Spring 2023

Space Force Design Project

Emily Greene
emg102@uakron.edu

Ashton Orosa
avo3@uakron.edu

Julia Patek
jp188@uakron.edu

Nathan Doty
ntd72@uakron.edu

Space Force Design Project

SENIOR DESIGN

MECE 471

HONORS PROJECT

MECE 497

By

1. Nathan Doty ---------------- Nathan Doty
2. Emily Greene -------------- Emily Greene
3. Ashton Orosa -------------- Ashton Orosa
4. Julia Patek ------------------Julia Patek

Faculty Advisor: Dr. Ajay Mahajan

Honors Advisor: Dr. Scott Sawyer

Honors Reader 1: Kayla Dremann

Honors Reader 2: Motaz Hassan

Dept. of Mechanical Engineering
College of Engineering
University of Akron

May 2023

Abstract

This report includes the details of a proof-of-concept project. The project was to set up a lab-scale piece of a spacecraft hull with attachments that can be scanned, then test if a small robot can accurately traverse the hull. For simplicity, the project was split into three main parts: the hull with attachments, the mobile robot, and the gripper that attaches the 3D scanner to a robotic arm. All parts were of equal importance in achieving success for this project and, as such, are explored in depth in the report. This project consisted of background research, design, manufacturing, testing, and an assessment of future improvements for all three aspects. Overcoming many obstacles in the design, build, and testing phases, the project was successfully completed. This is promising for the future of robots being able to identify and repair damage on spacecraft hulls while still in orbit. Detailed future improvements conclude this report to assist in the continuation of this research project.

Contents

1. Introduction

In 2003, a 1.7-pound chunk of thermally protective foam flew off the space shuttle "Columbia" during its launch. The loss was noted by ground control and reported to program management, who decided there was little they could do about the loss. The mission itself was a resounding success until atmospheric reentry. The loss of foam allowed excess heat to enter the spacecraft, catastrophically damaging its systems and resulting in the loss of its entire crew of seven. This famous spacefaring disaster has been studied and modeled since its occurrence, with analysts debating to this day what could have been done to prevent the destruction of the Challenger [11].

One potential manner of preventing or mitigating such disasters in the future is using autonomous in-orbit spacecraft repair. Using robotics, it could be possible to make repairs on spacecraft during missions while they are still in space, as opposed to waiting for them to land. A recent grant to the university from Space Force/AFRL attempts to start a feasibility study for this. The Space Force project consists of three different teams – a mechanical engineering team, an electrical engineering team, and our senior design team (under the oversight of the professors involved with the project).

The scope of this senior design project is to develop the lab-scale test apparatus, and does not entail the development of the algorithms, the source code, or the overall testing.

While the sponsor and intended user of the team's research is the U.S. Space Force, autonomous spacecraft repair has potential implications beyond just the Space Force, and even beyond the United States. The ability to repair spacecraft while on-mission with little to no human intervention could change all of space travel, making it safer and more cost-effective than ever before.

1.1 Objectives

As previously mentioned, this project is part of a larger grant awarded to UA from USSF/AFRL to develop a platform for potential repair of spacecraft when in-orbit. The work is divided into four main categories:

1. Identification of the defects using 3D scanning
2. Path planning to get a mobile robot to the defect and back

3. Optimized fixing of the defect
4. Communication for all aspects of the project

This senior project is a subset of task 2. The objective of this project is to create a testbed for a curved surface representing a spacecraft hull. This curved hull will then be scanned with a 6-degree of freedom robotic arm and a 3D scanned reference of the hull will be created. The algorithms and other complexities of the 3D scanning will be handled by a team of graduate students. Damage will then be added to the hull so the new scan can be compared to the reference 3D scan and a designed mobile robot can be equipped to fix or view the damage. This testbed and data will be used by various University of Akron graduate students for further research projects outside the scope of this senior design project.

The research objectives of this hull testbed are to learn about various aspects of spacecraft materials and designs. These were used to determine designs for the simulated hull and what type of failure modes would be needed. Research was also done on mobile robots and how a robot capable of traversing a metal surface, and other surfaces, would be created. After the research was completed, the goals needed to complete the project were determined and are listed below.

1. Design a 3-foot-wide by 2-foot-long curved, simulated spacecraft hull (or a few such hulls) that replicate the surface of a spacecraft. This hull should be able to hold its own weight, as well as that of the mobile robot. To accurately simulate a spacecraft, different materials and attachments should be tested.
2. Create a gripper for a robotic arm to hold a 3D scanner, which can help detect defects in the hull of the spacecraft. The gripper needs to be both secure and lightweight, as the robotic arm is only rated to hold 1 kilogram.
3. Create a small, self-propelled mobile robot that can navigate the curved hull, avoid obstacles, and move to the site of the defect.

Since the team has limited machine shop skills, it was vital to make use of the assistance offered in the University of Akron machine shop. This was needed so that the various manufacturing processes were done efficiently and without significant waste.

The mobile robot used in this project was also developed during a robotics class the team took during the Spring 2023 semester. Due to this, the robot was primarily designed during the Spring 2023 semester and built rapidly, so tests could be performed before the project ended.

Once all goals and objectives were met, a video, report, and project poster were created to present the project to the university and others.

2. Design

To accomplish the objectives of this project, the design process was conducted for each element. To begin, background research was done for the hull and mobile robot as these elements are complex and additional information was needed before the conceptual design process could begin. Once the information was gathered, the brainstorming and conceptual design processes were applied to each element. Through these processes, multiple ideas were created and evaluated, using tools such as morphological charts and weighted decision matrices, to determine how best to fulfill the requirements of the project. Once a design was chosen, it was evaluated using a failure modes and effects analysis (FMEA) chart. This design process was conducted for each section of the project and is detailed in this section.

2.1 Background Research

Before the design process could begin, research was conducted to gain a better understanding of the project and possible solutions. Since a replica of a spacecraft hull was the basis of this project, a good understanding about the exterior of spacecraft was vital for an accurate representation to be created. Information about spacecraft hulls, including but not limited to the materials that comprise most modern spacecraft hulls, attachments that can be found on them, and common forms of damage, was obtained through research. Research was also conducted to determine how a mobile robot would traverse the surface of the hull. Since space is a vastly different environment, only specific solutions could be implemented. To determine and understand these solutions, research was conducted and used to create viable solutions for traversing the hull.

2.1.1 Spacecraft Hull

The harsh environment of space includes many elements that materials must be able to withstand. These environmental factors include temperature spikes, gravity, radiation, pressure, impacts, and vibrations [6]. The temperature inside a spaceship must stay around 77°F while space can range anywhere from -150 to 550°F [6]. The radiation levels in space are much higher than on Earth because Earth's atmosphere helps shield the surface from them so whatever material selected must be able to withstand higher levels of radiation [6]. Space debris is a huge problem and is continuing to become even worse. In space, a piece of debris can be smaller than a bullet and move ten times faster [4]. This means that materials need to be very strong to withstand being hit by space debris [6].

The cabin pressure from inside a spacecraft can exert 15 psi [20]. So, if the material being used is not able to withstand that pressure, it can be extremely dangerous. When the spacecraft is launched into space, it can experience up to three times the gravitational force experienced on Earth [20]. Therefore, the material must be sturdy enough to withstand the extra force. It is particularly important that any material, but especially the material on the outside of the hull, be versatile and strong enough to hold up against the hardships of space. For this project, it must also be strong enough to hold a small robot after attachments are connected and it has been purposely damaged.

Being able to withstand the elements of space means that the most important properties in materials are specific strength and specific rigidity. For control stability reasons, magnetic metallics are widely avoided. More commonly used are aluminum alloys and graphite-epoxy composites. Aluminum alloys are used when higher thermal conductivity is required. The most typical alloys used are A7075 and A2024. Magnesium would also be a good option except it needs extra care to prevent corrosion [18].

There are many different parts that can be attached to a spacecraft’s hull [8]. Many of these items are vital to its functionality. Some examples are antennas, thermal control boxes, power grids, windows, and communication technology [13]. With this project having a focus on the robot being able to move around the surface of the hull, and with size restrictions, adding antennas and windows became the main priority for attachments. The other spacecraft attachments are always on a spacecraft but can be tucked away in a housing unit made of the same material as the hull or be attached on poles that separate it from the surface [13].

At this moment, NASA is tracking more than 500,000 pieces of space debris [2]. This debris can move at incredibly fast speeds. This means that when one impacts another object in space, it can cause a lot of damage. These impacts are called hypervelocity impacts, and cause tears and holes. For example, a piece of debris that was one millimeter in size caused damage over 100 times that size [2]. So, the damage on a mockup hull would have to be made using a high impact and high velocity method.

2.1.2 Mobile Robot

The mobile robot for this project must be able to adhere to a curved piece of metal, with various obstacles, and traverse it. Some additional requirements of the adhesive are the ability to turn on and off so the robot can move across the surface, small preload force requirements, and the ability to be reused [1]. The system must also be able to be used in space which creates the necessity for an additional requirement. This requirement is the ability to survive the space environment, such as the extreme temperature range and vacuum [1]. Given these requirements, research for the mobile robot was focused on adhesion methods that would be applicable in space.

The extreme environment of space makes many of the methods used on Earth not viable options. For instance, suction-based grippers are commonly used on Earth to allow robots to grip surfaces. However, due to the vacuum environment of space, these cannot be used [1]. In addition, many adhesives commonly used on Earth, such as glue and tape, cannot be used in space due to the large temperature range [1]. Given these requirements, two viable options were considered: gecko adhesive and magnets.

Gecko adhesives are a biomimicry material that replicates the bottom of a gecko's foot [1]. Comprised of a fibrillar structure with millions of fine hairs, the gecko foot utilizes Van der Waals forces to adhere to a surface [1]. The setae, another name for these hairs, cling to the surface when the foot is pressed flush against it [21]. However, as the foot is lifted, and the setae are straightened, they unstick as the adhesive force disappears [21].

The technology to create synthetic gecko adhesives has advanced tremendously and this material has begun being used in space. In a study by Aaron Parness and his team [1], two adhesion technologies were tested: gecko-like adhesives and electrostatic adhesives. Both robots were tested in space and were successful in experimentation [1]. The robot with gecko adhesive used four gecko adhesive pads in a square formation and moved in an inchworm style [1]. A study by a team led by Xuyan Hou [21] also developed a robot that implements gecko adhesion for space-climbing. The robot designed in this study had 8 legs, each with a footpad equipped with gecko adhesive [21]. Through simulation, this robot was determined to be able to function in a zero-gravity environment [21].

Another potential adhesion solution is the use of magnets. While no studies verifying that magnets alone would work in space, the electrostatic adhesives used in the study by Aaron Parness and his team [1] were a combination of magnetics and gecko-like materials. There are, however, many instances of magnets being used to allow robots to climb walls on Earth. A robot capable of carrying a high payload up a convex surface was created by a team lead by Junyu Hu [5]. This robot made use of a tank style chain, with 26 magnets attached, to traverse a curved surface against the pull of gravity [5]. Another robot created by a team under Minghui Wu [7] can wall-climb via a non-contact magnet. By using a large magnetic sucker, that can be moved up or down to adjust the adhesion force on the wall, this wheeled robot is able to traverse a vertical wall [7].

Both magnetic and gecko adhesion are two viable ways to traverse a spacecraft hull in space. By researching these two methods, a greater understanding was developed and thus it was possible to evaluate which method would work best for this design. The expanded understanding of these adhesion methods also allowed for materials to be discovered and considered for implementation.

2.2 Spacecraft Hull

To begin the project, the original requirements given were a 2 ft x 1 ft curved hull, with attachments, that must be able to hold a robot walking on it and take on purposeful damage for testing. For the hull quality function deployment (QFD), the consumer needs are sturdiness, attachments, a sufficiently curved surface, and one that is small enough to fit on the corner of a table. The functional requirements are that it has a large surface area, can be damaged, and can be moved. The QFD is displayed in **Figure 1**. From the results of the chart, the brainstorming and design process was able to begin.

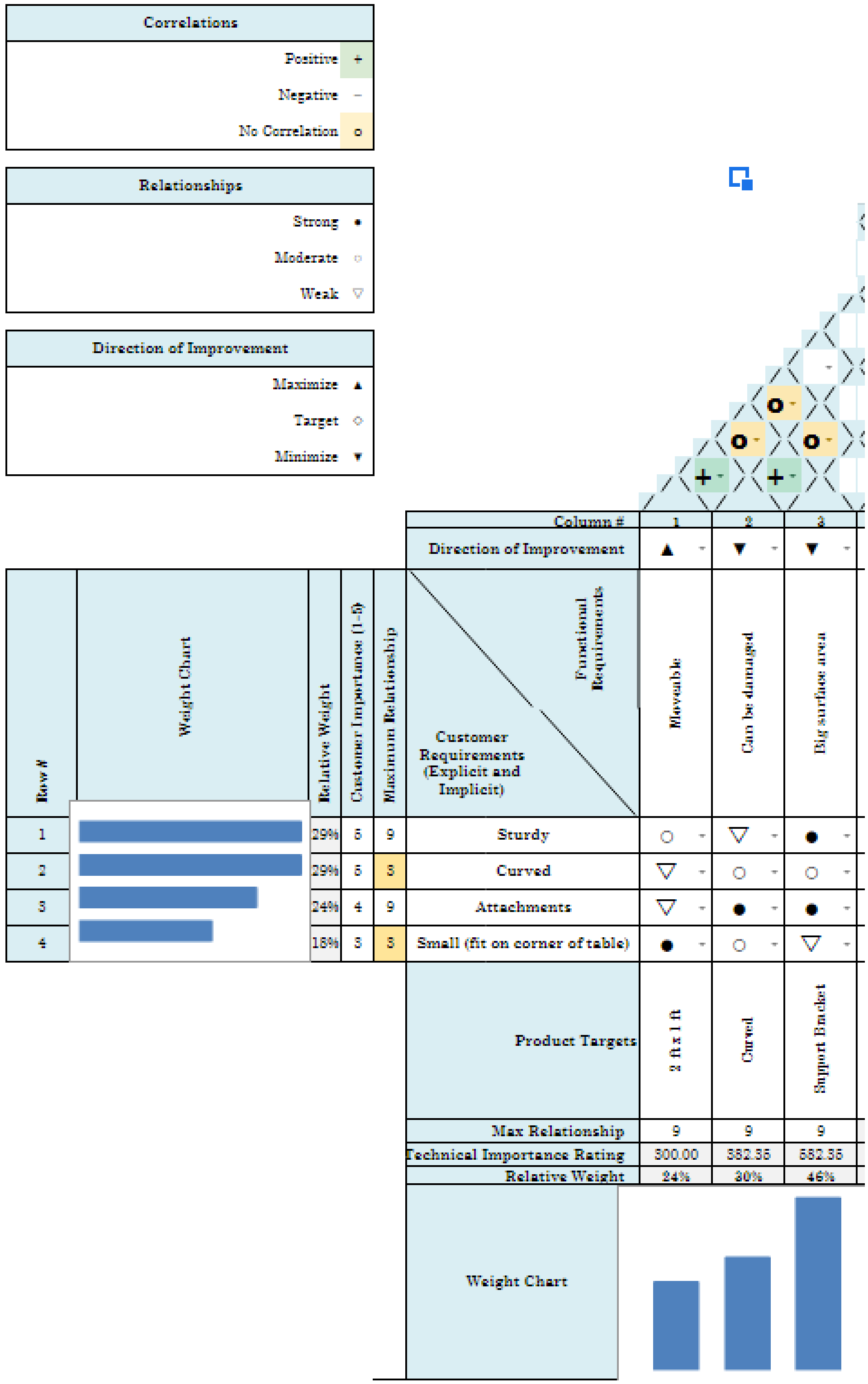


Figure 1: The quality function deployment for the hull.

The QFD shows that, for the hull, the support structure is the most important factor to ensure it can hold up the robot and the weight of the hull while curvature and size are the next most important elements. Based on this, multiple designs for the support structure were created to determine which would be best. Initially, three types of support structures were designed; however, it was determined that more should be created to choose the best design. The design in **Figure 2** would have X-shaped steel supports to hold together the back pegs while the hull itself would provide rigidity along the other direction of the support; the design might also require a bar to connect the structures together. The design in **Figure 3** is like the first design; however, the X support was removed. The last design, shown in **Figure 4**, would have curved supports where the hull rests, which is convenient, because the hull panel could then be riveted to the supports, creating a ridged support and an easier way to include rivets into the design. However, it would be difficult to manufacture the curved steel support structure precisely to the dimensions needed.

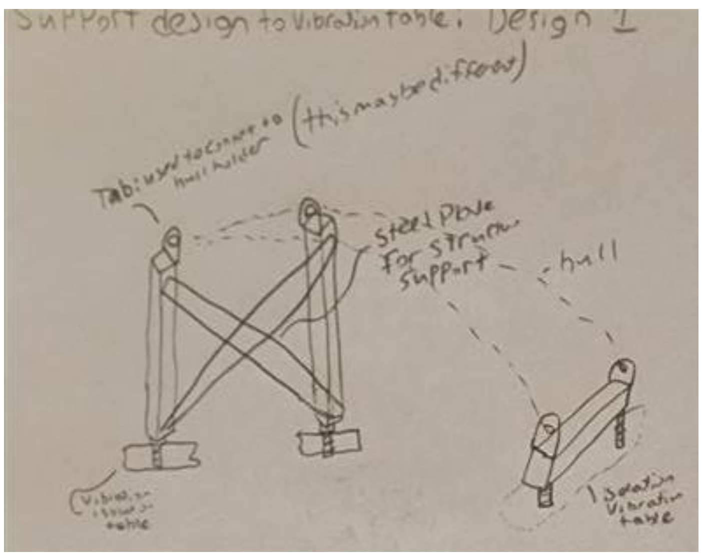


Figure 2: Shows an illustration of the hull support system design 1.

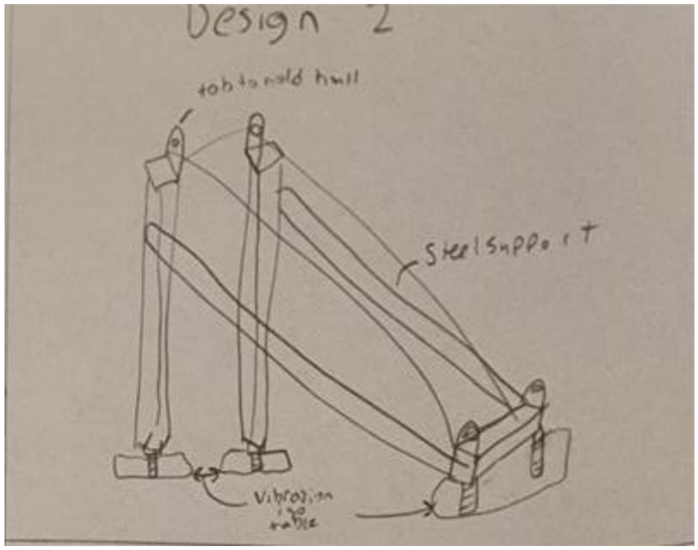


Figure 3: Shows an illustration of the hull support system design 2.

