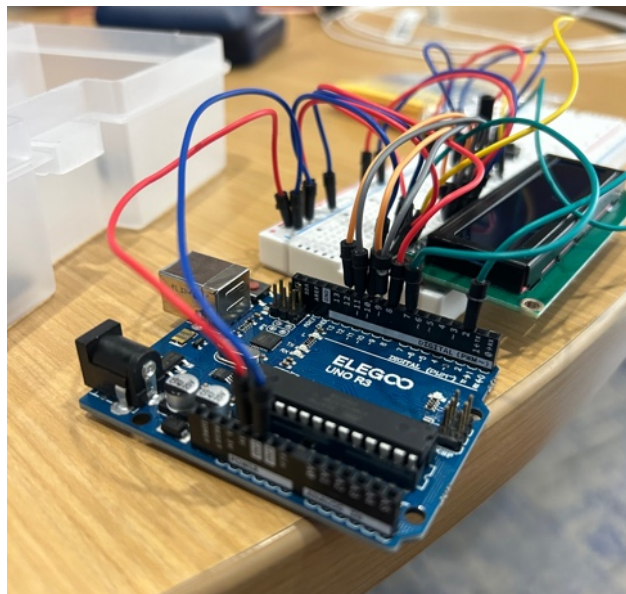


Figure 7-18: Bluetooth Module

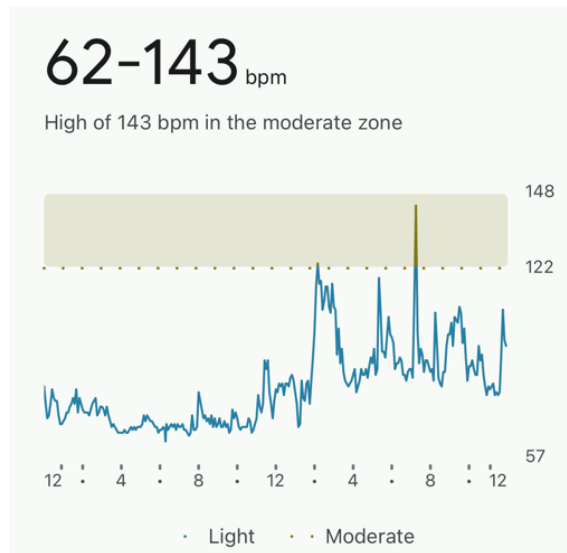


Figure 7-19: Heart Rate Tracker

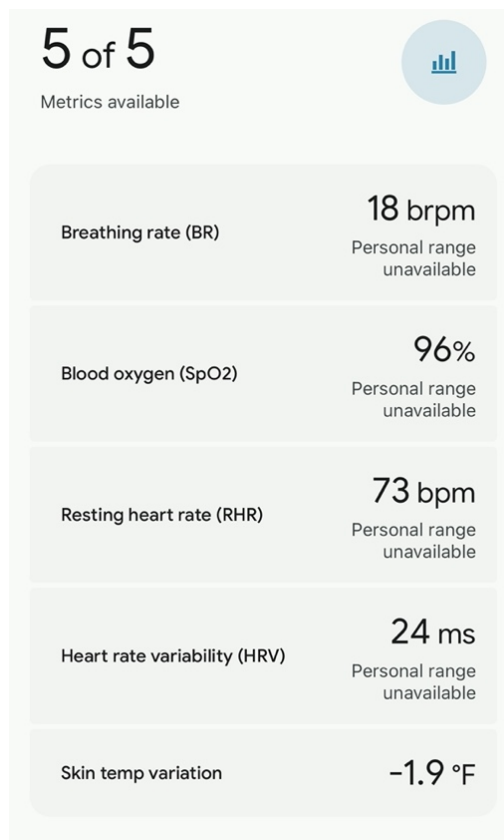


Figure 7-20: Select Health Metrics

Conclusion

Based on the results of the tests, it is clear that using the fuzzy skin setting for 3D-printed climbing rocks has a positive impact. The added texture makes the rocks easier to grip, which is

important for safety and performance. Surface scans showed that the fuzzy skin rocks had more surface variation compared to the smoother, harder to grip normal prints. This extra texture helps prevent slipping and makes climbing more secure.