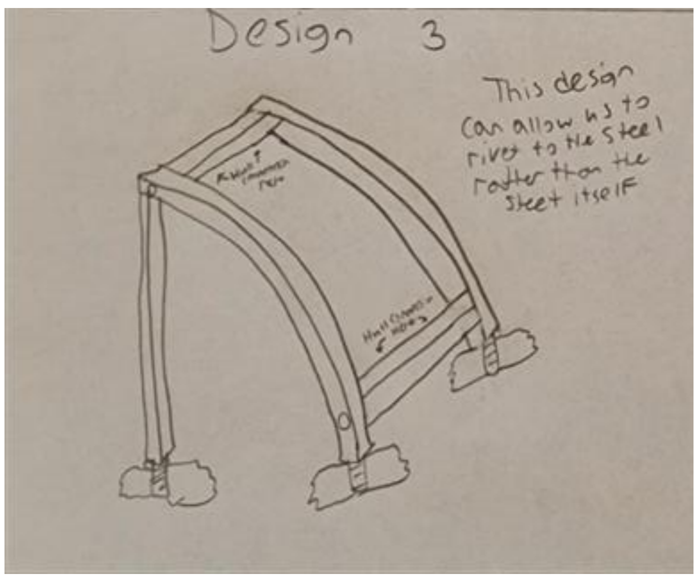


Figure 4: Shows an illustration of the hull support system design 3.

Another important aspect of the design was the inclusion of a way to hold the hull panel sheet to the hull support system, for which three different designs were created and are shown below. The design in **Figure 5** features a bolted design that has adjustability to make sure it can fit correctly on the table. This design would require holes to be drilled into the panel to insert bolts, and would have the highest stability of the designs. The design in **Figure 6** is a clamped set screw design in which the hull would rest in the clamp and set screws would be tightened to hold the hull panel. This design could come loose overtime and make it unstable. The last design, seen in **Figure 7**, would have a sleeve that could be made from metal or rubber to hold the hull. This design would be the cheapest and use the fewest resources but would be the least stable.

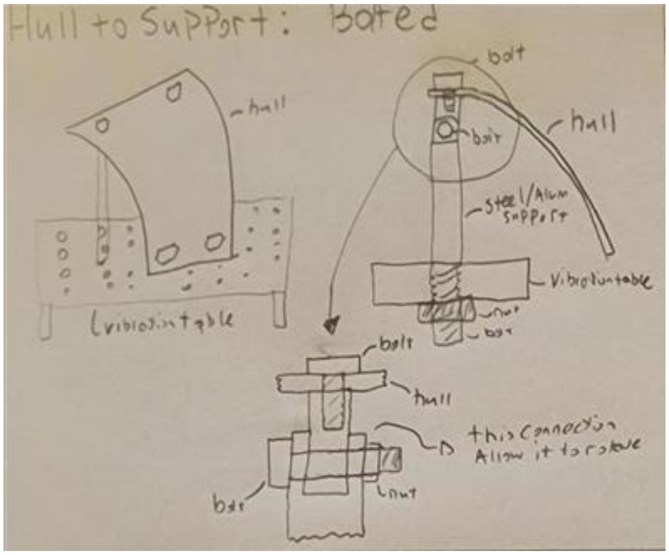


Figure 5: Shows an illustration of a bolted connection from the hull panel to the support.

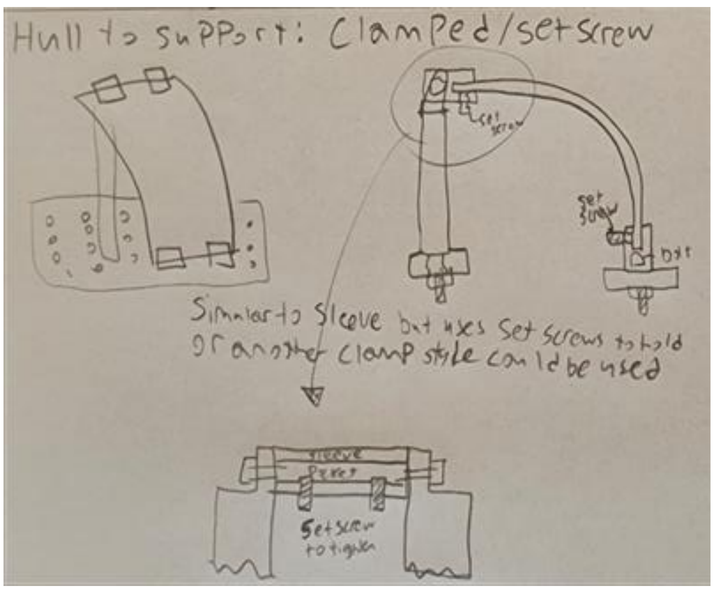


Figure 6: Shows an illustration of a clamp/set screw connection from the hull panel to the support.

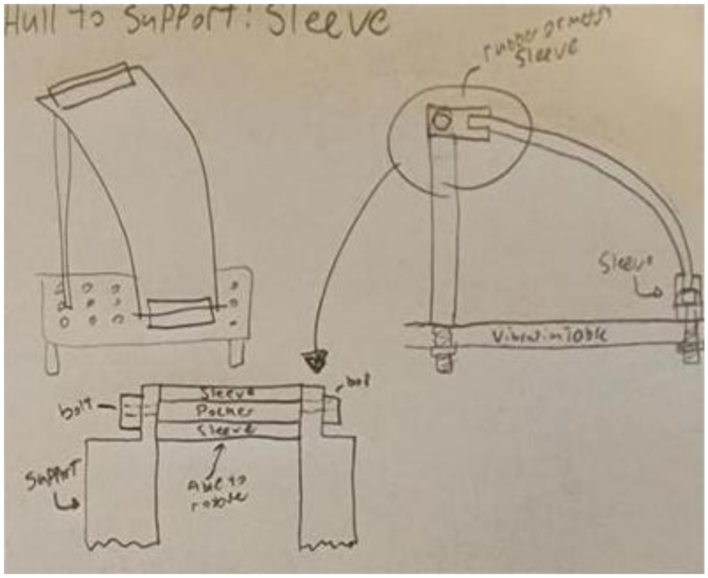


Figure 7: Shows an illustration of a sleeve connection from the hull panel to the support.

After multiple designs were produced, it was initially determined that multiple hulls were required to cover all necessary elements of spacecraft hulls. As such, the engineering constraints were updated to more accurately represent what was expected to be built and tested. A 12” x 24” hull consisting of four 3” curved pieces welded and riveted together with antennas, a 3” x 3” plexiglass window, and damages were required for the simulated hull. It would also have to be curved and strong enough to hold attachments and a robot. The three individual designs are explained in more detail.

Design A: aluminum hull 12” by 24” with 3” strips connected by either rivets or welding, no attachments.

Design B: aluminum hull 12” by 24” with 3” strips connected by either rivet or welding, with an antenna attachment.

Design C: aluminum hull with window, the window placed between two aluminum pieces. The aluminum pieces will have no rivets or welding and be 12” by 8” each. The window will be 12” by 8” of plexiglass.

All hull designs were expected to be created and 3D scanned to get an initial scan that could be referenced later. The hull has many failure modes and underwent design changes during the prototype phase, so it was beneficial to have multiple designs that could easily be changed to save on costs and resources. The morphological chart below (**Figure 8**) shows the different aspects that were put into the design.

Figure 8: Morphological chart for the design of the hull.

Taking the above designs, as well as talking further with advisors for the project, a new and improved final design was chosen. With limited time, it was decided that only one hull, 3’ wide by 2’ long with a thickness of 0.063”, would be created. The material for the hull was decided to be aluminum 3003 for easier machinability on campus. The final hull design has a radius of curvature of 45”, so it is curved but still manageable for the robot to maneuver on. The center of the hull was cut out and plexiglass was molded to the curve and bolted to the hull to simulate a window. A sketch of this final design can be seen in **Figure 9**. Looking at the previous designs and sketches, they are all combined to create this final design for one complete hull.

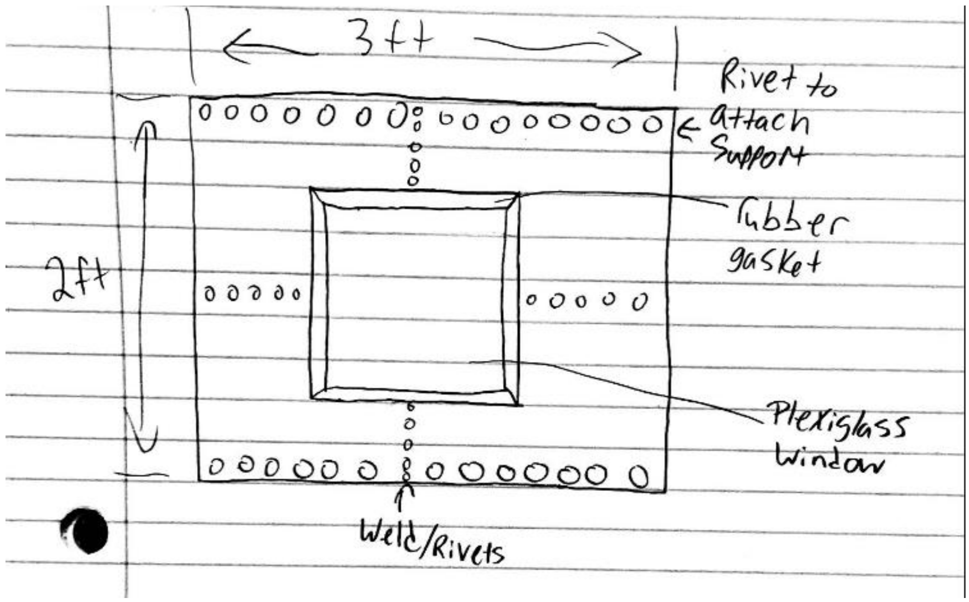


Figure 9: Shows the new updated design of the hull face.

For the support, further research was done on different pieces that could be used. From there the support parts were designed and sent to the machine shop on campus. This was done to make sure the design was exactly what was needed for the hull, including strong materials to hold the weight of the hull, all its attachments, and the robot. The supports are secured at both the top and bottom of the hull for full support. Along the ends, a pipe is riveted, and the ends of the pipes are welded to a half circular plate which is bolted to square tubing. The square tubing at the top half is longer than the bottom tubing, leaving a slope of 23 degrees. The bases of the square tubes are welded to a flat plate. These flat plates have holes at 1” apart to bolt the hull to the table. To help ensure that the supports will line up fully with the table, the half circular plates have tabs cut out for more freedom in movement when aligning everything. This can be seen more clearly in **Figure 10**. Just like the overall hull design, the support design was also created using aspects from the previous ideas.

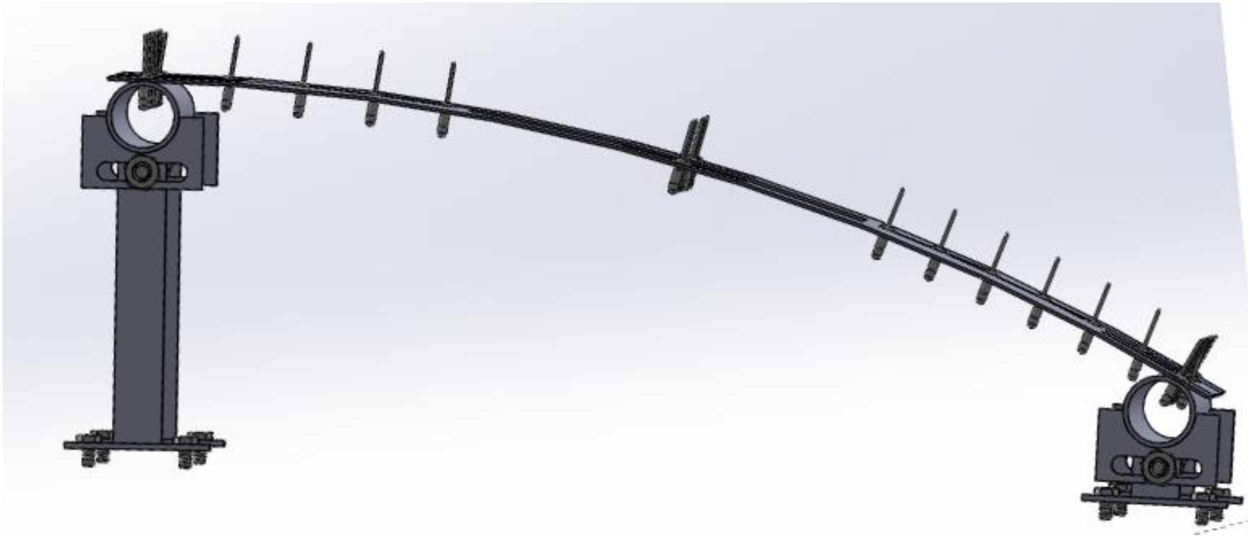


Figure 10: Shows a CAD assembly of the hull and how it attaches to the supports.

2.3 Mobile Robot

The mobile robot is the most dynamic element of the testing setup. It will be tasked with navigating to the site of exterior damage upon the hull as part of the feasibility test. While the challenge of choosing a design for such a robot was one of the most open-ended problems presented to the senior design team, there did exist engineering and economic challenges that constrained potential designs for the mobile robot.

2.3.1 Initial Evaluation

First, concepts for the robot were brainstormed and a morphological chart, shown in **Figure 11**, was developed to organize potential designs.

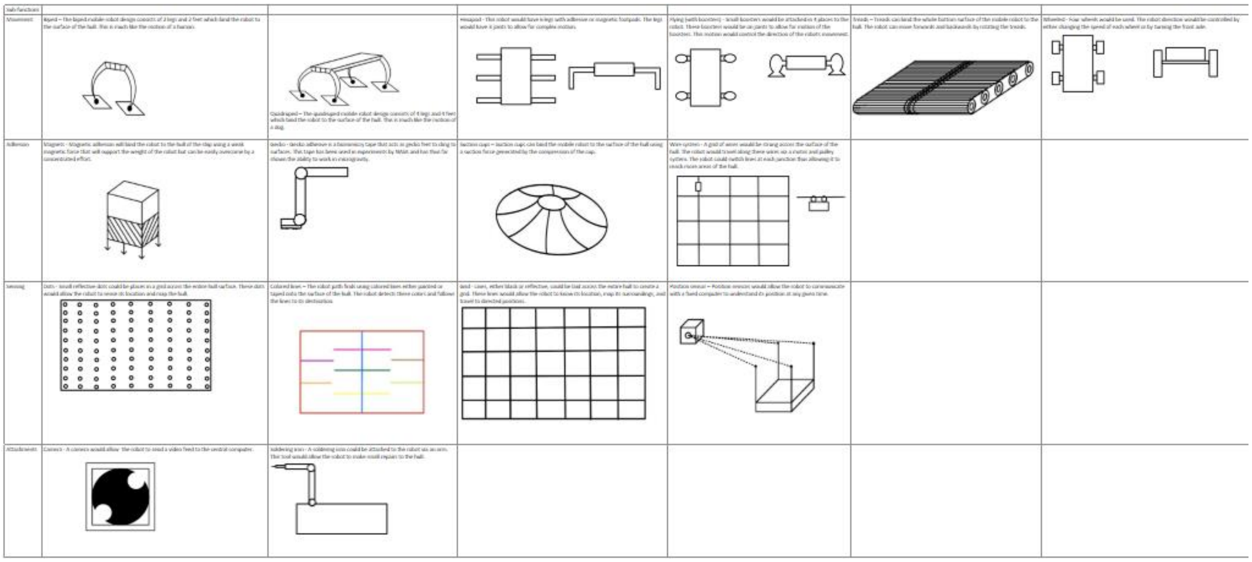


Figure 11: Shows a morphological chart with interchangeable design features in each row.

Next, a QFD process was conducted to determine the relative importance of engineering characteristics related to the mobile robot. The included engineering constraints and requirements are as follows:

- Low cost - The mobile robot needs to be as cheap as possible while still maintaining satisfactory quality.
- High speed - The robot needs to move quickly to its destination, such that movement tests are timely and multiple can be performed during one testing session.
- Lightweight - The robot needs to be light enough that it does not damage the hull of the spacecraft.
- Small size - The robot needs to be small enough that it can navigate around obstacles on the hull without hitting them.
- High durability - The robot needs to be able to withstand a small fall without being damaged to the point of needing repairs or requiring replacement.
- Easy to assemble - The robot must have a limited number of parts and a manual to make assembly timely and free of headache.

- High movement redundancy - The robot must be able to withstand a small failure in its movement without it leading to a catastrophic failure.
- Quadruped is ideal for the robot (see weighted decision matrix), but hexapod can be used if more grip strength is needed
- Must be open-source programmable
- Must be modifiable (able to add feet for the gecko tape)

The QFD is shown below in **Figure 12**.

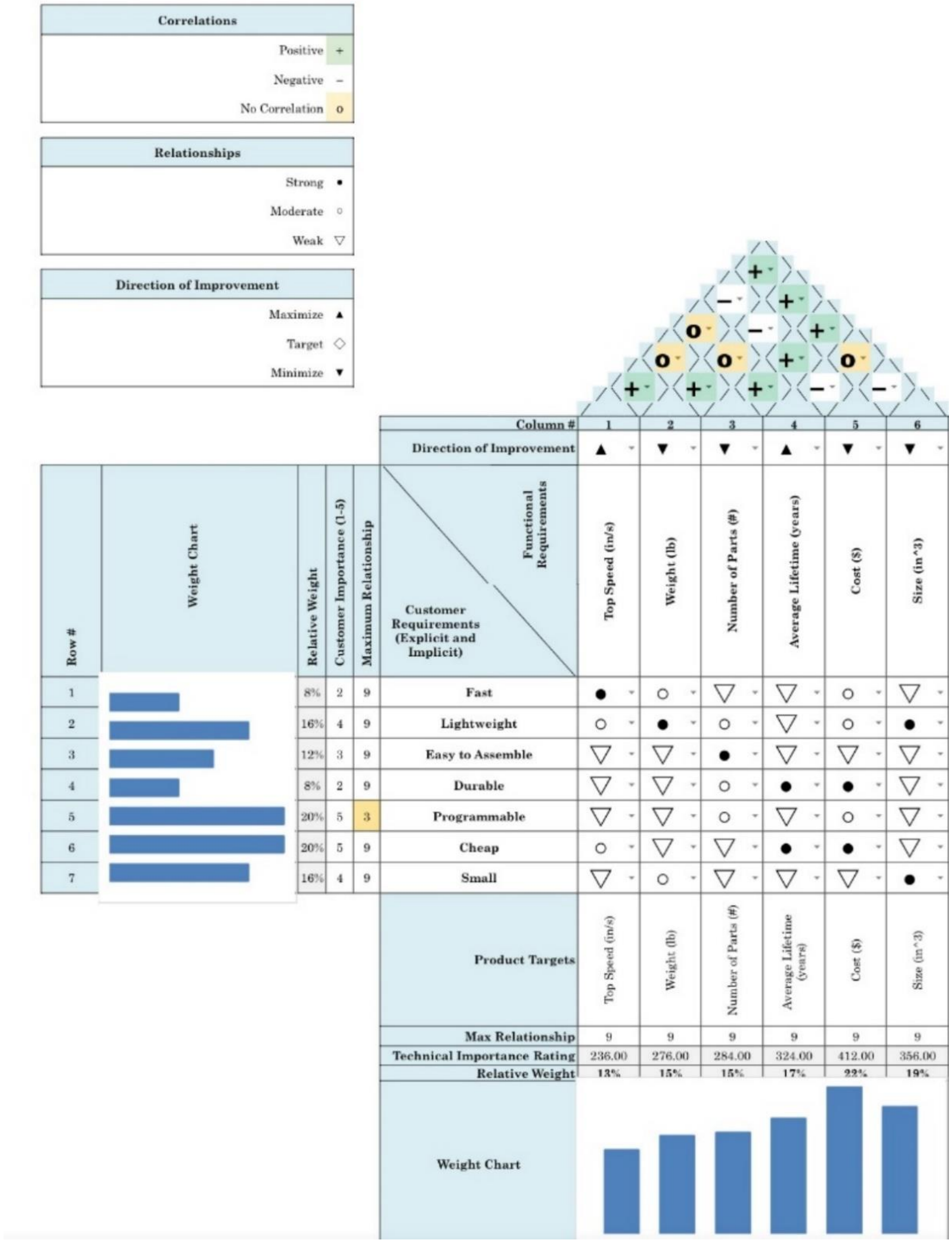


Figure 12: Shows the quality function deployment for the mobile robot.

The QFD shows that for the mobile robot design, the engineering characteristics that must be optimized (in order of importance) are cost, size, durability, weight, number of parts, and top speed.

2.3.2 Conceptual Design

Based on the information found in the first two rows of the morphological chart (as the contents of the second two rows could easily be added to an initial robot design as modifications), as well as from the QFD, four robot concepts were developed for comparison.

Concept A

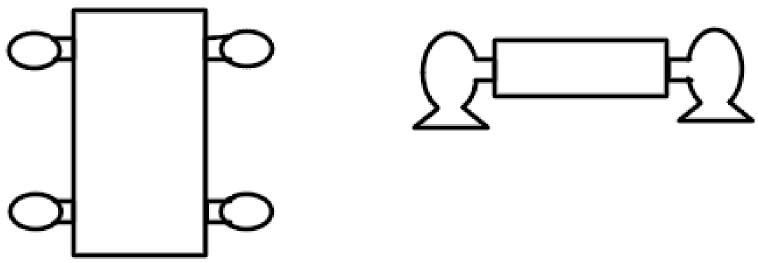


Figure 13: Shows an illustration of concept A for the robot.

Boosters: This design would use boosters for the movement and would never adhere to the surface of the hull. The boosters would be based on the SAFER and other similar devices used by astronauts to perform space walks. The SAFER device expels nitrogen gas as the propellant. The boosters would be attached via servo motors and joints to allow for a full range of motion.

Concept B

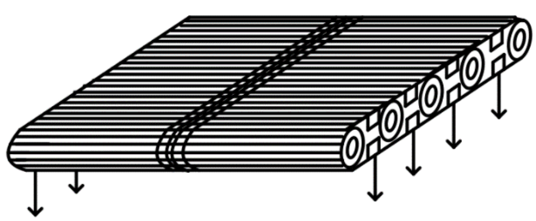


Figure 14: Shows an illustration of concept B for the robot.

Treads with Magnets: This design would consist of two treads that adhere to metal surfaces using magnets embedded in the treads. Turns would be handled by rotating one tread faster than the other. The treads, however, would be very wide and the general maneuverability of the robot would suffer as a result.

Concept C

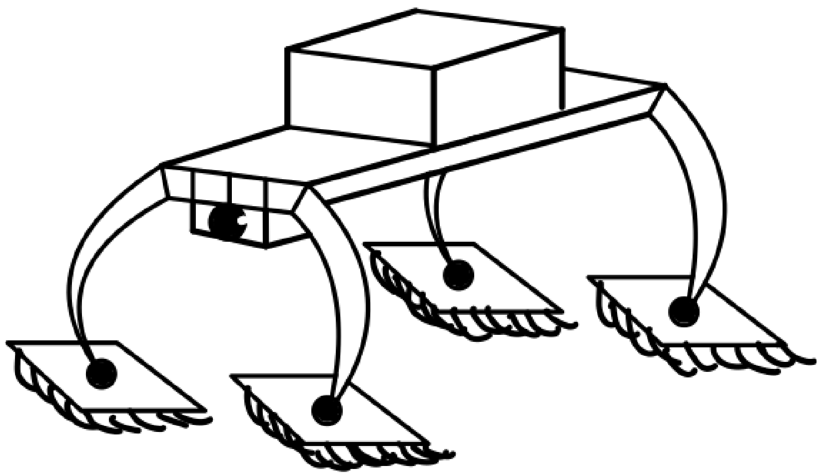


Figure 15: Shows an illustration of concept C for the robot.

Quadruped with Gecko Tape: This design would consist of the robot's body, containing any motors, sensors, and other electronic components. This body would connect to four legs, each containing two or perhaps three joints, which would allow the feet to move the robot forward. Gecko tape would adhere the four feet to the surface it is on. This robot could be outfitted with a camera on the bottom or the top side of the body of the robot.

Concept D

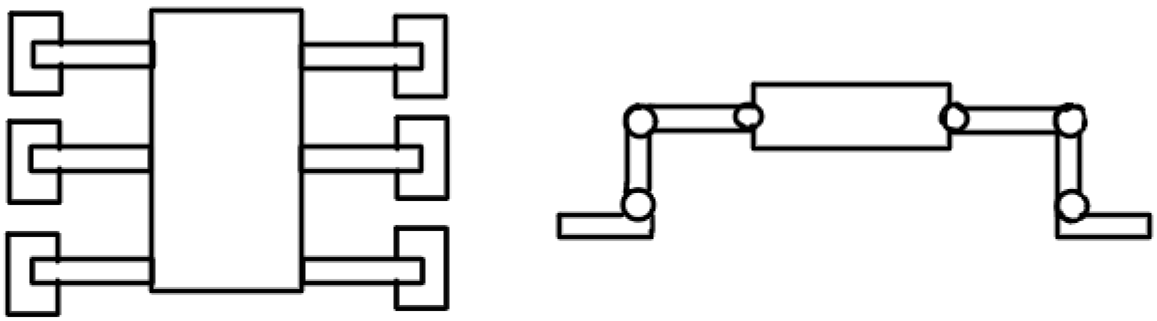


Figure 16: Shows an illustration of concept D for the robot.

Hexapod with Gecko Tape: This design would have six legs (hexapod) each with a gecko footpad. The legs would have two or three joints each, one at the body of the robot, one at the knee, and a possible joint at the foot. The larger number of legs would allow for more feet and thus a larger surface area of gecko tape. This greater amount of surface area would provide a stronger grip. The size of the footpads would be dependent on the strength of the gecko tape.

These four robots were then compared in a weighted decision matrix, **Table 1**, for final concept selection.

Table 1: Shows the weighted decision matrix for 4 different potential robot designs

Evaluation Criteria	Weighted Factor, W	Concept A	Concept B	Concept C	Concept D
Low cost	0.2	1	4	5	4
High speed	0.09	5	3	4	4
Lightweight	0.15	2	2	5	4
Small size	0.18	1	3	5	4
High durability	0.15	1	5	3	4
Easy to assemble	0.12	1	2	4	3
High Movement Redundancy	0.11	3	1	3	5
Total	1	**1.4**	**2.9**	**3.94**	**3.44**

As shown by the results of the weighted decision matrix, concept C (the quadruped with gecko tape) won out over the other options for robot designs. This design was further expanded upon as the project continued. Three major elements of the design that were expanded upon include the electrical components, the main body design, and the leg design. To help make more informed decisions regarding the robot design, the Adeept RaspClaws Hexapod Spider Robot Kit for Raspberry Pi [10] was purchased. This kit provided a basic idea of how a legged robot is constructed.

For the electrical components, an Arduino UNO Rev 3 was chosen as the board for the robot. This board is simple to use and allows for the attachment of shields. To attach multiple servo motors, a KEYSTUDIO 16-Channel 12-bit Servo Motor Shield was purchased. Eight MG90S micro servo motors from the Adeept robot kit are used to drive the robot. Two motors are used on each leg; one motor is used to move the leg forward and backward while the other lifts the lower portion of the leg. To provide power to the Arduino UNO, a 9V battery is used while four AA batteries provide power to the motor shield.

The main body of the robot was initially based on the Adeept robot design. The top body plate of the robot is used to attach the four legs of the robot, via the servo motors, to the body of the robot. The Arduino UNO is attached to the bottom body plate using three of the available bolt holes. These two plates are joined together using four Nylon standoffs from the Adeept kit. The top and bottom plates were drawn in Solidworks and 3D printed in the University of Akron 3D printing lab. These plates can be seen in the assembly picture featured in **Figure 18**.

Another major design specification that was developed was the leg. Initially, the leg design was like the Adeept robot but featured the addition of a foot so gecko tape could be used. This foot was attached to the bottom of the leg using a 2-millimeter shoulder bolt that allowed the foot to freely rotate. This foot design is shown in **Figure 17** and included in the full CAD model displayed in **Figure 18**.

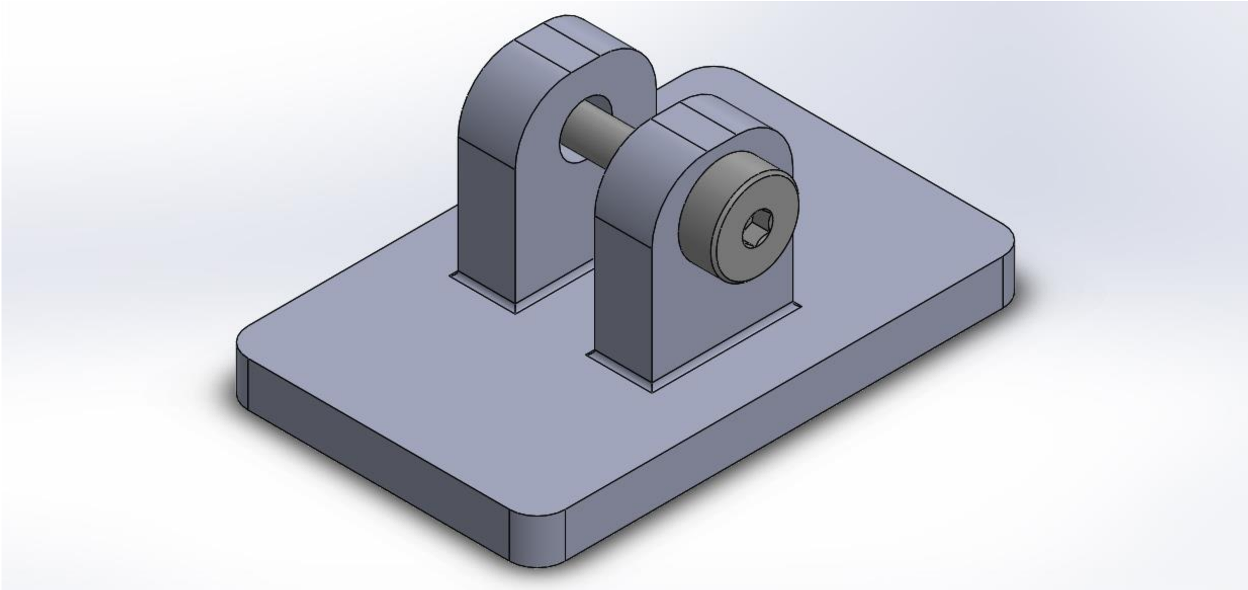


Figure 17: The hinged foot design was initially used and later modified to comply with new piston style leg design.

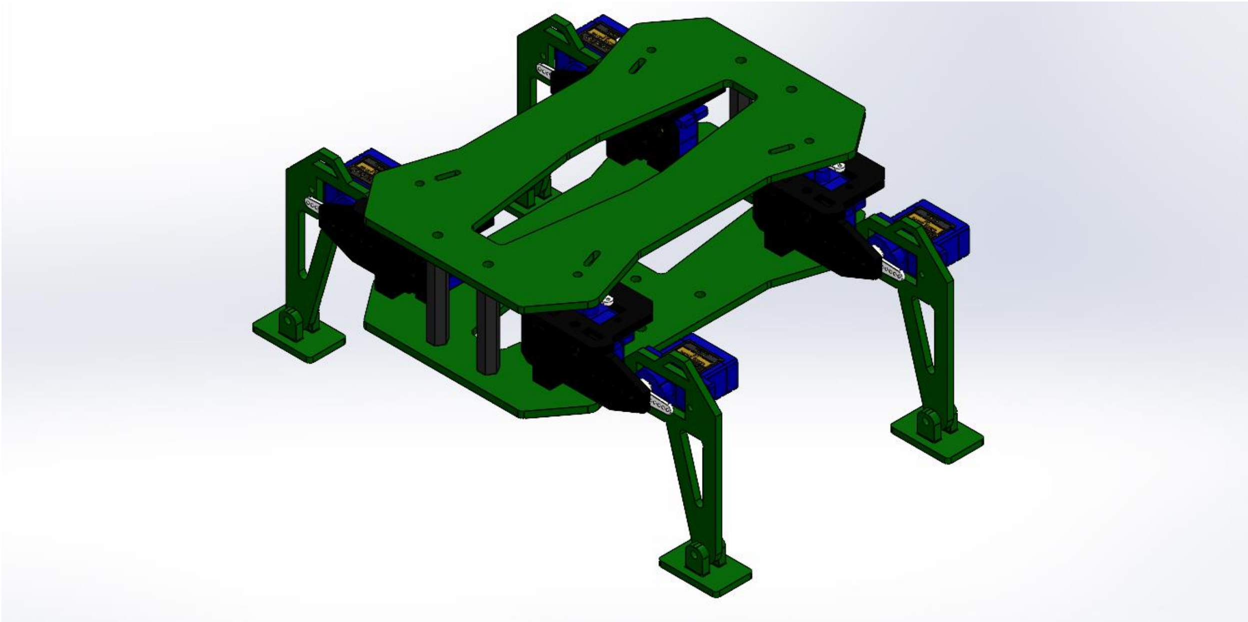


Figure 18: Original robot design. All green colored parts were 3D printed in the University of Akron printing lab while the black parts were from the Adeept robot kit.

Once this design was 3D printed and tested with gecko tape it was discovered that, despite the rotating foot, the gecko tape experienced mostly shear force. Since gecko tape is strongest in shear, the servo motor was unable to overcome the gripping force of the gecko tape and could not lift the foot. To reduce the shear force experienced by the foot when lifted, a piston style design was created. This design still makes use of feet with the ability to pivot to allow for better gripping of the curved surface of the hull. Extra care was taken to ensure the center of the servo motor aligns with the center of the shoulder bolt and that the outer face of the servo arm is coplanar with the outer face of the leg. These specifications were made to ensure the rod does not experience any binding while the robot is walking. The final robot design is shown in **Figure 19**.

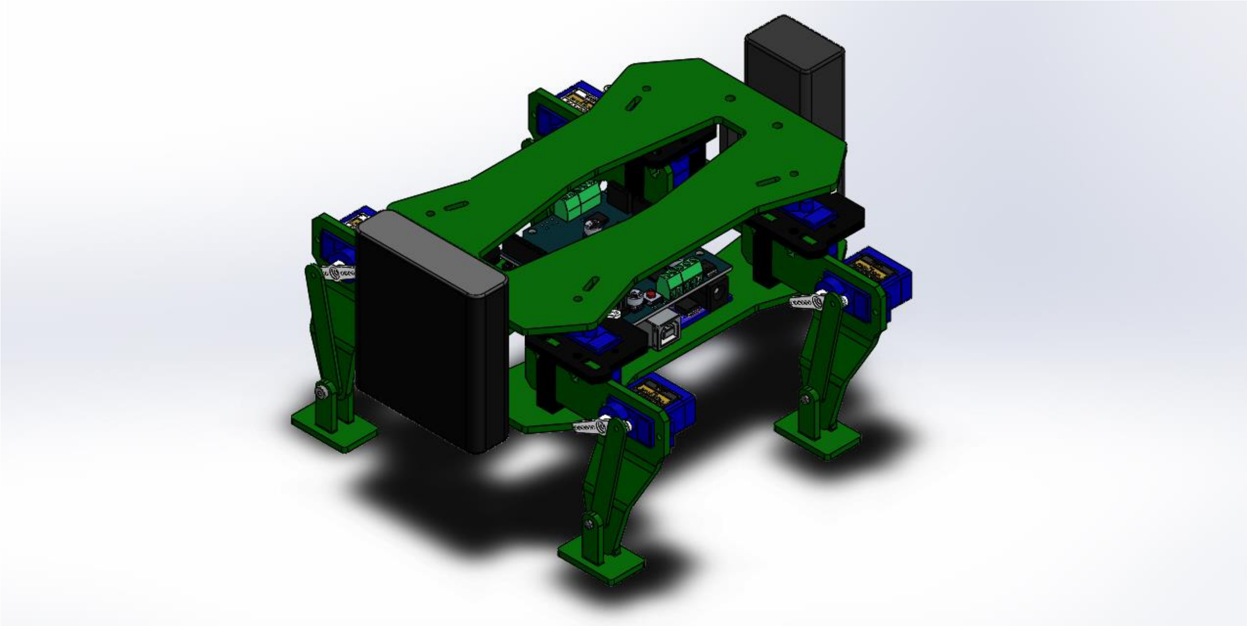


Figure 19: The completed assembly featuring piston style leg design. The left legs display the feet in a down position while the right legs show an up position.

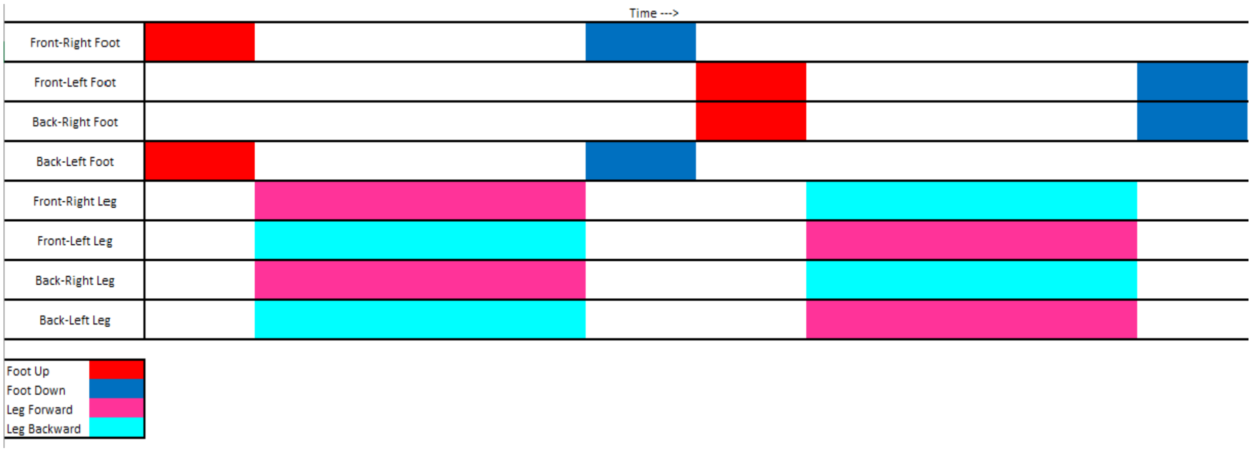


Figure 20: Gait diagram for the mobile robot.

Once the quadruped design for the mobile robot was finalized, a gait needed to be designed and coded. The goal of this gait, shown in **Figure 20**, was for the robot to walk as naturally as possible. After studying the movement of reptiles, the above gait was decided upon. First, the robot picks up two opposite feet, either front-right and back-left, or front-left and back-right, then it moves the corresponding legs forward. As those legs move forward, the remaining legs, whose feet are still in contact with the ground, move backward, swiveling the robot forward. Then, the feet that are still in the air move down until they are in contact with the ground. The opposite set of legs then lift and repeat the same process. While the robot is in motion, the gait diagram shown above repeats ad infinitum.