In the compression tests, the combination of PLA with 15% gyroid infill performed the best. It was the most rigid and could handle up to 6 kN of force without deforming, which meets the expected maximum load. While PETG was also a strong material, PLA had better rigidity. TPU was not a good option because it bent too much and couldn't support as much force.

The software testing also went well. The team connected the Arduino to different components like LEDs, a stopwatch, and a Fitbit using Bluetooth. The stopwatch could start, stop, and reset as expected. The lighting system worked by highlighting specific routes, and the Fitbit was able to track useful health data like heart rate and activity levels.

Overall, the tests showed that the climbing wall system is strong, reliable, and functional. The fuzzy skin setting improved grip, PLA with 15% gyroid infill provided the necessary strength, and the software added useful features for both performance and fitness tracking.

CONCLUSION

Objective

The objective of this project is to conceptualize and evaluate novel crew mobility modalities that leverage the reduced gravity of the Moon (16.5% of Earth's gravity) and Mars (38% of Earth's gravity) to enable efficient, safe, and engaging vertical and lateral movement within space habitats.

Conclusions

In environments with lower gravity such as the Moon and Mars, traditional Earth-type mobility techniques may not be optimal. Instead, reduced gravitational forces allow for possible alternative movement techniques—such as jumping, climbing, swinging, and pole-supported transport—that on Earth are typically unsafe or impractical. These kinetic forms of mobility can be easily integrated into daily activities and provide steady aerobic and musculoskeletal conditioning without the necessity of separate exercise sessions. Such traditional architectural elements as staircases may be a waste in such settings, being space-consuming, adding unnecessary bulk, and excluding physical effort in typical movement. Therefore, structures of the habitat must be engineered to specifically address the new means of mobility in order to maintain safety and building integrity while ensuring healthy movements patterns. Along with this, wearable sensors need to be incorporated to monitor health and performance in real time and over long durations continuously, to enable responsive re-adjustments and long-term crew well-being.

Constraints

Key design limitations for mobility systems within low gravity habitats are space, user protection, accessibility, and overall reliability over time. Space and weight constraints within the habitat require all mobility solutions to be small, light, and as minimally invasive as possible so they do not interfere with other essential systems or living areas. Crew safety during dynamic

motion is of utmost importance, requiring designs that allow for controlled, stable motion and reduce the risk of injury in novel gravitational environments. The systems must also be intuitive and adaptable, capable of accommodating a wide range of physical abilities, body types, and strength levels to accommodate use by all crew members. Finally, maintainability and durability are essential because the equipment must work reliably over long-duration missions and endure the special challenges of low-gravity conditions, including dust exposure, hostile temperatures, and limited access to repair equipment or replacement parts.

Probable Causes of Experiment Uncertainty

In reduced gravity environments, there are various sources of uncertainty that are considered in order to obtain accurate evaluation and reliable performance during the development and testing of mobility systems. During development and testing, the following sources of uncertainty must be considered: human variability, Earth-based gravity simulation limitations, sensor inaccuracies, material performance deviations, environmental influences, and physiological state.

Human variation is one of the key issues since variability in body structure, strength levels, and behavior among crew members can lead to inconsistent usage patterns and outcomes. Furthermore, with testing the team's final design on Earth, Earth-gravity simulations have intrinsic constraints and cannot accurately simulate the Moon/Mars's gravitational environment. This leads to model and experimental inaccuracies. Sensor systems, either worn or part of the habitat, can further suffer from calibration drift, low resolution, and data transmission errors, all of which can impair the quality of data collected. Material performance differences are another issue, such as properties as grip, friction, and mechanical life can differ in unpredictable ways with changing gravitational loads and environmental conditions. Furthermore, environmental factors like lunar dust, temperature fluctuations, and patch illumination can affect sensor performance and human perception, complicating mobility operations. Lastly, psychological state of crew members – like

stress, tiredness, cognitive load, and motivation – has a high likelihood to affect mobility efficiency and safety, both affecting user performance as well as interpretation of experimental results.