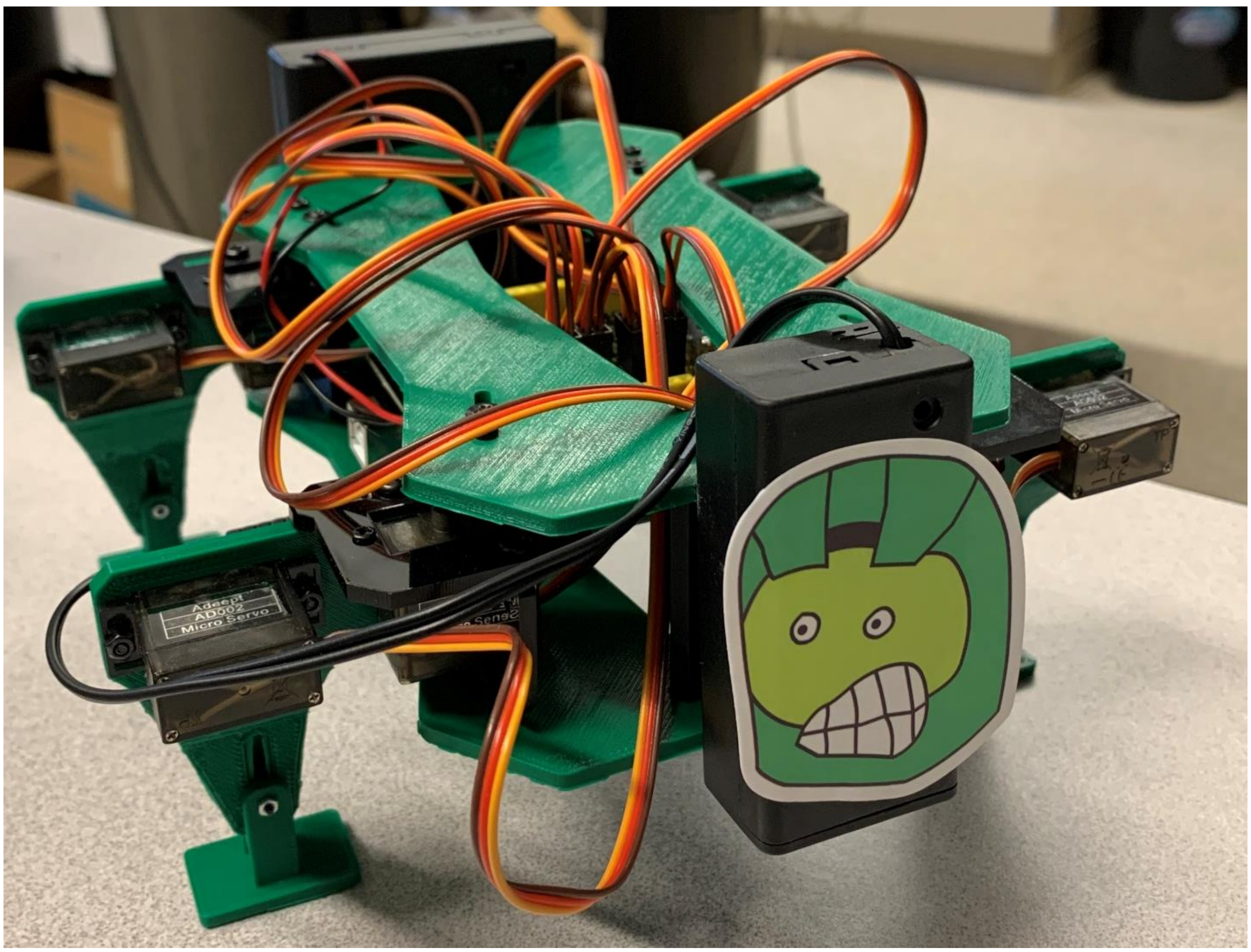


Figure 21: The completed robot.

The new leg style was 3D printed, and the final mobile robot was constructed. The completed robot is shown in **Figure 21**.

2.3.3 Evaluation

A risk assessment of the initial robot design was performed using a failure modes and effects analysis (FMEA) chart. This chart can be found in **Table 10** located in Appendix B. This chart evaluated the potential failures of the mobile robot and the effects of the failure.

Based on the results of the FMEA chart, the final robot design is constructed to protect the most sensitive parts of the robot, the Arduino UNO and motor shield, as these parts are nestled between the top and bottom body plates. These plates, however, were designed and printed before it was determined that two different power sources would be needed. Due to this, the AA battery pack was attached vertically to the back of the robot while the 9V battery case was attached vertically to the front of the robot.

Additionally, the design was originally intended to allow the robot to walk in both the forward and backward direction. However, it was determined after assembly that the robot can only move in one direction as the power cord for the Arduino UNO impedes the movement of one of the legs if moving in the backward direction. During testing, additional complications with the gecko tape were discovered and are discussed in the testing section.

2.4 Robotic Arm Gripper

To scan the simulated hull and detect damage, a 3D scanner will be used. A robotic arm will be used to control the 3D scanner, thus allowing for complete automation of the system. To mount the 3D scanner to the robot, a gripper was created. To design this gripper, constraints were determined, and solutions were brainstormed. These solutions were evaluated using multiple methods to ensure the best design was chosen. Once the final design was determined, the gripper was constructed and tested.

2.4.1 Initial Evaluation

To begin the design process, engineering requirements and constraints were determined. It was determined that the gripper must securely hold the 3D scanner to ensure that the scanner does not shift excessively when the robot moves. The gripper must also not interfere with the motion of the robotic arm. For instance, the end of the robotic arm rotates 360 degrees and should be able to do so with the gripper attached. The gripper should also be easily constructed so the team can manufacture the gripper and keep the cost low. Finally, the maximum capacity of the robotic arm is 1 kg, and the weight of the 3D scanner with the necessary cables is over the 1-kg capacity. Given this, it was decided that a 3D printed replica of the 3D scanner would be used instead. So, the gripper combined with the 3D printed scanner weight must be kept under 1 kg.

To begin the brainstorming process, a QFD method was used to determine the most important aspects of the gripper design. It was determined that the gripper should be lightweight, have low interference, and easily and securely grip the scanner. For the function requirements, the gripper should be easily manufactured, able to mount to the end of the robot, have a low weight, and a smaller size. **Figure 22** was used to determine the correlation between these requirements. As seen below, weight is the most important element of the design.

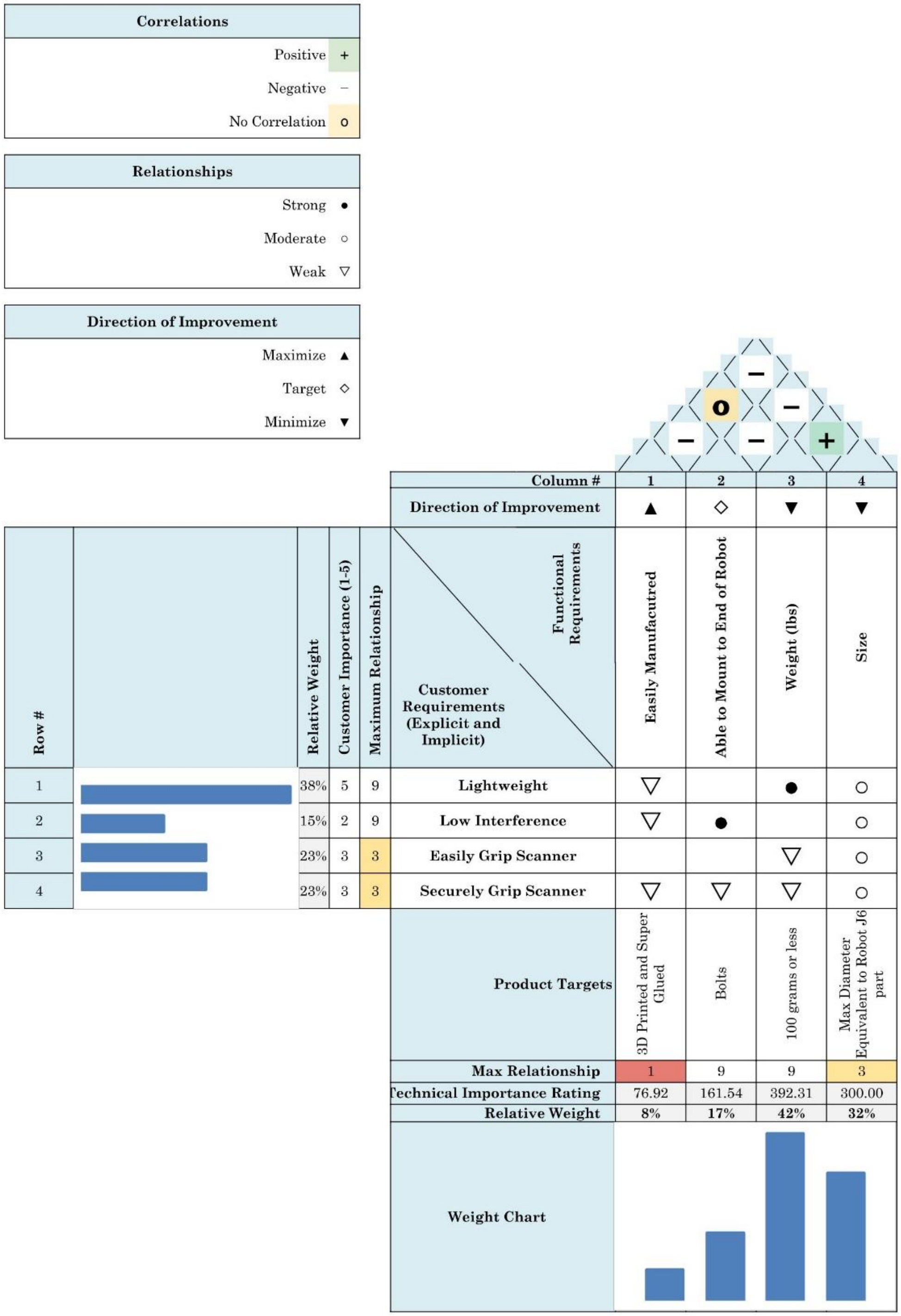


Figure 22: The quality of deployment for the gripper.

2.4.2 Conceptual Design

After the most important elements of the design were determined, the conceptual design process began. The gripper design was broken into two separate subfunctions: attachment to robot and attachment to 3D scanner. Two ideas for the attachment to robot subfunction were determined. These include a bolted-on connection plate, which would have the same overall diameter and bolt hole circle as the robot, and duct tapping the 3D scanner directly to the end of the robot. For the attachment to 3D scanner subfunction, three ideas were determined. First, a c-shaped clip could be 3D printed at the same diameter as the 3D scanner handle. This clip would have a gap small enough to hold the 3D scanner in place but large enough to squeeze the 3D scanner in. The second design is a cloth, or similar material, strap that would be attached to the connection plate and used to hold the 3D scanner. The final idea is a two-piece metal clamp. The two halves of the bracket would be on hinges to allow the clamp to open then the two halves would be held together via a latch in the middle. These designs can be found below in the morphological chart, **Figure 23**.

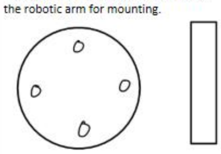
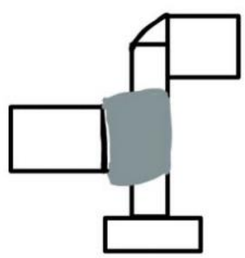
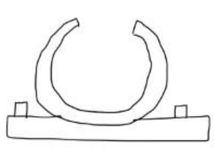
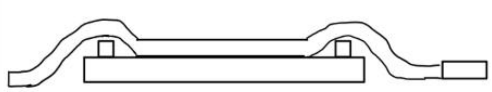
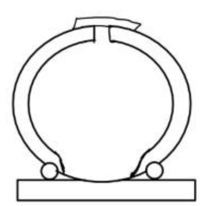
Sub-function			
Attachment to Robot	**Bolt plate** - A circular plate the same size as the face of the end of the robotic arm. The bolt hole pattern will match that of the robotic arm for mounting. 	**Duct tape or another similar adhesive** - The 3D scanner would be attached to the end of the robot by wrapping duct tape around the two. The J6 motion of the robot may be restricted by this method. 	
Attachment to 3D scanner	**C clip** - A c shaped piece with a gap slightly smaller than the diameter of the 3D scanner handle. The 3D scanner could be forced into the clip and held in place until forcibly removed. 	**Strap** - A cloth strap with a plastic or metal clip on the end allowing for full adjustability of the tightness of the strap. The strap would be connected to the attachment plate via superglue or a similar adhesive. 	**Two piece clamp** - Two semicircular bracket pieces would be mounted to the attachment plate via hinges so the parts could rotate to release and grip the 3D scanner. A latch in the center would connect the two halves and pull them together. 

Figure 23: The morphological chart for the gripper.

Using the morphological chart above, four complete concepts were created.

Concept A

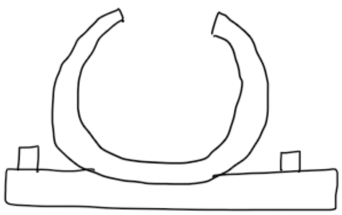


Figure 24: A c clip and connection plate are used in the concept A gripper design.

Concept A uses the c clip and the connection plate to form a gripper. This design would be either one 3D printed part or two 3D printed parts connected. Some advantages of this design include that it would be either one piece or simple to assemble. Some disadvantages include that the print would be more complex, the scanner may not be held securely if the clip is not sized correctly, and the clip has the potential to snap and break when attempting to force the 3D scanner in.

Concept B

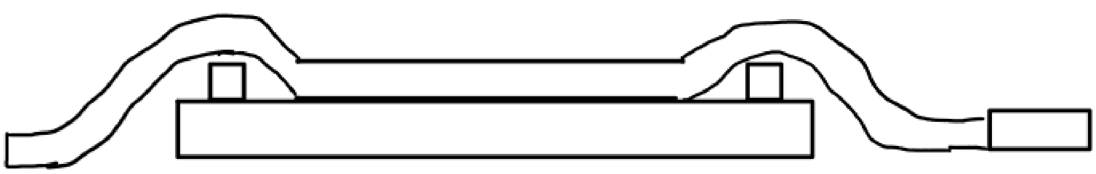


Figure 25: A strap and connection plate are used in the concept B gripper design.

Concept B uses the strap and the connection plate to form a gripper. The advantages of this design are that the connection plate would be easy to 3D print, the strap would make the gripper easily adjustable, and the strap would provide a secure grip on the 3D scanner. The disadvantages are that it may be a bit more work to initially attach the 3D scanner and the hold on the 3D scanner may decrease if the clip does not hold the strap securely.

Concept C

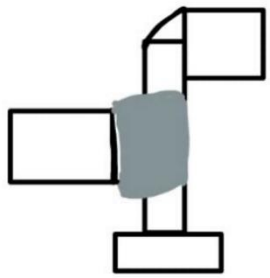


Figure 26: Concept C is shown above using duct tape as the connection to the robotic arm.

Concept C uses the direct attachment idea and involves duct tape connecting the 3D scanner directly to the robot. Some advantages of this design include the simplicity of it and that it will hold the 3D scanner securely. Some disadvantages include that it could restrict the robot arm's motion and leave a residue on the robot or the 3D scanner.

Concept D

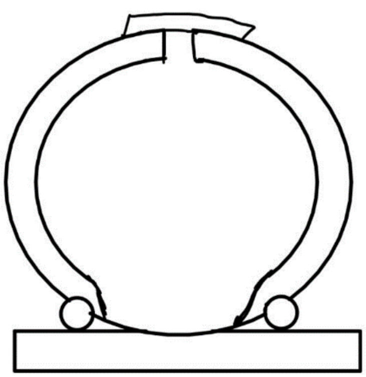


Figure 27: A two-piece clamp and connection plate are used in the concept D gripper design.

Concept D uses the two-piece clamp and the connection plate. Some advantages include the high level of grip it would provide and the ease of removing the 3D scanner. A disadvantage is the complexity of the design as the clamp involves hinges and would likely be more difficult to build than the other concepts.

To evaluate the above designs, an objective tree and weighted decision matrix were employed. The objective tree was created to assist in the creation of the weighted decision matrix and is displayed in **Figure 28**. This tree helped determine what elements of the design are the most important by putting a weight on each of the factors. It was again decided that weight is the most important factor when considering gripper designs.

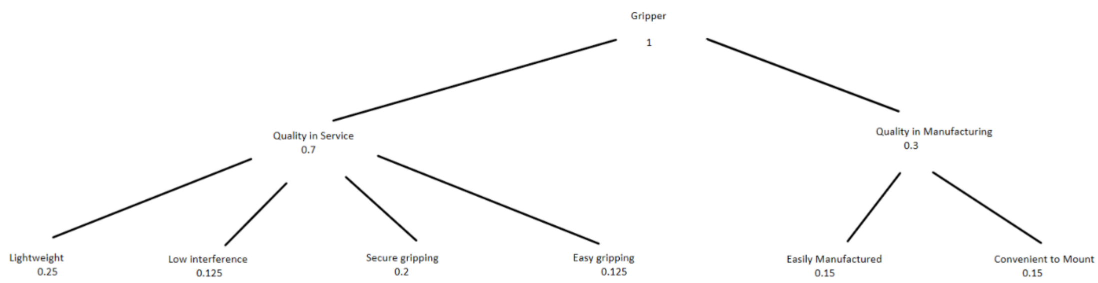


Figure 28: The objective tree for the gripper design. The values used in the construction of the tree were used in the decision matrix featured in Table 2.

Using the above objective tree, the weighted decision matrix, shown in **Table 2**, was created. Each concept was judged based on the evaluation criteria and scored on a scale of 1 to 5. The scale is as follows: 1 – unsatisfactory, poor, or unusable; 2 – barely acceptable, tolerable, or deficient; 3 – adequate, usable, or satisfactory; 4 – good; and 5 – ideal or very good. As seen in the chart below, concept B was determined to be the best and was selected as the final design.

Table 2: The weighted decision matrix for the gripper design. Based on the scores, concept B was selected as the final design.

Evaluation Criteria	Weighted Factor, W	Concept A	Concept B	Concept C	Concept D
Lightweight	0.25	3	4	3	3
Low Interference	0.125	4	4	2	5
Secure Gripping	0.2	3	5	4	4
Easy Gripping	0.125	3	5	2	4
Easily Manufactured	0.15	3	5	4	2
Convenient to Mount	0.15	4	4	1	4
Total	1	3.275	4.475	2.8	3.575

For the selected design, a connection plate with a bolt hole circle of counterbored clearance holes was 3D printed. An elastic, hook-and-loop strap was superglued to the plate and used to attach to the 3D scanner. An elastic, hook-and-loop strap was selected as a replacement for the cloth strap after further research. The elastic strap provides a more secure grip on the scanner to prevent shifting.

A CAD model was created in Solidworks to provide a representation of the selected gripper design. An engineering drawing of the part is shown in **Figure 29.**

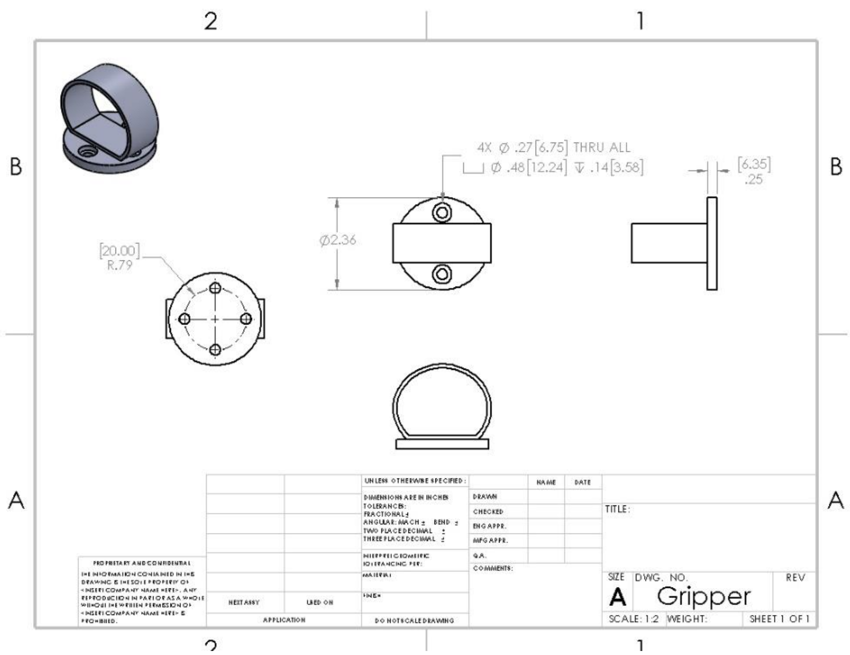


Figure 29: A drawing of the selected gripper design.

2.4.3 Evaluation

A risk assessment of the selected gripper design was performed using an FMEA chart. This chart can be found in **Table 11** located in Appendix B. This chart evaluated the potential failures of the gripper and the effects of the failure. Many of the effects of failure involve damage to the 3D scanner. Since it was later determined that a 3D printed copy of the scanner will be used, this is no longer a concern.

After the design was determined, a plan for building and testing the gripper was constructed. The first step of the building process was to finalize the design as soon as the robotic arm arrived. Once the robotic arm arrived, dimensions, such as the diameter of the end of arm face, the bolt hole circle diameter, and the bolt size, were gathered and used to modify the CAD design. These dimensions were also used to determine the thickness of the plate and the infill percentage used when 3D printing the connection plate. Once the design was finished, the connection plate was printed. Next, the strap was attached to the plate with superglue and further testing was conducted including weighing the completed assembly. While testing, design modifications were made to improve the gripper's hold on the 3D printed scanner. These changes include modifications to the elastic hook-and-loop strap as well as the addition of fabric paint. Further details can be found in the testing section. After all modifications were completed, the final gripper was determined to weigh 28 grams while the total weight of the 3D printed scanner and the gripper was determined to be 389 grams. This is below the 1 kg payload capacity of the robotic arm so it can be used in the proof of concept for the overall research project.

3. Design Verification

All designs were evaluated after completion using measurable standards of quality and success. For both the hull and mobile robot portions of the project, these measurable parameters included the allowable stress and deformation of the hull, the minimum allowable torque of the robot's motors, and the maximum allowable stress of the gecko tape.

3.1 Testing Procedures

All major components of the design were tested for safety, stability, and (in some cases) successful operation. A large variety of testing processes were used to evaluate the hull, mobile robot, and gripper. The procedures used to test and verify the ability of each component to fulfill its requirements are combined to confirm that the overall project produced a complete proof of concept. These procedures are specified in the sections below.

3.1.1 Spacecraft Hull

It is vital that the hull is strong enough to be able to stand and withhold the weight of the mobile robot. It was decided that the hull strength would be tested theoretically to ensure no damage would be done by any weight added to it. This was agreed upon because of the potential cost of materials, shipment time, and machining time if any part of the hull or hull support needed to be fixed. After researching multiple theoretical load and stress calculations for a curved surface, as well as consulting Associate Professor Dr. Manigandan Kannan, the best way was chosen. This method was to treat the hull as a flat surface with two fixed ends and a uniform distributed load of 2 lbs. per 24 inches in length and find the moment. Using the calculated moment value, the tensile and compressive stresses were found for the curved hull. A weight of 2 pounds was used as an extra precaution, since the robot's weight was found to be 513 grams (about 1.13 lb). The dimensions of the hull are as follows: the radius of curvature is 45 inches, the thickness is 0.063 inches, and the shortest length is 24 inches. The shortest length was used to provide the smallest area and thus find the largest stresses, once again as a safety measure. The tensile stress was found to be 2.691 psi, while the compressive stress was -2.864 psi. Both stresses are virtually the same and very minimal. Therefore, the robot is completely safe to traverse the hull without damage occurring. All calculations can be seen in **Figure 30**.

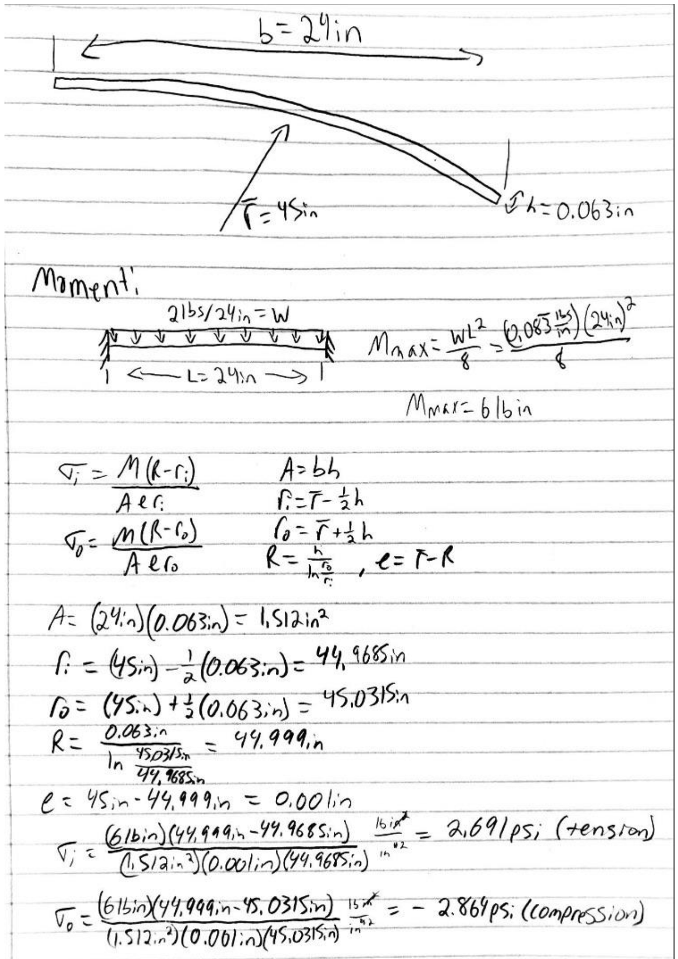


Figure 30: The theoretical testing for the hull strength.

The surface of the hull also needs to be scanned during the larger research project. Initially this was not possible as the reflective surface of the hull was not conducive to being scanned with the 3D light scanner. To allow the hull to be scanned, a white powder spray was applied, as well as reflective marker stickers, to the surface. This allowed the hull to show up in scans, but the scanner needed to be held at an awkward angle. Additionally, the white powder spray made it difficult for the gecko tape to grip the hull as the white powder would coat the surface of the tape. With that in mind, the entire hull was painted with white acrylic paint and covered in stickers; this allowed it to show up in 3D scanning more easily and the gecko tape did not have as difficult of a time attaching to the hull.

The requirements and verifications for the hull can be found in **Table 8**, but a summary is given here as well. The radius of curvature of the hull was found to be within 5 degrees of the required

45 degrees and the angle from the top surface of the hull was 23 degrees. It was low-cost to make, being under $200, and was found to have the necessary strength to hold the robot. There are rivets, antennas, a plexiglass window, and bolts for obstacles and attachments. Finally, after it was fully painted white, it can be scanned.

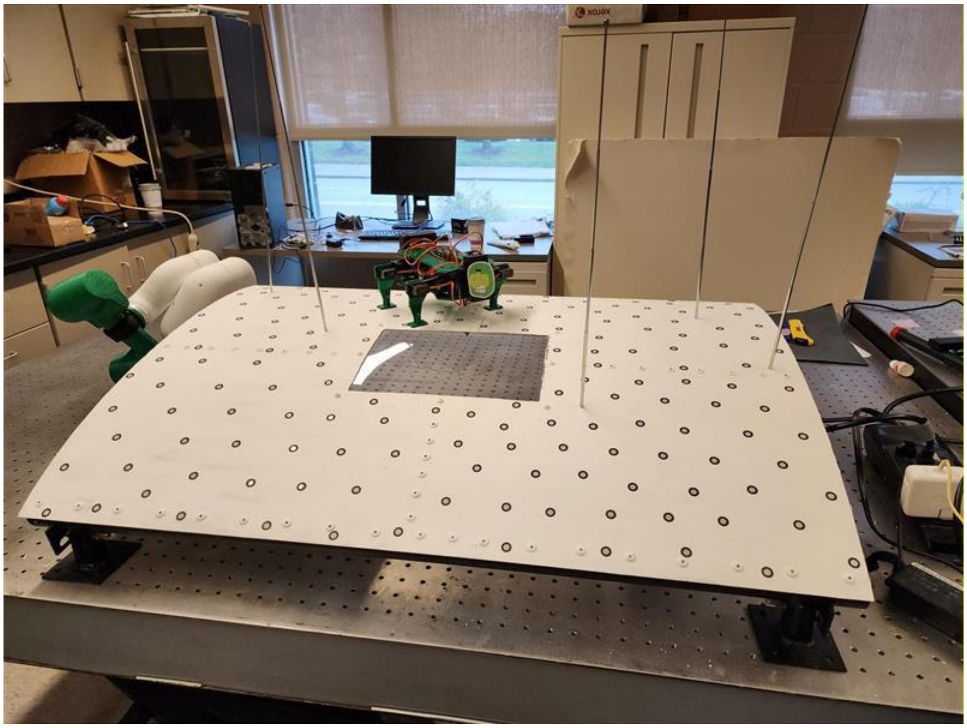


Figure 31: Completed hull build

3.1.2 Mobile Robot

For the mobile robot to be considered successfully functional, it had to be able to navigate a curved hull, which is made up of various materials and discontinuous attachments, which it must move around without hitting. While there is still work to be done with regards to the robot's ability to navigate intelligently, it has been shown to be capable of traversing the curved surface.

First, a test was run to validate that the robot could move laterally on a flat surface without adhesive gecko tape binding it to the surface. During the first test, the robot was very sluggish and needed to be re-coded, resulting in the much faster gait it now uses.

Second, the robot's ability to move with gecko tape binding its feet to a flat surface had to be tested. This test pointed to the necessity of redesigning the legs. The old leg design attempted to break the gecko tape's grip in shear, which was the tape's strong direction, resulting in the motors stalling due to insufficient torque. The new design fully breaks the gecko tape in the normal direction, meaning that new motors did not need to be found.

When testing the new design, the robot was able to lift the foot with a piece of gecko tape approximately half the size of the foot affixed to the bottom. This was a significant improvement from the initial foot design. To determine more quantitative results for using gecko tape on the feet of the robot, the torque values were calculated. The torque rating for MG90s servo motors running at 6V is 2.2 kg*cm [12]. To estimate the torque required by the second motor, the equation torque equals length multiplied by force is needed. In this equation, length is the distance from the center of the motor to the location where the rod is attached. This distance is approximately 12.25 mm. The force is the gravitational force on the foot assembly and rod as well as the normal force of the gecko tape. The mass of the foot assembly is 3 grams, so it has a force of 0.029 N. In addition to the gravitational force, the motor must be able to overcome the adhesive force of the gecko tape. During testing, this force was determined to be 21.5 N for a 1 inch by 1 inch piece of gecko tape on unpainted metal. The amount of gecko tape necessary to secure the robot on the unpainted hull surface was unable to be determined due to difficulties testing the gecko tape in shear and the entire hull being painted before determining an appropriate amount of gecko tape. So, the approximate total force the motor must overcome is 21.53 N for a 1" by 1" piece of gecko tape. Using the above calculation, the necessary torque would be 0.263736 Nm or 2.689 kg*cm. This is more than the motor can overcome. So, if an unpainted surface were to be used stronger motors would likely need to be implemented.

Third, the robot's ability to navigate a curved surface free of obstructions had to be tested. While the gecko tape had trouble adhering to the acrylic surface of the hull, meaning it often fell on the more vertical portions, the robot generally performed well with the curvature of the hull alone. The mobile robot was tested on this surface and when gecko tape pieces of 2 inches by 2 inches were used on the feet, the gecko tape was unable to get a good grip on the hull. This is likely due to both the size of the foot compared to the gecko tape and the lack of grip the gecko tape is capable of on the acrylic surface. A more comprehensive testing procedure of the gecko tape was conducted, and the results can be found in the gecko tape testing section. In the future, a different type of paint needs to be used on the hull, or a clear coat needs to be applied, to improve the gecko tape's adhesion.

While the robot is mechanically sound, and can be used for the feasibility test, more work is needed for the robot to navigate around obstacles. For one, an integrated position sensor needs to be introduced and Dijkstra's pathfinding algorithm needs to be programmed into the robot. However, due to time constraints (as the legs needed to be unexpectedly redesigned, and the group needed to program the robot in C++, an unfamiliar language), the ability to path find was not programmed. The parameters prioritized in the quality function deployment for the robot (**Figure 12**) were tested and described in the requirement and verification table in appendix A.

The criteria for the mobile robot design are detailed in **Table 1**. The mobile robot that was constructed was able to fulfill these criteria relatively well. After completion, the mobile robot cost $223.72 as shown in **Table 5**. The speed of the robot is approximately 0.355 in/s after it was slowed down to improve its stability. The robot weighs 513 grams. This is lightweight, and well below the amount that would cause any damage to the hull. The dimensions of the robot are 7.5 inches long, 6.5 inches wide, and 4 inches tall. This is small enough to be able to navigate the hull, so it is sufficient for the proof of concept. Another robot requirement was high durability. As mentioned above, the more sensitive hardware is protected between the 3D printed plates. These plates have 100 percent infill and have a high enough strength to withstand forces applied if a fall occurs. Next, the robot is easy to assemble. It is clear how all parts go together, and assembly can be completed with a single screwdriver. Finally, the robot needs to have high movement redundancy. When testing the robot, especially as it moved along the hull, it often had trouble staying adhered to the painted surface. While this could be fixed by adding more legs and converting the robot into a hexapod, it could also be fixed by:

a. Adding more gecko tape to each foot, with the drawback being that this would increase the width of the robot, OR
b. Switching to a different paint, as the paint used seems to greatly weaken the gecko tape's ability to adhere to surfaces.

The goal of the robot is to intelligently navigate the hull to find damaged sections. For it to achieve this goal, it would need an integrated position sensor and a digitized 'map' of the hull.

First, all the obstacles on the hull need to have their positions catalogued. In **Figure 32** below, the obstacles are shown in dark blue. Next, these obstacles need to be grown. The process of growing obstacles provides a computationally efficient method of ensuring the robot never hits an obstacle by overestimating the size of the obstacle. These grown obstacles are shown in light blue. Then, the corners of these grown obstacles are denoted as nodes and any other corners visible from them are denoted as segments. Full lists of these nodes and segments act as inputs for the Dijkstra algorithm, which outputs the shortest path between any 2 points on the hull. This path is shown in green below. Finally, any small obstacles on the hull are shown in other colors. Rivets are illustrated in red and screws in magenta. While the robot can still pass over them, they are included for the purposes of visualization of the hull.

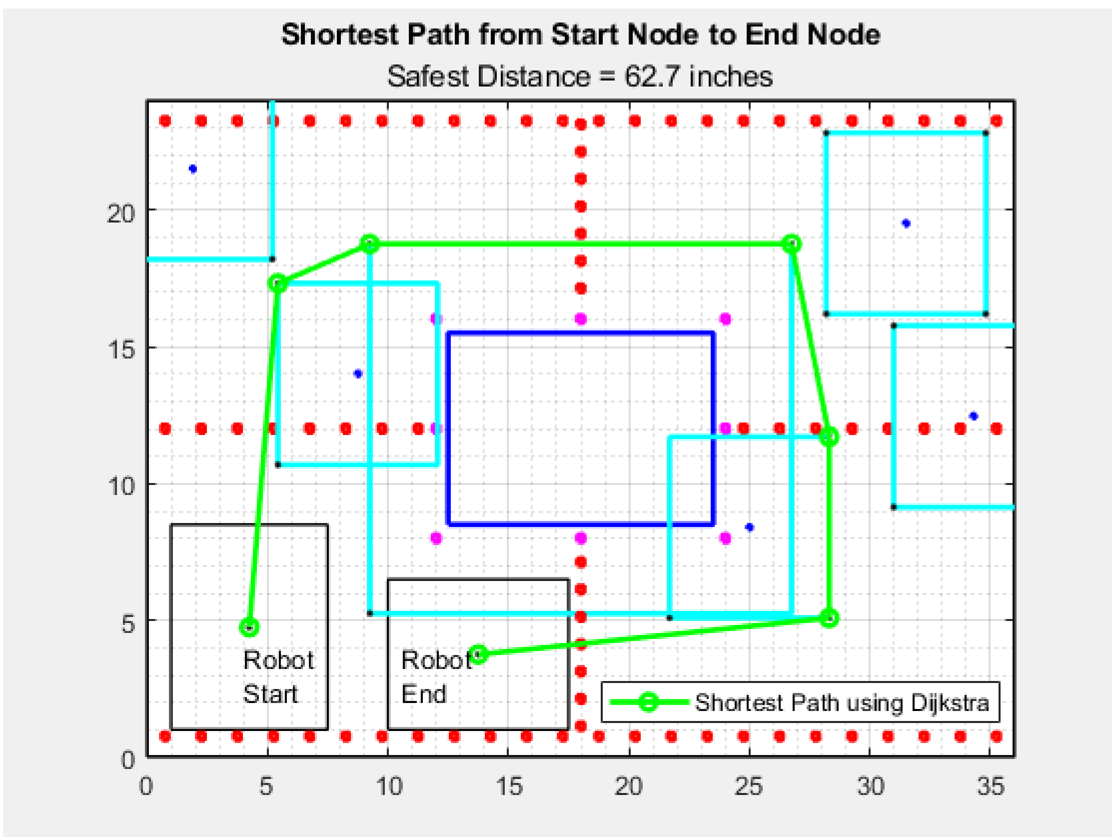


Figure 32: Mobile robot path planning using Dijkstra algorithm

3.1.3 Robotic Arm Gripper

Multiple tests were conducted to ensure the gripper will function as intended. These tests ensured that: the strap can securely grip the printed 3D scanner, the connection between the strap and the connection plate is secure, the connection between the connection plate and the robot is secure, the gripper does not interfere with the robot's motion, and the 3D printed scanner is able to be held securely when the robot moves.

The first test was conducted to ensure the strap is able to hold the 3D scanner securely. The strap was wrapped around the printed 3D scanner and secured. It was then slid up and down the handle, as well as twisted around, to monitor the amount of resistance. There was some resistance, so the testing proceeded to the next step.

The second test was done to ensure that the strap's connection to the plate is secure. This was completed by applying a force greater than the weight of the 3D scanner to the connection. The connection held, and no significant effects could be seen, so the gripper proceeded to the next test. For the third test, the printed 3D scanner was secured by the strap. The connection plate was then lifted and moved in a similar way to the movement of the robotic arm. The amount of shifting was monitored to ensure that the gripper could hold the printed 3D scanner securely.