FUTURE GOALS

Due to the delayed start in constructing the final CDR design, the team will be unable to complete all the originally planned tasks within the available time frame. If the project progresses, the team plans to fully integrate all Arduino modules into a cohesive system, incorporate a data synchronization and evaluation system, program LED climbing paths, and create an instruction manual.

Arduino Module Integration

All Arduino modules will be fully integrated into a unified system architecture. This consolidation ensures seamless data communication between subsystems, allowing for efficient processing and storage of information relevant to each climb session.

Data Synchronization and Evaluation System

The fitness wearable data, timing module, and force sensor inputs will be synchronized within the Arduino-based system. This integration enables a comprehensive evaluation of each climber's performance, including metrics such as heart rate, duration of climb, and force exertion on holds. By processing these data sets collectively, the system provides a holistic view of user activity and can be used for performance assessment and comparative analysis.

Climbing Path Visualization

To enhance user experience and guidance, LED lighting will be implemented along the climbing wall. These lights will highlight preset climbing paths, allowing users to easily identify and follow designated routes. This feature not only improves safety and accessibility but also allows for dynamic training or competitive climbing scenarios.

Instruction Manual Development

A detailed instruction manual will be created to support the operation of both the bosun chair and the climbing wall system. The manual will include step-by-step guides for setup, usage instructions, safety procedures, and maintenance recommendations. It will also feature visual diagrams of climbing path options and chair configurations to ensure clarity and ease of use for all users and operators.

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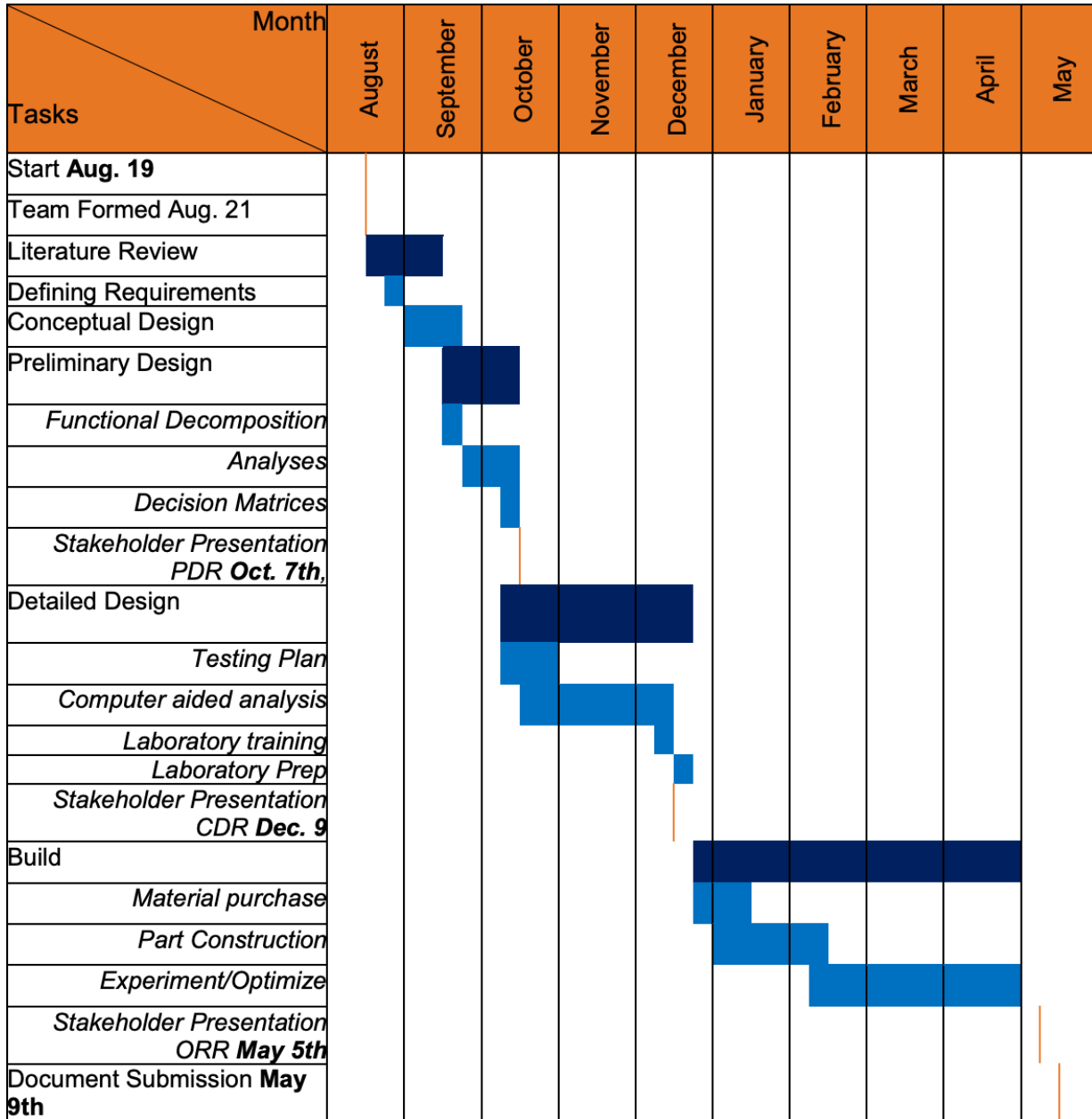
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APPENDIX A