While performing the third test, it was discovered that, due to the length of the strap, the hook-and-loop section was unable to clasp fully. This can be seen in **Figure 33**. This led to a less secure connection and a concerning amount of shifting. To help fix this problem, the end of the hook section of the strap was trimmed and the piece was super glued further in as seen in **Figure 34**. This change increased the amount of area available for the strap to get a secure hold. The modified strap was tested, and the shifting was decreased. However, there was still shifting, that became significant depending on how the connection plate is moved. To decrease this shifting, additional material was needed for further improvement. So, fabric paint was added to the inside of the strap to provide more gripping. With the addition of fabric paint, the shifting was decreased to an acceptable level.

Figure 33: The initial hook-and-loop strap was unable to fully clasp due to the length of the strap being too long.

Figure 34: The modified hook-and-loop strap.

For the fourth test, the gripper was attached to the robot with the necessary bolts. The initial plate design lacked counterbored holes, so the provided screws were too short. To rectify this issue, counterbores were added to the Solidworks model and a new plate was printed and used for the final gripper. The band also needed to be trimmed around the bolt holes to allow the connection plate to attach properly, and this can be seen in **Figure 35**. The robotic arm was run through its entire range of motion to ensure the connection plate remained secure and did not inhibit the robot’s motion. Due to time constraints, the robotic arm was moved by hand instead of programming the robot to perform these movements. Once this test was passed, the printed 3D scanner was attached to the gripper and the robotic arm motions were performed again. Shifting of the printed 3D scanner was minimal. Additionally, the robotic arm was positioned upright to observe how the gripper held. While it was slightly tilted, it was not considered a concern as the 3D scanner can be held at any angle. This is shown in **Figure 36**.

Figure 35: The final gripper attached to the end effector of the robotic arm. The area of the strap that interfered with the bolts was removed.

Figure 36: When the robotic arm is in the upright position, the forces acting on the gripper cause the printed 3D scanner to be held slightly tilted.

The described tests above verify that the gripper is able to securely grip the 3D printed scanner, causes no interference with the robotic arm's movements, is easily mounted on the robot arm, and is easily manufactured. Additionally, the weight of the gripper and 3D printed scanner was determined to be 389 grams, below the 1 kg threshold, and can be considered lightweight. Finally, the gripper is partially able to easily grip the 3D printed scanner. Since the strap had to be attached to the connection plate in a loop it is unable to fully open. Due to this, it must be stretched to get it over the top of the 3D printed scanner. This can be difficult and may take multiple attempts. However, once the gripper is over the top of the scanner, it can be easily adjusted on the handle section. These requirements and verifications can be found in **Table 8** in Appendix A.

3.1.4 Gecko Tape Testing

To test the gecko tape, a Nidec Force Gauge was utilized. This measured the force that can be withstood by the gecko tape when attached to PLA and aluminum. Seven samples were tested three times for accuracy and to find an average. The testing orientation was normal, and the sizes were 1x1 in, 2x2 in, 1x2 in, 1.5x1.5 in, 0.5x0.5 in, 0.2x1 in, and 0.125x1 in. The aluminum was then painted, and the tests were conducted again to see how the paint affects the gecko tape. To test this, two new parts needed to be designed and built. To help simulate the robot and hull for the most accurate and relevant forces, one part was 3D printed PLA and the other was machined aluminum. Both parts and the testing set up can be seen in **Figure 37**. The aluminum part had a hole drilled into it so that a hook attachment could be used for the force gauge. The PLA part was placed into the vice grip and the adhesive side of the gecko tape was applied to it; then the aluminum part was placed on top of the tape. A 2 lb weight was used to act as the weight of the robot pushing down and securing the tape to the aluminum. Finally, the force gauge was used to see how much force was needed to pull the aluminum part off of the gecko tape. Results can be seen below in **Table 3**.

Figure 37: The PLA, gecko tape and aluminum testing part setup.

Table 3: Testing results of the gecko tape from the Nidec Force Guage.

Size (in)	Area (in^2)	Bare aluminum to PLA Normal Stress (lbs)				Painted aluminum to PLA Normal Stress (lbs)			
		#1	#2	#3	Avg	#1	#2	#3	Avg
2 x 2	4	11.330	10.004	10.409	10.581	1.821	1.619	1.551	1.664
1.5 x 1.5	2.25	8.385	8.273	8.385	8.348	1.686	1.304	0.922	1.304
1 x 1	1	4.923	4.901	4.699	4.841	1.236	0.967	0.809	1.004
0.5 x 0.5	0.25	3.395	2.338	3.305	3.012	1.124	0.764	0.450	0.779
1 x 0.2	0.2	1.506	1.506	1.574	1.529	1.079	0.674	0.540	0.764
1 x 0.125	0.125	1.102	1.326	0.922	1.117	0.719	0.517	0.315	0.517

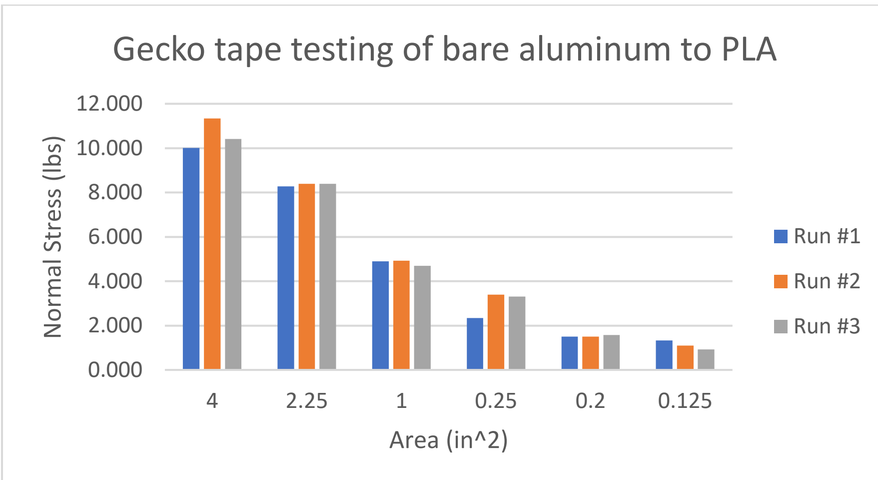


Figure 38: Bar plot of Stress vs. Area for gecko tape testing of bare aluminum to PLA.

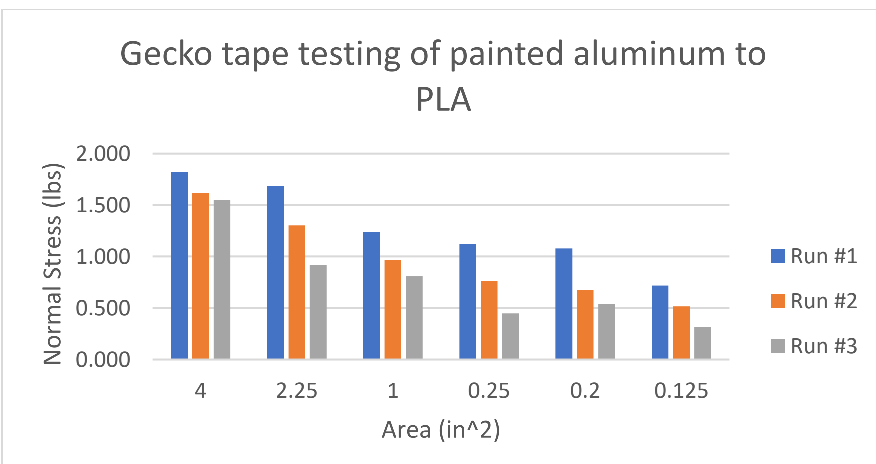


Figure 39: Bar Plot of Stress vs. Area for gecko tape testing of painted aluminum to PLA.

As shown by the plots above, when the painted aluminum was used, the force needed to separate the gecko tape adhesive from the aluminum was much lower. Given this, the paint is detrimental to the adhesive capabilities of the gecko tape that was chosen; therefore, acrylic paint is not a viable option for the hull, and additional testing should be done to determine a better paint.

3.2 Tolerance Analysis

Since the focus of this project was to design a testbed, rather than a prototype or instrument, tolerances can be relatively large in order to allow easy machining. One major concern related to tolerance, however, was the tolerance of the 3D scanner. The tolerance of the scanner must be sufficiently small to detect even small defects in the hull. However, if the tolerance of the scanner is much lower than the tolerance of the surface of the hull itself, the computer may consider acceptable deviations in the hull's surface to be defects. To get around this, rather than comparing the 3D scan to an idealized build of the hull, the scan will instead be compared to an archived scan of the undamaged hull. This way, small imperfections on the surface that are within the tolerance of the hull's surface finish will be present in both scans and will not be noted by the computer's algorithm and considered defects. While initial scans of the hull were performed as part of this project, damage was not introduced so scans were not compared. This will be done by graduate students as the research continues beyond the scope of this project.

4. Costs

This design project has accumulated many different types of cost associated with the research, design, and building of the testbed. Firstly, after all designs were created, a bill of material (BOM) was used to generate the total cost of components for each subsection of our project. Outside of materials, labor costs for each person were also calculated. Each person's rate was determined by taking an average engineering salary and multiplying it by the number of hours worked for each member. Some outside costs for using the engineering machine shop and the machine shop technician’s time were also accounted for along with other miscellaneous costs associated with the project. The university and other costs were estimated as these were not documented in total. The cost for this project was $441.31 for the parts, $20,490.00 for the labor and $20,931.31 total as shown below.

4.1 Parts

The cost of the project was broken into subsections such as the hull testbed, mobile robot, and robot gripper. Each subsection lists all the items needed to complete the full design and total cost of the parts. For the mobile robot and gripper, the 3D printing lab at the University of Akron was utilized. To estimate some of this cost, a roll of PLA filament was added to the bill of material for the mobile robot. Some parts of the hull were provided by the university machine shop and team member Nathan so the cost for those materials were estimated based off prices found on the McMaster-Carr site.

Table 4: Bill of Materials for Hull

Product	**Description**	**Cost**	**Additional info**	**Link**
Plexiglass	Fielect Clear Acrylic Sheet 11.69” x 8.27”	$ 9.99	1 count	Plexiglass Sheet (Amazon)
Gasket	Locking Rubber Gasket Window Seal 13/64” x 3/32”	$ 19.99	Not used	Locking Gasket Seal (Amazon)
Aluminum	Aluminum Sheet 24” x 36” x 0.063”	$ 43.96	1 count	3003 Series Aluminum Sheet (Mcmaster)

Steel Tubing	Circular Steel Tubing 0.049" OD 1.5" x 72"	$ 22.00	Provided by Nathan D.	
Steel Tubing	Square Steel Tubing 0.065" OD 1" x 36"	$ 20.00	Provided by Nathan D.	
Steel Plate	Steel Sheet 12" x 12"x 0.125"	$ 42.00	Provided by University	
Rivets	50 count of small head rivets 3/16" x 3/8"	$ 4.00	Provided by Nathan D.	
Bolts 3/8"	4 count of High strength steel bolts 3/8" x 1.5"	$ 8.00	Provided by Nathan D.	
Nuts 3/8"	4 count of steel nuts	$ 3.50	Provided by Nathan D.	
Bolts 1/4"	4 count of Low strength steel bolts 1/4" x 1"	$ 5.00	Provided by Nathan D.	
Paint	Apple Barrel Acrylic Paint White	$ 2.67	8 oz	Acrylic Paint (Amazon)
Epoxy	Loctite Five Minute Epoxy Instant Mix	$ 6.09	Not Used	Loctite Epoxy (Amazon)
Antennas	Telescopic Metal Antenna with screwed end	$ 8.98	5 count	Metal Long Antenna (Amazon)
Total Cost		$ 196.18		

Table 5: Bill of Material for Mobile Robot

Product	**Description**	**Cost**	**Additional info**	**Link**
Robot Kit	Adeept RaspClaws Hexapod Spider Robot Kit	$ 72.99	pieces of this kit were used in the final design	Robot Kit (Amazon)
Gecko Tape	Foam gecko tape, adhesive on both sides, plastic liner	$ 29.99	Temperature range: 15-120 degrees Fahrenheit	Reusable Grip Tape (McMaster-Carr)
Arduino UNO	Arduino UNO REV3	$ 29.95		Arduino UNO REV3 (Amazon)
Motor Shield	KEYESTUDIO 16-Channel 12-bit Servo Motor Driver Board I2C	$ 9.99		KEYESTUDIO 16-Channel Servo Motor Driver Board (Amazon)

	Interface for Arduino R3 Controller			
PLA Filament	Filament used for 3D printed elements of the robot	$ 19.99		PLA Filament (Amazon)
9V Battery	Energizer 9V Batteries, Max Premium 9 Volt Battery Alkaline	$ 6.61	2 pack	Energizer 9V Batteries (Amazon)
9V Battery Case	Gikfun 9v Battery Holder with ON/Off Switch for Arduino	$ 8.28	2 pack	9v Battery Holder (Amazon)
AA Batteries	Duracell Coppertop AA Batteries	$ 7.29	6 count packs	Duracell Coppertop AA Batteries (Amazon)
AA Battery Case	Ogrmar On/Off Switch 4 x 1.5V AA Battery Case Holder Leads Black w Cap	$ 6.99	2 pack	AA Battery Case Holder (Amazon)
Shoulder Bolts	Alloy Steel Shoulder Screws, 2mm Shoulder Diameter, 10 mm Shoulder Length, M1.6 x 0.35 mm	$ 20.04	6 bolts	Shoulder Screws (McMaster-Carr)
Nuts	Zinc-Plated Steel Hex Nut M1.6 x 0.35 mm	$ 11.60	50 pack	Hex Nut (McMaster-Carr)
Total Cost		$ 223.72		

Table 6: Bill of Material for Gripper

Product	**Description**	**Cost**	**Additional info**	**Link**
Strap	Elastic hook-and-loop strap	$ 13.87	10 pack	Elastic Reusable Cinch Straps (Amazon)
Adhesive	Loctite Super Glue	$ 3.88		Loctite Super Glue (Amazon)
Fabric Paint	Tulip Dimensional Fabric Paint	$ 3.66		Dimensional Fabric Paint (Amazon)
Total Cost		$ 21.41		

4.2 Labor

The total number of hours worked by each person was calculated from our logbook and was multiplied by the average rate of a mechanical engineer. These hours represent the hours logged from September 2022 to April 3rd, 2023. During the project, time was spent in the engineering department machine shop, 3D printing area, and with professors and technicians so the costs for those hours were estimated. The other costs come from the time with our graduate student team during our weekly meetings and were estimated as well.

Table 7: Labor Costs for Fall 2022 and some future projections for Spring 2023.

Labor Costs			
Person	Hours	Rate per hr.	Cost
Emily G.	176.5	$35	$6,177.50
Ashton O.	127	$35	$4,445.00
Julia P.	84.25	$35	$2,922.50
Nathan D.	117	$35	$4,095.00
University Resources (Estimate)	15	$50	$750.00
Other Costs (Estimate)	30 x 2 people	$35	$2,100.00
Total Labor Cost			**$20,490.00**

5. Standards

This design project involves three primary subsystems that are very diverse in nature. Due to this, a large variety of codes and standards can be applied to this project. To simplify the listing and description of these standards, the project is broken down into four parts: overall, simulated hull, mobile robot, and 3D scanning system.

For the overall project, many standards can be applied. One of these standards is ASME Y14.100 – 2017 "Engineering Drawing Practices" [23]. This standard contains information on engineering drawings such as essential requirements and reference documents [23]. The standard helps to explain the proper techniques used for preparation and revision of these drawings [23]. This standard can be used to ensure that the drawings created to manufacture the hull and gripper are up to standard. By meeting the standard, the drawings are ensured to be easy to read and understand, which can make the manufacturing process simpler.

For the hull, a symposia paper was found that would be helpful in the project. The symposia paper, ASTM STP47541S, "Welding Processes Applicable to Aluminum" [19], explains the best practices for welding aluminum. When scanning the details of the hull, welding will likely be used in the future and, since the material will be aluminum, best practices and safety protocols should be followed to ensure the hull can be constructed safely and well [19]. The paper describes various thicknesses of aluminum sheet metal and the corresponding welding methods and gases that should be used for each.

There are two standards that were considered when testing the mobile robot. The first standard is ASTM E2827/E2827M-20 "Standard Test Method for Evaluating Response Robot Mobility Using Crossing Pitch/Roll Ramp Terrains" [15n. This standard provides a test method for verifying a robot can maintain traction, prevent rollover, and perform self-righting, when necessary, on a discontinuous pitch/roll ramp terrain [15]. The standard involves the use of a low cost and easily fabricated test apparatus along with a simple procedure [15]. The standard then details how to evaluate the robot's capabilities. The testing procedures used in this standard could be replicated to be used on the simulated hull instead of the described test apparatus.

The second standard considered for use when testing the mobile robot is ASTM E2802/E2802M-21e1 "Standard Test Method for Evaluating Response Robot Mobility Using Variable Hurdle

Obstacles" [16]. This standard is formatted and contains similar information as the previous standard described. The only difference is that the test is designed for variable hurdle obstacles. The simulated hull will have hurdles, such as the rivets, welds, and window framing, that the mobile robot must be able to overcome. The methods used in this standard can be used to design adequate tests for our simulation.

For the 3D scanning element of the design project, ASTM E2641-09(2017) "Standard Practice for Best Practices for Safe Application of 3D Imaging Technology" [14] can be used. This standard communicates and documents the best practices for consistent and successful use of 3D imaging technology [14]. This standard also provides operator responsibilities, safety awareness, and safety plans [14]. Since a 3D scanner will be used in the final testing of the overall research project, it is important that correct safety procedures are followed to ensure no one is harmed and no equipment is damaged.

6. Societal, Ethical, and Environmental Concerns

This project could potentially benefit society at large. As space travel becomes more widespread and more dangers arise, such as space junk which is caused by UV degradation of spacecrafts and satellites, a reliable method to identify and fix issues will be needed [4]. Rather than abandoning a satellite when damage occurs, the potential to use a 3D scanner to scan the affected parts and send a robot to perform the repair can make space travel more sustainable. Sustainability in space will help reduce the environmental concerns of sending more rockets into space. This project can also protect the lives of those who are on the ISS or other spacecraft by allowing astronauts to send a robot to scan the ship, identify damages, and fix problems on the spacecraft, which could prevent future disasters such as Columbia.

This project also has potential financial and social implications as well. While structures in space require minimal upkeep due to the low-gravity, low-pressure environment, they are also subject to more extreme conditions in other ways. For example, hypervelocity impacts can create small holes or cracks in the exterior of spacecraft, which can be propagated by the extreme temperature variations seen in space [17]. With autonomous repair, resources that would have been allocated to the replacement or manual repair of such fractures could be used elsewhere.

These robots could advance space exploration by easily repairing issues instead of needing to send other support out to fix it or risk reentering Earth while damaged. Fixing spacecrafts is a lot more affordable than building new ones [3]. It is also better for the environment not to launch multiple spacecrafts, and instead have these robots attached to the ships and deployed once in space. So, to have this project prove the capability of these robots could help spacecraft become more sustainable.

Overall, this project is a proof of concept for a revolutionary system. If a spacecraft has a system that can identify and repair the hull while traveling, the effects will be monumental. Spacecraft will be able to remain functional for far longer, thus contributing less to the increasing amount of space debris surrounding the Earth. Additionally, with the ability to repair the hulls of spacecraft with robots, the need for astronauts to go on potentially dangerous spacewalks is minimized. The technology developed in this senior design project will add to other developments and research that will eventually make this system of automation a reality.