GANTT CHART



APPENDIX B
ASSEMBLY COMPONENTS

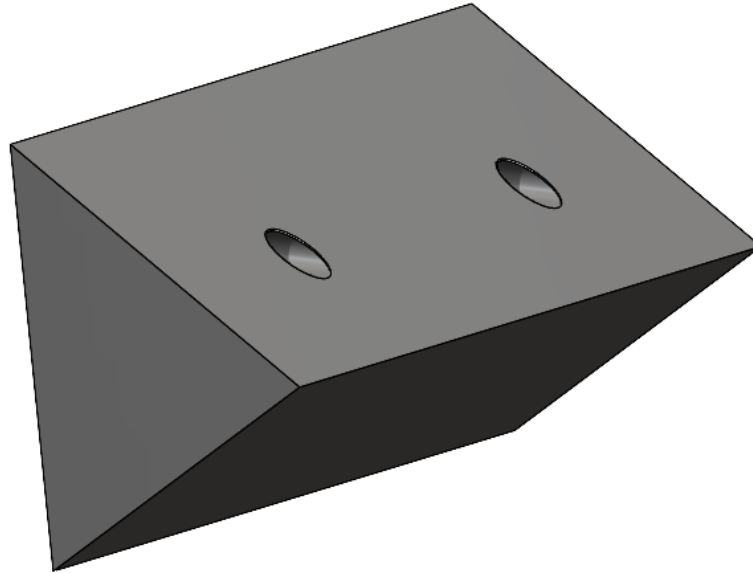


Figure B-1: Wedge Handhold

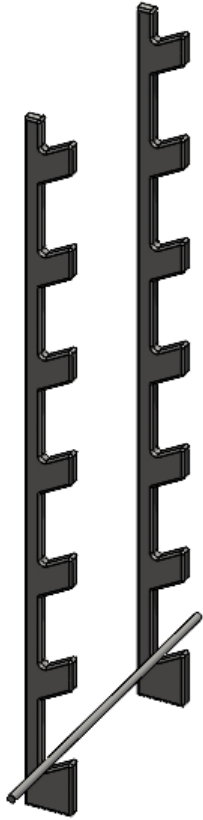


Figure B-2: Salmon Ladder

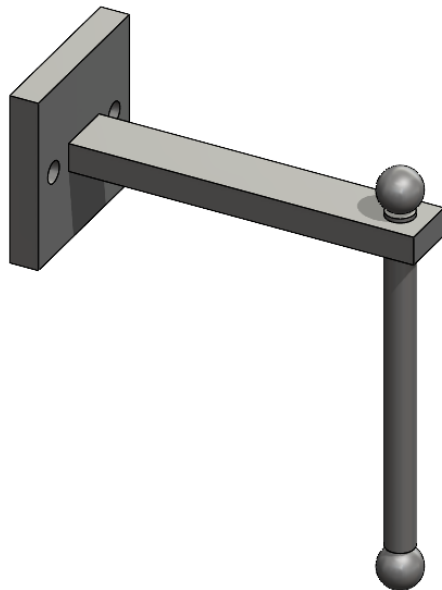


Figure B-3: Rope Handhold

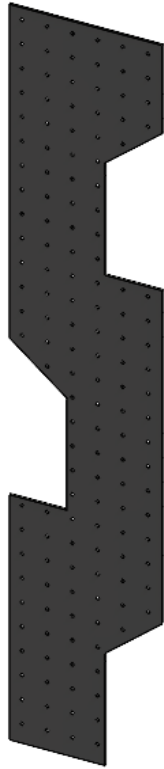


Figure B-4: Rock Wall

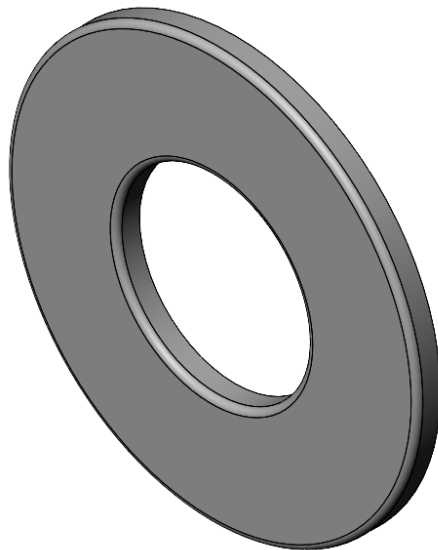


Figure B-5: Washer for Handhold



Figure B-6: Bolt for Handhold

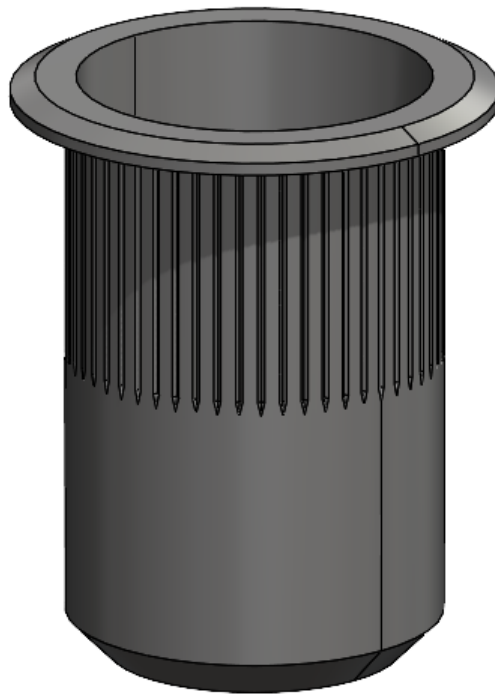


Figure B-7: Rivet Nut



Figure B-8: Rock Handhold

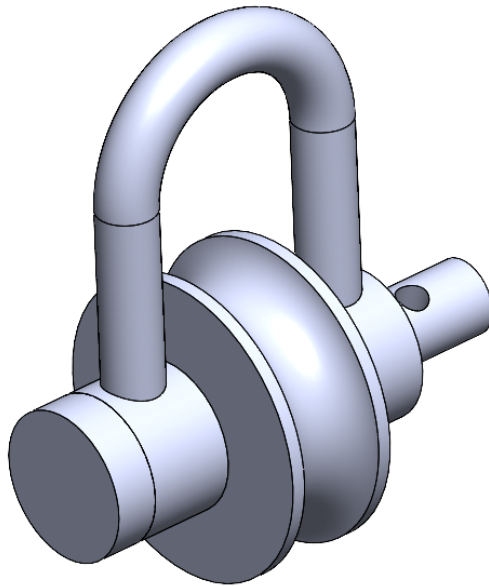


Figure B-9: Top of Bosun D-Ring