7. Conclusion

For this proof-of-concept project, there were three distinct parts - the spacecraft hull, the mobile robot, and the robotic gripper. All of them underwent the entire design process of research, design, manufacture, and testing. After trial-and-error testing and redesigns, all aspects were in working order and provided what was needed from them.

A variety of challenges occurred throughout the project. The biggest problem for the simulated spacecraft hull was having to redesign it after realizing certain aspects would not work and a different set of requirements was necessary. This took a lot of time that threw off the expected timetable. Another challenge was figuring out how to make the metal surface show up when 3D scanned. To take the shine off of the surface, a white powder spray was applied, and that helped it become scannable. However, this negatively impacted the ability of the gecko tape, located on the bottom of the robot's feet, to stick to the hull; so, the hull was fully painted white with acrylic paint instead. This allowed the hull to show up properly in scans and the gecko tape to better attach to the hull. Even with this being a better option for the robot and gecko tape, it still hinders the full ability of the gecko tape, so a different paint should be applied and tested in the future.

A variety of challenges were faced when designing and building the robot as well. The overall task of designing and building a mobile robot was daunting, as the team had no experience with robotics or electrical systems. Once a design had been chosen and assembled, it was determined that the design was not compatible with gecko tape, and a major design change was needed to allow the legs to overcome the gripping force of the gecko tape. Another challenge was coding the robot to walk, as the motor shield used is only compatible with Arduino IDE and the team had limited experience coding in C/C++. Finally, once it was working and able to traverse a flat surface, it was discovered that the robot is unable to climb the steeper sections of the hull. However, the robot can traverse the flatter sections of the hull, and is sufficient for this proof-of-concept project.

The gripper also faced challenges in the testing phase. It was determined that the strap length needed to be shortened and fabric paint was necessary to help keep the 3D printed scanner from shifting out of place. This helped to secure it properly and minimize any shifting. Additionally, the connection plate needed to be reprinted to add counterbores so the bolts that came with the robotic arm could be utilized. Once those changes were made, the gripper was able to fulfill its requirements.

There are many changes that can be made in the future to improve this project. These improvements would be primarily focused on the robot, but there are some changes that could be made for the gripper and spacecraft hull. Since the gripper was tested and fixed, the only update it would need is getting the robotic arm that it attaches to coded and fully functioning. In the future, if the actual 3D light scanner is to be used by a robotic arm, the FANUC robot owned by the university would need to be used and a new gripper design would be needed. The updates for the hull would be the addition of mock damage to see how it will scan. The damage could include scratching the paint, hitting it with a hammer, and removing an antenna. There could also be welds added to the hull's surface to have more attachments and features. Additionally, new paint options should be explored, as the acrylic paint is difficult for gecko tape to adhere to, but the hull cannot be left unpainted due to scanning difficulties.

The robot would require the most changes because the robot built during this project lacks the ability to traverse the full hull. When attempting to climb the more curved sections of the unpainted hull, the gecko tape is unable to get a sufficient grip and the robot begins to slide off. The addition of more gecko tape may help to resolve this issue when the hull is unpainted. However, the micro servo motors, obtained from the Adeept kit and believed to be MG90s micro servos, do not have a high enough torque to lift the foot if more gecko tape is attached to the unpainted surface, as discussed in the robot testing section. If an unpainted surface were to be used, stronger motors would likely need to be implemented.

The hull, however, is currently painted with white acrylic paint. The gecko tape was tested on this as well, and showed impaired gripping capabilities, as discussed in the testing section. Given this, the gecko tape is unable to allow the robot to climb on the acrylic painted surface. So, it is likely that either another paint, a different form of gecko tape, or other adhesive will need to be used.

Another option for improving the gripping capacity of the robot would be to add two additional legs. The addition of these legs would allow for more gecko tape to be adhered to the surface at all times. This may help reduce the slipping currently experienced by the robot. An alternative option to additional legs would be to add a two-link articulated arm to the top of the robot. This arm would feature a large area of gecko tape on the end, and would allow the robot to stick to the hull via this arm while the feet move forward. This arm could alternatively be used to help pull the robot forward when it is on the more inclined sections of the hull.

An additional problem that may occur when the robot is attempting to traverse the hull is an unexpected shear force acting on the gecko tape. When the robot is on an inclined, curved surface, gravity is pulling the robot downwards. This force may be causing the robot to begin to slip down the surface of the hull, thus adding a shear force to the gecko tape. A way to counteract this would be to move the leg forward, to bring the gecko tape into a normal position, before lifting the foot.

It should be noted that the force of gravity in space would be next to zero. So, the shear forces the gecko tape is experiencing would be greatly reduced and the robot could likely traverse the hull as it does on the flatter sections. To verify this, the hull could be repositioned, so the supports are the same height. This would remove the additional incline seen in the current design and remove some of the shear forces experienced by the robot.

Overall, the purpose of this proof-of-concept project was to get a 3D scan of a spacecraft hull and have a robot walk on the hull. To achieve this, there was a lot of testing and many adjustments that needed to be made. However, at the end of the project, the main goals were accomplished. The simulated spacecraft hull appears in 3D scanning, including rivets and the plexiglass window, but other features, such as antennas, do not show up well and appear as small divots instead. While the mobile robot is unable to traverse the entire hull, it is able to walk on the sections with less incline, thus proving that it can maneuver on the curved surface with the use of gecko tape to cling to the surface. This proof-of-concept project can now be used for the next steps of the larger Space Force research project.

References

[1] A. Parness, R. Smith, C. Fuller, N. Wiltsie, S. Kalouche, D. Ruffatto, M. Dadkhah, J. Karras, K. Carpenter, and M. Spenko, "Zero Gravity Robotic Mobility Experiments with Electrostatic and Gecko-Like Adhesives Aboard NASA's Zero Gravity Airplane," 2015. [Online]. Available: https://web.stanford.edu/~kalouche/docs/zero_g.pdf. [Accessed: 06-Nov-2022].

[2] A. Rathi, "Photos: This is the damage that tiny space debris traveling at incredible speeds can do," *What spacecrafts look like when hit by minuscule space debris traveling at incredible speeds*, 21-Jul-2022. [Online]. Available: https://qz.com/773511/photos-this-is-the-damage-that-tiny-space-debris-traveling-at-incredible-speeds-can-do/amp. [Accessed: 11-Nov-2022].

[3] Garner, R. (2020, April 23). Astronauts, Robots & the history of fixing & building things in space. NASA. Retrieved October 30, 2022, from https://www.nasa.gov/feature/goddard/2020/astronauts-robots-and-the-history-of-fixing-and-building-things-in-space

[4] I. Whitcomb, "How do tiny pieces of space junk cause incredible damage?," *LiveScience*, 14-Mar-2021. [Online]. Available: https://www.livescience.com/tiny-space-junk-damage.html. [Accessed: 11-Nov-2022].

[5] J. Hu, X. Han, Y. Tao, and S. Feng, "A magnetic crawler wall-climbing robot with capacity of high payload on the convex surface," 15-Nov-2021. [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/S0921889021001925. [Accessed: 05-Nov-2022].

[6] M. Choi, "What materials can survive in space?," *National Technical Systems*, 23-Sep-2019. [Online]. Available: https://nts.com/ntsblog/materials-survive-in-space/. [Accessed: 10-Nov-2022].

[7] M. Wu, G. Pan, T. Zhang, S. Chen, F. Zhuang, and Z. Yan-zheng, “Design and optimal research of a non-contact adjustable ... - sage journals,” 23-Jan-2013. [Online]. Available: https://journals.sagepub.com/doi/10.5772/54008. [Accessed: 06-Nov-2022].

[8] P. Davis, Ed., “Basics of space flight - solar system exploration: NASA science,” *NASA*. [Online]. Available: https://solarsystem.nasa.gov/basics/chapter11-1/. [Accessed: 11-Nov-2022].

[9] “Materials Data Handbook: Aluminum Alloy 6061 - NASA technical reports server (NTRS),” *NASA*, 06-Aug-2013. [Online]. Available: https://ntrs.nasa.gov/citations/19720022808. [Accessed: 07-Nov-2022].

[10] “Resourceslink - Adeept,” RaspClaws . [Online]. Available: https://www.adeept.com/video/static1/itemsfile/49523Tutorial_V2.pdf. [Accessed: 30-Mar-2023].

[11] R. Rocha, “Accident Case Study of Organizational Silence & Communication Breakdown: Shuttle Columbia, Mission STS-107,” *nasa.gov*, 27-Jan-2011. [Online]. Available: https://www.nasa.gov/pdf/553084main_Case_Study_Silence_Breakdown_Columbia_Rocha.pdf. [Accessed: 09-Nov-2022].

[12] “Shop,” Tower Pro. [Online]. Available: https://www.towerpro.com.tw/product/mg90s-3/. [Accessed: 04-Apr-2023].

[13] Space Foundation Editorial Team, “Components of a satellite,” *Space Foundation*, 10-Feb-2021. [Online]. Available: https://www.spacefoundation.org/space_brief/satellite-components/. [Accessed: 11-Nov-2022].

[14] “Standard practice for best practices for safe application of 3D imaging technology,” 06-May-2022. [Online]. Available: https://www.astm.org/e2641-09r17.html. [Accessed: 07-Nov-2022].

[15] “Standard test method for evaluating response robot mobility using crossing pitch/roll ramp terrains,” 07-Apr-2020. [Online]. Available: https://www.astm.org/e2827_e2827m-20.html. [Accessed: 07-Nov-2022].

[16] “Standard test method for evaluating response robot mobility using variable hurdle obstacles,” 21-May-2021. [Online]. Available: https://www.astm.org/e2802_e2802m-21e01.html. [Accessed: 07-Nov-2022].

[17] The European Space Agency. (n.d.). Hypervelocity impacts and protecting spacecraft. ESA. Retrieved October 30, 2022, from https://www.esa.int/Space_Safety/Space_Debris/Hypervelocity_impacts_and_protecting_spacecraft

[18] T. Yasaka and J. Onoda, “Spacecraft Structures,” in *Encyclopedia of Physical Science and Technology*, Third.

[19] W. Dunlap, “Welding processes applicable to aluminum,” *Welding Processes Applicable to Aluminum*, 01-Jan-1931. [Online]. Available: https://www.astm.org/stp47541s.html. [Accessed: 07-Nov-2022].

[20] W. Wassmer, “The materials used in artificial satellites and Space Structures,” *AZoM.com*, 05-Jun-2020. [Online]. Available: https://www.azom.com/amp/article.aspx?ArticleID=12034. [Accessed: 11-Nov-2022].

[21] X. Hou, Y. Su, S. Jiang, L. Li, T. Chen, L. Sun, and Z. Deng, “Adhesion mechanism of space-climbing robot based on discrete element and dynamics,” Apr-2018. [Online]. Available: https://journals.sagepub.com/doi/epub/10.1177/1687814018772934. [Accessed: 05-Nov-2022].

[22] Y. Liu and T. W. Seo, “AnyClimb-II: Dry-adhesive linkage-type climbing robot for uneven vertical surfaces,” 13-Mar-2018. [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/S0094114X17310571. [Accessed: 05-Nov-2022].

[23] “Y14.100 - engineering drawing practices: ASME,” 2017. [Online]. Available: https://www.asme.org/codes-standards/find-codes-standards/y14-100-engineering-drawing-practices/2017. [Accessed: 07-Nov-2022].

Appendix A: Requirement and Verification Table

Table 8: System Requirements and Verifications

Requirement	Verification	Verification status (Y or N)
1. Hull a. Curvature of radius of 45 b. Angle of hull from surface to top of hull of 20 degrees c. Low cost d. High strength e. Window f. Obstacles g. Able to be 3D scanned	1. Verification a. Measured to be within +/- 5 degrees b. Hull is at a 23 degree angle c. Total cost of: $196.18 d. Hull is rated to hold 2.8 psi of force e. Plexiglass window was inserted in middle of hull f. Antennas, rivets, window, bolts were added g. Surface had to be fully painted to be scanned	Y
2. Mobile Robot a. Able to walk on table without assistance b. Able to walk with gecko tape c. Can walk on a slightly curved surface d. Able to navigate around obstacles on a curved surface e. Low cost f. High speed g. Lightweight h. Small size i. Highly durable j. Easy to assemble k. High movement redundancy	2. Verification a. Has a stable gait on a flat surface b. Can pick up feet with gecko tape c. Can walk on the hull with gecko tape d. Not met. No pathfinding algorithm was encoded e. Total cost of: $223.72 f. Speed of: 0.355 in/s g. Weight of: 513 g (1.1 lb) h. Approx. volume of: 195 $in.^3$ i. Electronics located as close to centroid as practical j. Separable part count of: 149 k. 4 legs, minimum of 2 in contact with the ground at any given time	Y
3. Gripper a. Lightweight b. Low interference	3. Gripper Verification	Y

c. Easily able to grip scanner d. Securely grip scanner e. Convenient to mount f. Easily manufactured	a. Gripper and 3D printed scanner are below 1 kg threshold b. The gripper does not interfere with the movement of the robotic arm c. The gripper is relatively easy to attach d. The 3D printed scanner experiences low levels of shifting when attached with the gripper e. The gripper can be mounted to the robotic arm using the bolt holes f. The gripper is easily constructed	

Appendix B: FMEA Charts

Table 9: FMEA chart for the hull.

Item	Function	Potential Failure Mode	Potential Effect(s) of Failure	Severity	Potential Cause(s) of Failure	Occurrence	Current Design Controls (Prevention)	Current Design Controls (Detection)	Detection	RPN
Antennas	Attach to hull to mockup antennas in space for the robot to traverse around.	Antennas do not properly attach.	Not being able to accurately try scanning on the hull for attachments.	5	Not attaching it properly.	4	none	It will be seen if it is attached or not.	2	40
Window	Attach to hull to mockup windows in space for the robot to traverse around.	Can't get the plexiglass to curve properly.	Not having another obstacle to prove the robot can get around it.	6	Not curving it properly.	4	none	It will be seen if it is attached or not.	2	48
Bracket	Help to support the hull.	Not properly holding the hull and it falls/breaks.	Breaking the hull by dropping it.	8	Not having a strong enough base.	3	none	Checking the bracket for defects.	4	96

Hull	Mockup of a part of a space craft.	Too weak for a robot to walk on it, can't hold up after purposely damaging it.	The hull is broken and not able to test anything.	9	Being too thin of a material.	3	none	Checking the hull for defects.	4	108

Table 10: FMEA chart for the mobile robot.

Item	Function	Potential Failure Mode	Potential Effect(s) of Failure	Severity	Potential Cause(s) of Failure	Occurrence	Current Design Controls (Prevention)	Current Design Controls (Detection)	Detection	RPN
Legs	The legs allow the robot to traverse the hull.	The legs are unable to move or break.	The robot cannot traverse the hull.	8	A joint or other element of the leg may break. Motors may malfunction making the legs unable to move.	4	The robot will have an adequate number of legs to bear the weight of the robot. These legs will be made of high-quality parts and materials.	The robot will be inspected before running and will be walked across a flat surface before the curved hull.	5	160
Adhesion	The adhesive on the bottom of the robot’s feet allows it to cling	The adhesive fails and releases from the hull.	The robot falls and is damaged.	9	The force on the adhesive is too high and fails. The feet become excessively	6	The robot will have an adequate number of feet to ensure the adhesive does not fail.	The footpads should be inspected for wear and dirt.	3	162

	to the curved surface.				dirty and will not cling.		The footpads should be cleaned before each run to ensure proper adhesion.			
Camera	The camera allows the robots perspective to be observed.	The camera stops operating.	The robot is unable to display or record.	4	The camera malfunctions, the wiring is damaged, or the camera does not receive power.	3	The camera will be installed carefully, and equipment will be inspected before use.	The camera will be turned on and checked before running the simulation.	2	24
Battery	The battery provides power to the robot to allow it to move and operate the camera.	The battery does not provide power.	The robot cannot move, and the camera will not power on.	8	The battery is not charged, malfunctions, or the wiring is unable to transfer power to the rest of the system.	7	The battery should be charged before running tests. The battery will be carefully installed, and care will be taken to wire it properly.	Battery power levels should be checked before starting the simulation.	1	56

Table 11: FMEA chart for the gripper.

Item	Function	Potential Failure Mode	Potential Effect(s) of Failure	Severity	Potential Cause(s) of Failure	Occurrence	Current Design Controls (Prevention)	Current Design Controls (Detection)	Detection	RPN
Connection plate	3D printed plate connects gripper to robot via 4 bolts.	3D printed plate breaks and disconnects from robot.	The 3D scanner detaches and falls potentially damaging the 3D scanner and other equipment. The fall could also cause minor injuries to a nearby person.	9	The load on plate is more than the 3D printed material can handle and causes failure.	2	The load will be centered, and adequate material thickness will be used to ensure the plate can bear the load of the scanner.	The plate, specifically around bolts, will be inspected before attaching 3D scanner and checked before running the program.	2	36
Strap	The strap holds the 3D scanner to the connection plate.	Strap breaks or fails so that 3D scanner is no longer connected to the robotic arm.	The 3D scanner detaches and falls potentially damaging the 3D scanner and other equipment. The fall	9	The strap could rip, the clip could break or allow the strap to slip loose, or the hook-and-	3	A strap that is thick, has a solid clip or strong hook-and-loop, and is rated for a much higher load than the load seen by the robotic	The strap will be inspected to ensure there are no signs of wear and the clip or hook-and-loop are secure	2	54

			could also cause minor injuries to a nearby person.		loop could pull apart.		arm will be used.	before each simulation.		
Connection of strap to plate	Superglue or a similar adhesive will attach the strap to the connection plate.	The adhesive fails and the strap disconnects from the plate.	The 3D scanner detaches and falls potentially damaging the 3D scanner and other equipment. The fall could also cause minor injuries to a nearby person.	9	The adhesive could be unable to correctly adhere to either the strap or the plate. The adhesive could also break down overtime.	1	An adhesive that adheres to the material of the strap and the connection plate as well as has the proper strength will be used.	The adhesive will be examined before running the simulation to ensure the strap is secure.	2	18