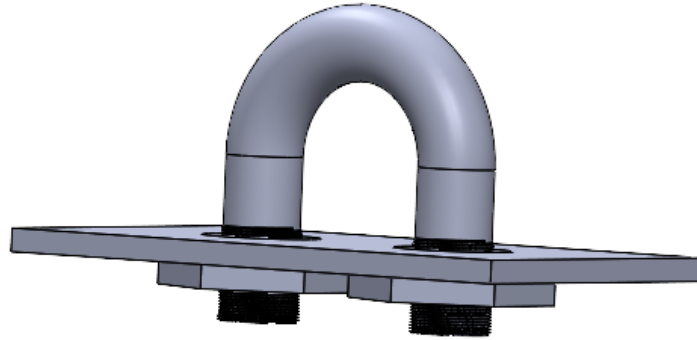


Figure B-10: D-Ring for Top Plate

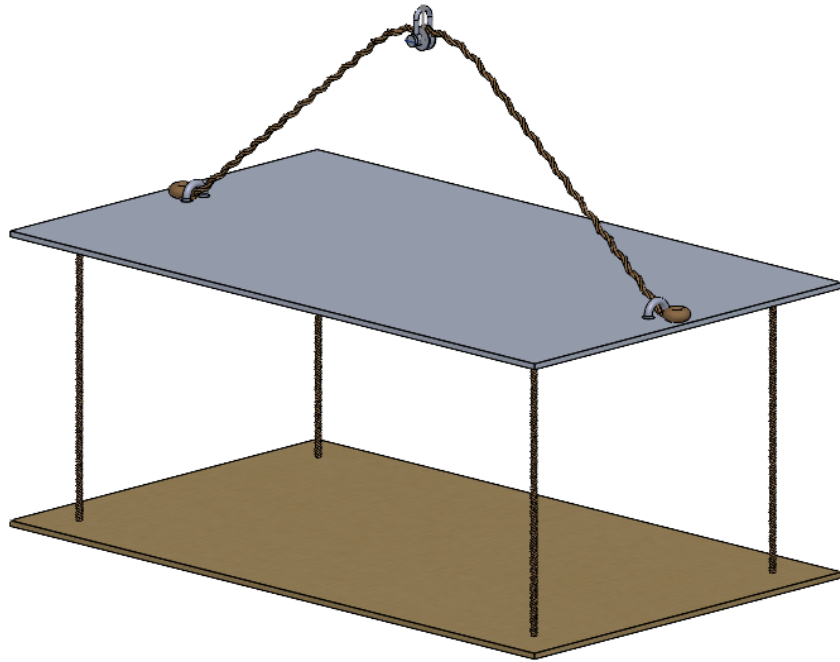


Figure B-11: Bosun Chair Assembly

APPENDIX C

MATERIALS AND BUDGET

Table C-1: Rock Wall Materials

ITEM	UNIT COST	QUANTITY	COST*
Salmon Ladder			
Rope Hand Hold			
Polycarbonate Sheet			
Total Cost			

Table C-2: Bosun Chair Materials

ITEM	UNIT COST	QUANTITY	COST*
Belay Clip			
Climbing Rope			
Pulley Block			
Safety Seatbelt System			
D-Rings			
Rope Fitting			
Total Cost			

Table C-3: Software Materials

ITEM	UNIT COST	QUANTITY	COST*
Fitbit Inspire 3			
Bluetooth Low Energy Module			
Arduino UNO Rev3 Kit			
SD Card Module			
ICP Force Sensor			
DAQ Cables			
DAQ Cables			
USB-202 12-Bit DAQ Module			
Total Cost			

Table C-4: Miscellaneous Materials

ITEM	UNIT COST	QUANTITY	COST*
Tarp			
2" x 4" x 8' Lumber			
2" x 4" x 16' Lumber			
4" x 4" x 10' Lumber			
Foam Crash Pad			
5" Bolt			
3" Bolt			
Wood Screws			
Washers			
Nuts			
Corner Bracket			
Offset Bracket			
Bolts			
Navy Blue Spray Paint			
Orange Spray Paint			
Total Cost			

* Cost column accounts for taxes and fees that were added in the purchasing process.

APPENDIX D

ARDUINO CODE

Bluetooth LED Path Lighting Code