Appendix C: Code

Code for mobile robot's motion:

```
      delay(350); //350 millisecond delay before next action
      pwm.setPWM(11, 0, 225); //Put front left foot down
      pwm.setPWM(5, 0, 130); //Put back right foot down
      delay(400); //400 millisecond delay before next action

      // Front Right/Back Left
      pwm.setPWM(7, 0, 200); //Pick front right foot up
      pwm.setPWM(9, 0, 130); //Pick back left foot up
      delay(350); //350 millisecond delay before next action

      while (pulselen10 > hip_10_back and pulselen4 < hip_4_back and pulselen6 >
hip_6_fwd and pulselen8 < hip_8_fwd) {
        pwm.setPWM(10, 0, pulselen10); //Move front left hip forward 20 ticks from
center position
        pwm.setPWM(4, 0, pulselen4); //Move back right hip forward 50 ticks from
center position
        pwm.setPWM(6, 0, pulselen6); //Move front right hip backward 35 ticks from
center position
        pwm.setPWM(8, 0, pulselen8); //Move back left hip backward 40 ticks from
center position
        if (pulselen10 > hip_10_back) {
          pulselen10--;
        }
        if (pulselen4 < hip_4_back) {
          pulselen4++;
        }
        if (pulselen6 > hip_6_fwd) {
          pulselen6--;
        }
        if (pulselen8 < hip_8_fwd) {
          pulselen8++;
        }
        delay(5);
      }

      delay(350); //350 millisecond delay before next action
      pwm.setPWM(7, 0, 120); //Put front right foot down
      pwm.setPWM(9, 0, 200); //Put back left foot down
      delay(400); //400 millisecond delay before next action
}
```

```
#include <Servo.h>

#include <Wire.h>
#include<Adafruit_PWMServoDriver.h>

// called this way, it uses the default address 0x40
Adafruit_PWMServoDriver pwm = Adafruit_PWMServoDriver();
// you can also call it with a different address you want
//Adafruit_PWMServoDriver pwm = Adafruit_PWMServoDriver(0x41);
// you can also call it with a different address and I2C interface
//Adafruit_PWMServoDriver pwm = Adafruit_PWMServoDriver(0x40, Wire);

// Depending on your servo make, the pulse width min and max may vary, you
// want these to be as small/large as possible without hitting the hard stop
// for max range. You'll have to tweak them as necessary to match the servos you
// have!

#define SERVO_FREQ 50 // Analog servos run at ~50 Hz updates

#define hip_4_back 285
#define hip_4_fwd 85

#define hip_6_back 335
#define hip_6_fwd 195

#define hip_8_back 80
#define hip_8_fwd 240

#define hip_10_back 155
#define hip_10_fwd 235

void setup() {
 Serial.begin(9600);
  Serial.println("8 channel Servo test!");

  pwm.begin();

  //We do not know what these lines do but PLEASE DO NOT DELETE THEM!!! You will
kill John and if you do it too many times he will get arthritis.
 pwm.setOscillatorFrequency(27000000);
  pwm.setPWMFreq(SERVO_FREQ);  // Analog servos run at ~50 Hz updates

  pwm.setPWM(4, 0, 235); //Motor 4 > back right hip, center at 235
  pwm.setPWM(5, 0, 130); //Motor 5 > back right foot, down position at 130
  pwm.setPWM(6, 0, 230); //Motor 6 > front right hip, center at 190
  pwm.setPWM(7, 0, 120); //Motor 7 > front right foot, down position at 120
```

```
  pwm.setPWM(8, 0, 200); //Motor 8 > back left hip, center at 200
  pwm.setPWM(9, 0, 215); //Motor 9 > back left foot, down position at 215
  pwm.setPWM(10, 0, 175); //Motor 10 > front left hip, center at 175
  pwm.setPWM(11, 0, 215); //Motor 11 > front left foot, down position at 215

  delay(5000);

}

void loop() {
  // John's walking loop

      // Front Left/Back Right
      pwm.setPWM(11, 0, 140); //Pick front left foot up
      pwm.setPWM(5, 0, 200); //Pick back right foot up
      delay(350); //350 millisecond delay before next action

      int pulselen10 = hip_10_back;
      int pulselen4 = hip_4_back;
      int pulselen6 = hip_6_fwd;
      int pulselen8 = hip_8_fwd;

      while (pulselen10 < hip_10_fwd and pulselen4 > hip_4_fwd and pulselen6 <
hip_6_back and pulselen8 > hip_8_back) {
        pwm.setPWM(10, 0, pulselen10); //Move front left hip forward 20 ticks from
center position
        pwm.setPWM(4, 0, pulselen4); //Move back right hip forward 50 ticks from
center position
        pwm.setPWM(6, 0, pulselen6); //Move front right hip backward 35 ticks from
center position
        pwm.setPWM(8, 0, pulselen8); //Move back left hip backward 40 ticks from
center position
        if (pulselen10 < hip_10_fwd) {
          pulselen10++;
        }
        if (pulselen4 > hip_4_fwd) {
          pulselen4--;
        }
        if (pulselen6 < hip_6_back) {
          pulselen6++;
        }
        if (pulselen8 > hip_8_back) {
          pulselen8--;
        }
        delay(5);
      }
```

Code for mobile robot's pathfinding:

```
%Terrestrial Tinkerers
%Nathan Doty
%Emily Greene
%Ashton Orosa
%Julia Patek

%April 2023

clear
clc
close all
```

Object and Obstacles Growing Code:

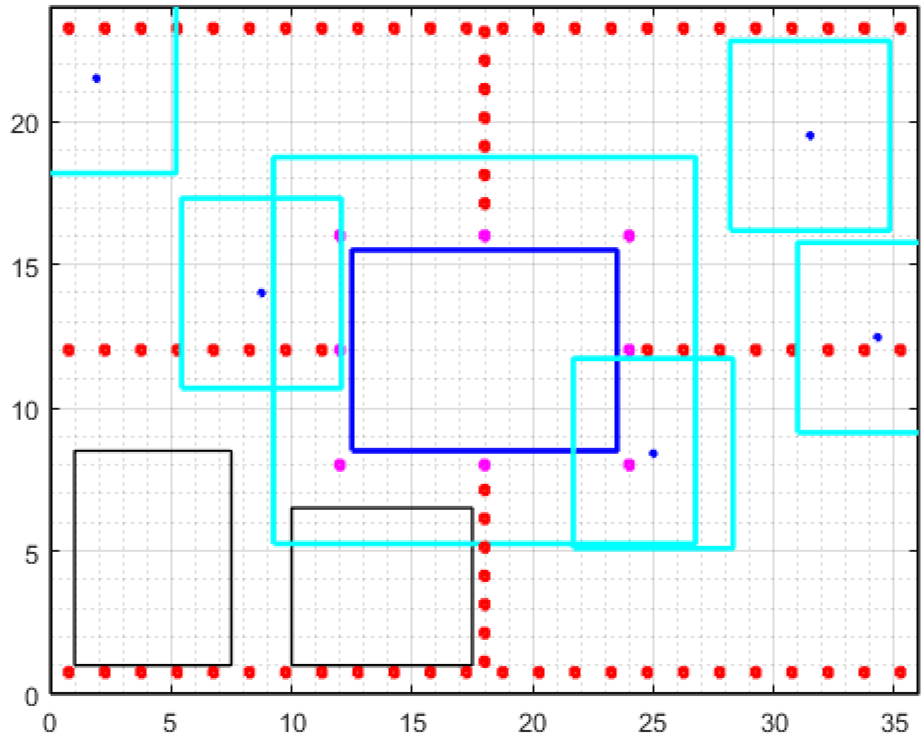
```
%Start Point
xstart=[1 1 7.5 7.5 1];
ystart=[1 8.5 8.5 1 1];
plot(xstart,ystart,'k','LineWidth',1)
hold on

%End Point
xfinish=[10 10 17.5 17.5 10];
yfinish=[1 6.5 6.5 1 1];
plot(xfinish,yfinish,'k','LineWidth',1)

%Path Perimiter
xbound=[0 0 36 36 0];
ybound=[0 24 24 0 0];
plot(xbound,ybound,'k','LineWidth',1)

%plot parameters
axis([0 36 0 24])
grid on
grid minor

% Plexiglass window
x1=[12.5 12.5 23.5 23.5 12.5];
y1=[8.5 15.5 15.5 8.5 8.5];
plot(x1,y1,'b','LineWidth',2)

% Plexiglass window grown
grow = 3.25;
x1g=[12.5-grow 12.5-grow 23.5+grow 23.5+grow 12.5-grow];
y1g=[8.5-grow 15.5+grow 15.5+grow 8.5-grow 8.5-grow];
plot(x1g,y1g,'c','LineWidth',2)

%Rivets bottom row
xr1 = [];
yr1 = [];
```

```
rivetDist = 1.5;
num = 0;

for count = 1:1:24
    xr1= [.625+rivetDist*num .625+rivetDist*num .875+rivetDist*num ...
        .875+rivetDist*num .625+rivetDist*num];
    yr1= [.625 .875 .875 .625 .625];
    num = count;
    plot(xr1,yr1,'r','LineWidth',2)

    xr1 = [];
    yr1 = [];
end

%Rivets top row
xr2 = [];
yr2 = [];
rivetDist = 1.5;
num = 0;

for count = 1:1:24
    xr2= [.625+rivetDist*num .625+rivetDist*num .875+rivetDist*num ...
        .875+rivetDist*num .625+rivetDist*num];
    yr2= [.625+22.5 .875+22.5 .875+22.5 .625+22.5 .625+22.5];
    num = count;
    plot(xr2,yr2,'r','LineWidth',2)

    xr2 = [];
    yr2 = [];
end

%Rivets horizontal row
xr3 = [];
yr3 = [];
rivetDist = 1.5;
num = 0;

for count = 1:1:7
    xr3= [.625+rivetDist*num .625+rivetDist*num .875+rivetDist*num ...
        .875+rivetDist*num .625+rivetDist*num];
    yr3= [.625+11.25 .875+11.25 .875+11.25 .625+11.25 .625+11.25];
    num = count;
    plot(xr3,yr3,'r','LineWidth',2)

    xr3 = [];
    yr3 = [];
end

for count = 16:1:24
    xr3= [.625+rivetDist*num .625+rivetDist*num .875+rivetDist*num ...
        .875+rivetDist*num .625+rivetDist*num];
    yr3= [.625+11.25 .875+11.25 .875+11.25 .625+11.25 .625+11.25];
    num = count;
    plot(xr3,yr3,'r','LineWidth',2)
```

```
    xr3 = [];
    yr3 = [];
end

%Rivets vertical row
xr4 = [];
yr4 = [];
rivetDist = 1;
num = 0;

for count = 1:1:6
    xr4= [.625+17.25 .625+17.25 .875+17.25 .875+17.25 .625+17.25];
    yr4= [1+rivetDist*num 1.25+rivetDist*num 1.25+rivetDist*num ...
        1+rivetDist*num 1+rivetDist*num];
    num = count;
    plot(xr4,yr4,'r','LineWidth',2)

    xr4 = [];
    yr4 = [];
end

for count = 16:1:23
    xr4= [.625+17.25 .625+17.25 .875+17.25 .875+17.25 .625+17.25];
    yr4= [1+rivetDist*num 1.25+rivetDist*num 1.25+rivetDist*num ...
        1+rivetDist*num 1+rivetDist*num];
    num = count;
    plot(xr4,yr4,'r','LineWidth',2)

    xr4 = [];
    yr4 = [];
end

%Bolts around window
xb1=[11.875 11.875 12.125 12.125 11.875];
yb1=[15.875 16.125 16.125 15.875 15.875];
plot(xb1,yb1,'m','LineWidth',2)

xb2=[11.875+6 11.875+6 12.125+6 12.125+6 11.875+6];
yb2=[15.875 16.125 16.125 15.875 15.875];
plot(xb2,yb2,'m','LineWidth',2)

xb3=[11.875+12 11.875+12 12.125+12 12.125+12 11.875+12];
yb3=[15.875 16.125 16.125 15.875 15.875];
plot(xb3,yb3,'m','LineWidth',2)

xb4=[11.875 11.875 12.125 12.125 11.875];
yb4=[15.875-8 16.125-8 16.125-8 15.875-8 15.875-8];
plot(xb4,yb4,'m','LineWidth',2)

xb5=[11.875+6 11.875+6 12.125+6 12.125+6 11.875+6];
yb5=[15.875-8 16.125-8 16.125-8 15.875-8 15.875-8];
plot(xb5,yb5,'m','LineWidth',2)
```

```
xb6=[11.875+12 11.875+12 12.125+12 12.125+12 11.875+12];
yb6=[15.875-8 16.125-8 16.125-8 15.875-8 15.875-8];
plot(xb6,yb6,'m','LineWidth',2)

xb7=[11.875 11.875 12.125 12.125 11.875];
yb7=[15.875-4 16.125-4 16.125-4 15.875-4 15.875-4];
plot(xb7,yb7,'m','LineWidth',2)

xb8=[11.875+12 11.875+12 12.125+12 12.125+12 11.875+12];
yb8=[15.875-4 16.125-4 16.125-4 15.875-4 15.875-4];
plot(xb8,yb8,'m','LineWidth',2)

%Antennas (measurments are not accurate 100%)
num = (1/8)/2; %diameter of antenna (needs changed)
x2=[8.75-num 8.75-num 8.75+num 8.75+num 8.75-num];
y2=[14-num 14+num 14+num 14-num 14-num];
plot(x2,y2,'b','LineWidth',2)

x3=[1.9-num 1.9-num 1.9+num 1.9+num 1.9-num];
y3=[21.5-num 21.5+num 21.5+num 21.5-num 21.5-num];
plot(x3,y3,'b','LineWidth',2)

x4=[25-num 25-num 25+num 25+num 25-num];
y4=[8.4-num 8.4+num 8.4+num 8.4-num 8.4-num];
plot(x4,y4,'b','LineWidth',2)

x5=[34.3-num 34.3-num 34.3+num 34.3+num 34.3-num];
y5=[12.45-num 12.45+num 12.45+num 12.45-num 12.45-num];
plot(x5,y5,'b','LineWidth',2)

x6=[31.5-num 31.5-num 31.5+num 31.5+num 31.5-num];
y6=[19.5-num 19.5+num 19.5+num 19.5-num 19.5-num];
plot(x6,y6,'b','LineWidth',2)

%Antennas Grown
grow =3.25;
x2g=[8.75-num-grow 8.75-num-grow 8.75+num+grow 8.75+num+grow 8.75-num-grow];
y2g=[14-num-grow 14+num+grow 14+num+grow 14-num-grow 14-num-grow];
plot(x2g,y2g,'c','LineWidth',2)

x3g=[1.9-num-grow 1.9-num-grow 1.9+num+grow 1.9+num+grow 1.9-num-grow];
y3g=[21.5-num-grow 21.5+num+grow 21.5+num+grow 21.5-num-grow 21.5-num-grow];
plot(x3g,y3g,'c','LineWidth',2)

x4g=[25-num-grow 25-num-grow 25+num+grow 25+num+grow 25-num-grow];
y4g=[8.4-num-grow 8.4+num+grow 8.4+num+grow 8.4-num-grow 8.4-num-grow];
plot(x4g,y4g,'c','LineWidth',2)

x5g=[34.3-num-grow 34.3-num-grow 34.3+num+grow 34.3+num+grow 34.3-num-grow];
y5g=[12.45-num-grow 12.45+num+grow 12.45+num+grow 12.45-num-grow ...
    12.45-num-grow];
plot(x5g,y5g,'c','LineWidth',2)

x6g=[31.5-num-grow 31.5-num-grow 31.5+num+grow 31.5+num+grow 31.5-num-grow];
```

```
y6g=[19.5-num-grow 19.5+num+grow 19.5+num+grow 19.5-num-grow 19.5-num-grow];
plot(x6g,y6g,'c','LineWidth',2)
```



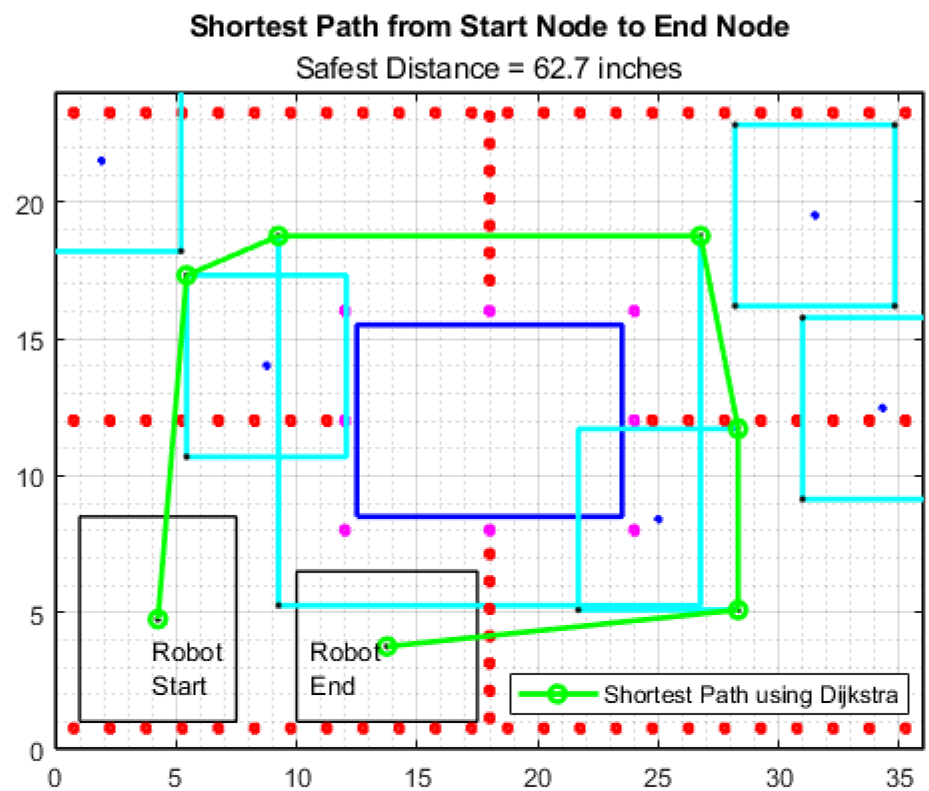
Shortest Path Code:

```
  nodes = [ 1  4.25 4.75 ;
            2 5.4375  10.6875 ;
            3 5.4375  17.3125 ;
            4 5.2125   18.1875 ;
            5 9.25    18.75 ;
            6 26.75  18.75 ;
            7 28.1875  22.8125 ;
            8 28.1875   16.1875 ;
            9 34.8125    16.1875 ;
           10 34.8125  22.8125 ;
           11 30.9875  15.7625 ;
           12 30.9875   9.1375 ;
           13 28.3125  11.7125 ;
           14 28.3125 5.0875 ;
           15 21.6875  5.0875 ;
           16 9.25   5.25 ;
           17 13.75 3.75];

segments= [ 1   1   2 ;
            2   1   3 ;
```

```
            3   1   4 ;
            4   2   3 ;
            5   2   4 ;
            6   3   4 ;
            7   3   5 ;
            8   4   5 ;
            9   4   7 ;
            10  5   6 ;
            11  5   7 ;
            12  6   7 ;
            13  6   8 ;
            14  6   12 ;
            15  6   13 ;
            16  7   10;
            17  7   8 ;
            18  8   9 ;
            19  8   11 ;
            20  8   12 ;
            21  8   13 ;
            22  9   11;
            23  9   10;
            24  11  12;
            25  11  13;
            26  11  14;
            27  12  13;
            28  12  14;
            29  13  14;
            30  14  15;
            31  14  17;
            32  15  16;
            33  15  17;
            34  16  17];
start_id=1;
finish_id=17;

hold on
num_nodes=17;
plot(nodes(:,2),nodes(:,3),'k.') % plot the nodes

% run path planning algorithm
[distance,path] = dijkstra(nodes,segments,start_id,finish_id);
disp(['Shortest path = ' num2str(path)]);
disp(['Shortest path distance = ' num2str(distance)]);

%figure(h)
for k = 2:length(path)
    m = find(nodes(:,1) == path(k-1));
    n = find(nodes(:,1) == path(k));
    h2 = plot([nodes(m,2) nodes(n,2)],[nodes(m,3) nodes(n,3)], ...
        'go-','LineWidth',2);
end

% Plot Settings
```

```
title('Shortest Path from Start Node to End Node', ...
    sprintf('Safest Distance = %0.1f inches', distance))
legend([h2],{'Shortest Path using Dijkstra'},'Location', ...
    [0.69 0.15 0.05 0.05])
text( 4 , 3 ,['Robot', char(10), 'Start'])
text( 10.5 , 3 ,['Robot', char(10), 'End'])
```

```
Shortest path = 1    3    5    6   13   14   17
Shortest path distance = 62.6507
```



Published with MATLAB® R2022b

Dijkstra algorithm function code license: