Tumble Bot

Final Design Review

Sponsored by: NASA Jet Propulsion Laboratory

Project Members:
Lena Beyer
Liam Chaffey
Blake Gonzales
Jensen Severance

Mechanical Engineering Department
California Polytechnic State University
San Luis Obispo

December 12, 2019

Table of Contents

Table of Figures

Abstract

Passive locomotion is the ability for an object to move from one place to another by the means of the environment. In nature species such as tumbleweed, fox tails, plankton, and man o' war jellyfish rely on passive modes of transportation for survival and are able to cross vast distances with little to no expenditure of their own energy. This document seeks to explore the feasibility of building a machine relies on the energy of Mars' environment to explore the Martian surface.

The "Tensegrity Tumbleweed Locomotion" (nicknamed Tumble Bot) senior project was sponsored by NASA Jet Propulsion Laboratory (JPL). The goal of this project was to create a proof-of-concept design that uses passive locomotion to traverse at least 20% of Mars' surface. The structure must be capable of transporting a 1.5 kg payload of instrumentation that would be used to collect data and images of the surface. Ideally Tumble Bots would be able to be deployed in several locations all over the Martian surface so that a basic knowledge of the surface conditions over a wide area could be developed. This knowledge would then serve to guide future missions that would conduct more in-depth testing of areas of interest. Ideally the ball would be able to overcome small obstacles and be able to get out of small holes.

Extensive research, ideation, and testing was done to determine the optimal design for a structure that would meet as many of the design criteria as possible. The design criteria evolved substantially over the first two quarters of this project as the difficulty of this problem was more thoroughly understood. Folding, overcoming rocks, getting out of holes, and assembly of a fully functional prototype were all removed from the design requirements. This project was pitched as a tensegrity structure, but during the design process it was decided that tensegrity structures with curved members met the design criterion better than the traditional tensegrity structures with straight members. The members continued to be modified to make the structure more spherical. Ultimately it was decided that a non-tensegrity structure would best meet the weight requirements while still producing a spherical geometry.

The engineering challenge addressed by this project was a very large, open-ended problem. The final design presented in this report roughly outlines the optimal design, but still has room for improvement. Development of a more optimal design could continue beyond the time that was allotted to complete this project.

This Final Design Review aims to guide the reader through the development of this project and explains what analysis was done in order to draw the conclusions outlined in this report. The progression of the design process is clearly explained with the hope that it can be easily followed and built upon by future endeavors to make a successful Tumble Bot. Included in this document are suggestions of how this project could best be continued.

Chapter 1. Introduction

Mars exploration has historically been a costly and time-consuming endeavor. Current mars rovers are cumbersome robotic systems saddled with a heavy power supply and packed with measurement equipment to support scientific research. Thus far, the dominant trend in rover design has been to outfit the system with many different measurement systems so that a single Mars mission can supply multiple research campaigns with data. The drawback of this strategy is that it results in a massive, fragile payload that requires a large, slow-moving robotic vehicle to lug it around the surface. Each rover is extremely costly and has a plethora of failure modes to the complexity of the system. Entry descent and landing procedures for these monolithic machines require are daunting to develop as engineers must use novel and costly techniques to slow the massive yet fragile package to the planet's surface. Signal latency when communicating between Earth and Mars ranges from 4-24 minutes depending on the transmission frequency. This delay makes remote control impossible, thus requiring the rover to be autonomous. However, leaving the navigation up to a computer processor leads to erroneous navigation decisions and slow movement.

One of the major motivations of this project was to find a way to gather data from various points across the Martian surface without having to send a fully-fledged rover. The Tumble Bot would serve as a cheap way to scout and identify sections of the surface for future rovers to investigate. They could be deployed in swarms and carry a variety of instruments. Wind would spread them around the surface passively so they would not require any control input from Earth. They could be dropped into hazardous terrain to determine if it would be fit for the rover and images of their surroundings would be relayed back to Earth. Tumble Bot would be able to move significantly faster than Curiosity, Opportunity, and Spirit and would be much easier to deploy without damaging the payload. A passive exploration system like this one would be perfect for the early stages of planetary exploration where data from anywhere across the planet's surface is of interest.

Heightened curiosity in Mars has increased the demand for scientific data, thus increasing the demand for practical robots which can collect it. Due to the commercialization of space travel competitive markets have reduced the cost and increased the frequency of launches allowing low cost disposable rovers to become a solution for supplying science community with the data they need.

The primary focus of this project is to develop a system that does not have to use its own power for movement; it must rely on passive locomotion. The source of movement of this system must come from the environment, so power sources are limited to wind and radiant energy. Minimal devices with active power can be used they must be extremely low power. A 1.5kg payload is to be carried in the center of the Tumble Bot so that space is to remain open. The proposed system design must be compatible with current launch technology and typical payload sizes. Ideally the system would be able to be compacted for transport and then expand upon ejection from the launch capsule but figuring out the intricacies of how Tumble Bot is to fold for deployment is outside of the scope of this project.

This Final Design Review includes background on the needs and wants of the sponsors, notes on a similar Cal Poly senior project that was previously sponsored by JPL, fundamentals and applications of tensegrity structures, and currently existing rovers that are designed to float in the Martian atmosphere. The Objectives section defines the project Problem Statement, the Needs and Wants, Quality Function Deployment, and Specifications Table for the project. The Conceptual Design section details the concept design process and its results. The Final Design section details the final design of Tumble Bot. The Manufacturing section outlines the processes that the team completed to explore the idea of using carbon fiber, as well as suggestions of what manufacturing process would be used in producing the final prototype. The Design Verification section summarizes a systematic approach to verify the needs and wants of the sponsor are met. The Project Management section provides an overview of the evolution of the design process as analysis was conducted throughout the entirety of the project. This section also describes how the analysis results guided the design methodology. The Conclusion section of this report outlines the conclusions that were drawn throughout the project as well as suggestions as to how this project could be continued.

Chapter 2. Background

2.1 Interviews with Sponsors

During the first sponsor meeting with Anna Woodmansee, it was made clear that the scope of the project is much more open-ended than expected. She explained the advantages/goals of using a tensegrity structure to explore Mars but communicated that it could be a tensegrity 'inspired' structure instead. The design constraints that were initially given by Anna included the following: fit in current shuttle cargo-bays, cost less than $2000, must be functionally collecting data for 2-4 weeks, avoid using materials that off-gas, and be able to withstand a vacuum.

After the on-site visit to JPL, Christine Gebara and Anna Woodmansee refined the design requirements to include the following: withstand a 500-meter drop, roll on 20% of Martian surfaces, roll over 50% of rocks on Mars, and get out of a hole that is 1/8 of Tumble Bot's diameter. In addition, the 1.5 kg payload must contain both a camera and a small solar panel, as well as be able to communicate with a Master.

2.2 Past Cal Poly Senior Project

A previous Cal Poly senior project was sponsored by JPL for a similar design. Although they did use a tensegrity structure, their rover was fully automated and depended on mechanically shifting the center of gravity of the structure to achieve locomotion [1]. Because their project scope and design goals differ greatly from Tumble Bot, a lot of their results do not help meet the current design requirements. However, their calculations and simulated data for the deflection of the structural members used in their design are still potentially useful.

2.3 Tensegrity Research

"Rolling Tensegrity Driven by Pneumatic Soft Actuators" is an article published by the Institute of Electrical and Electronics Engineers (IEEE) which discusses how each member of a tensegrity structure translates as the structure moves. This article is a good resource for understanding the mechanics of tensegrity structures. The main takeaways from this article is that tensegrity structures deform under gravity to achieve a stable state at which the gravitational potential energy reaches its local minimum. A common structure for rolling tensegrity structures is a six strut "icosahedron" which consists of eight regular triangles and twelve non-regular isosceles triangles. The motion of an icosahedron is shown in Figure 1. The locomotion for this type of tensegrity structure can be described by a sequence of transitions among 20 stable states which has consistent axial symmetric contact with respect to flat ground [2].

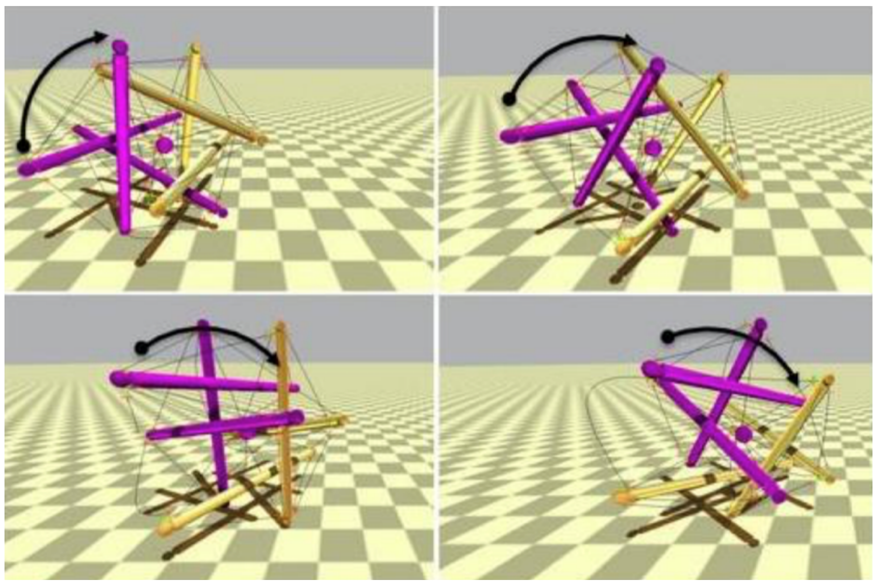


Figure 1. The motion of a six-strut icosahedron.

Also, the deformation of a tensegrity structure results in gradient changes in gravitational potential energy which generates a moment of gravitation force around the area in which the structure contacts the ground [3]. A current product that NASA has developed is called a "Super Ball Bot" which is a terrestrial robot based on a tensegrity toy that uses this type of locomotion to navigate terrain. The "Super Ball Bot", shown in Figure 2, has a sphere-like matrix of cables and joints that could withstand being dropped from a spacecraft and would hit the ground and bounce. A major benefit of this design is that the landing and mobility platforms, based on tensegrity structures, allow for lower-cost and more reliable planetary missions [4].

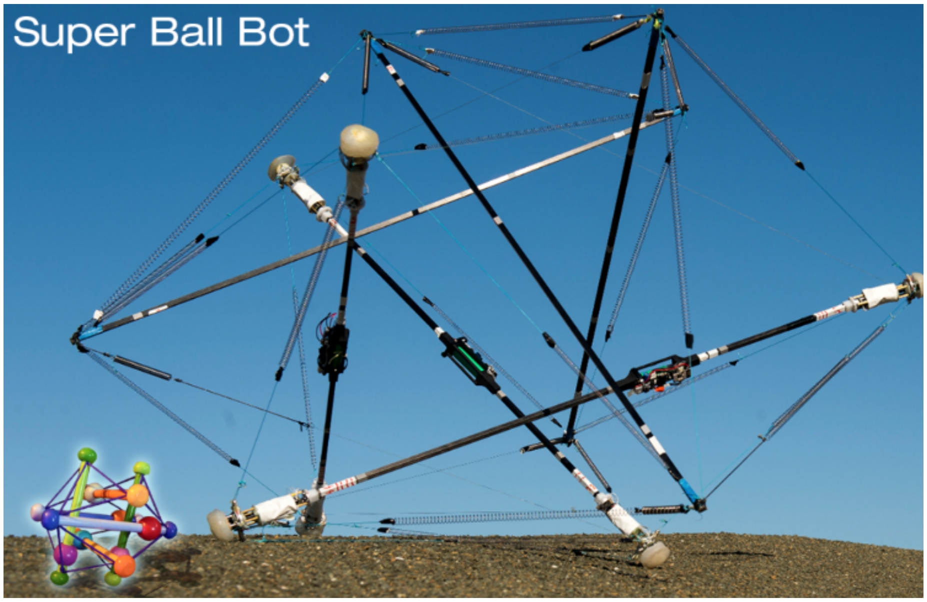


Figure 2. NASA “Super Ball Bot”.

2.4 Mars Balloon Research

Another type of locomotion to draw inspiration from is a floating structure that would float around the Martian atmosphere. Currently existing solutions that take this approach are NASA’s Ultra Long Duration Balloon (ULDB) and Solar Montgolfiere (hot-air balloon). The Ultra Long Duration Balloon, shown in Figure 3, is a giant balloon that would rapidly inflate with helium as it descended into the Martian atmosphere. The balloon’s internal pressure would be higher during the day than at night and the balloon volume would remain the same. The benefits of this design include that it is strong, lightweight, leak-proof, and has a lifetime of 100 days [5].

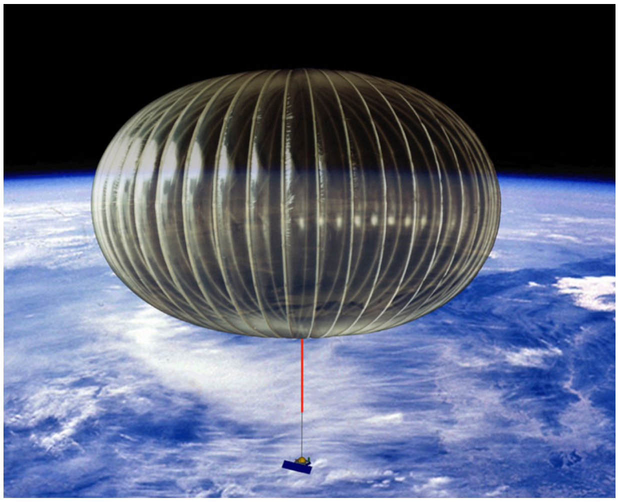


Figure 3. The Ultra Long Duration Balloon (ULDB)

The Solar Montgolfiere, shown in Figure 4, would float in the air much like the ULDB, but would not use Helium. Instead it would have an opening at the bottom of the balloon that would fill up with Martian “air” while falling to the surface. The balloon would then be rapidly heated by the sun, and the heated air would provide buoyancy. The benefits of this design are that it is not vulnerable to leaks, it will have a soft landing on descent, and would go back into the atmosphere to take data. However, the lifetime is limited to just a few hours because it is only buoyant until the sun goes down [5].

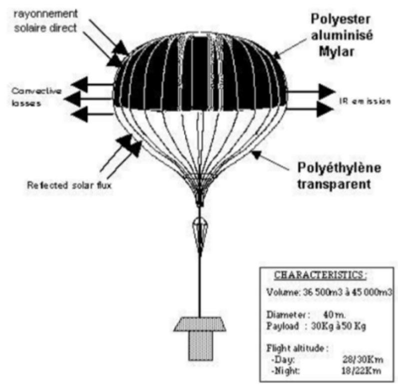


Figure 4. Solar Montgolfier schematic.

2.5 Cloud 9

Cloud 9 was originally proposed by Buckminster Fuller (the inventor of the tensegrity structure) as a means for supporting humans living in the upper atmosphere. Fuller estimated that a large enough tensegrity structure would be light enough to float if it contained atmospheric air that was just 1° F above the exterior air [6]. A temperature difference this small could easily be maintained by basic human activity inside the tensegrity ball. Fuller theorized that humans could passively tour the world inside these giant “Cloud 9” tensegrity spheres.

Later, Russian scientists proposed that the most hospitable environment in the solar system (excluding Earth) was the upper atmosphere of Venus, and that the most plausible way to inhabit that environment was with a structure like Buckminster Fuller’s Cloud 9 concept [7]. The blend of gasses that is found on Earth are buoyant in Venus’s dense carbon dioxide rich atmosphere, and a floating Star Wars style “cloud city” could be supported there if a large enough tensegrity sphere could be constructed to contain the gasses. There would be no pressure gradient between the inside and the outside of the balloon so small punctures would not result in catastrophic failure, and it could be easily repaired. Humans would even be able to traverse the outside of Cloud 9 with only a thin layer of acid and radiation protection and an air source. Figure 5 is an artistic representation made by NASA of a buoyant tensegrity sphere colony in Venus’s upper atmosphere.

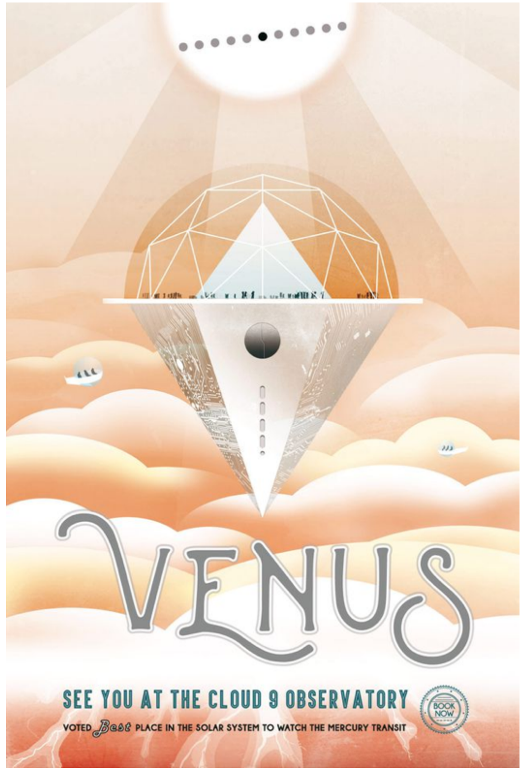


Figure 5. Cloud 9 inspired colony deployed on Venus.

2.6 Mars Helicopter

The Mars Helicopter, as shown in Figure 6, was designed as a scouting platform to help identify promising science targets or map the terrain ahead of the Mars 2020 Rover [8]. The Mars Helicopter is 80 cm in height and weighs 1.8 kg. The payload contains flight avionics, batteries, and sensors which are all contained within a warm electronics box that is insulated and heated to protect against nighttime temperatures as low as -140 °C. The helicopter contains Lithium-Ion batteries that are recharged each day by the onboard solar panel [9]. The solar panel substrate is attached to the mast, and the cells are mounted onto the substrate.

The cameras aboard the Mars Helicopter require an image processing frame rate of 30 Hz and all image processing has to be executed within the 33ms time limit between two successive frames [8]. During testing of the Mars Helicopters visual tracking features, it was found that visual feature tracking inevitably produces occasional outlier measurements. These outliers can corrupt the filter state estimate if they are not down weighted or discarded.

When disconnected from the rover, the Mars Helicopter can still communicate with Earth via radio link. The helicopter contains a loaded quarter wave monopole positioned near the center of the solar panel at the top of the helicopter assembly and also serves as a ground plate [9]. The radio aboard the Mars Helicopter has over-the-air rates of 20 kbps or 250 kbps over a max distance of 1000 meters.

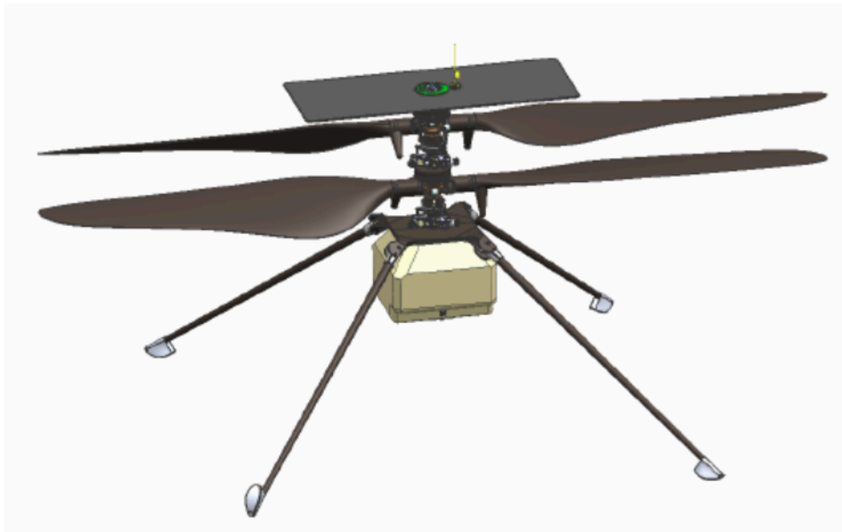


Figure 6. Mars Helicopter CAD drawing.

Chapter 3. Objectives

3.1 Problem Statement

The goal of the Tumble Bot project was to design and prototype a passive structure that used the energy already present in the Martian environment to move about the surface of the planet. The scope of this project was to design and build a rover that leverages passive locomotion to traverse at least 20% of the Martian surface. The structure must contain a 1.5 kg payload and be compatible with a camera array.

Tumble Bot should be able to and roll over 50% of the rocks on Mars without getting stuck and initiate movement with 5 m/s wind speeds. Some important design considerations included being able to withstand a vacuum, large temperature swings, radiation, dust storms, fit inside the existing deployment fairings, be relatively cheap.

3.2 Boundary Diagram

Figure 7 provides a visual representation of the systems that this project was concerned with. The dotted line includes the entirety of the spherical rolling structure of the rover but excludes the payload indicating that the design of the payload is not a concern for this project. The Cal Poly senior project team was tasked with developing a proof-of-concept for the Tumble Bot body that could passively transport at least 1.5 kg and would leave an open area in the middle of the structure for JPL to secure their desired payload.

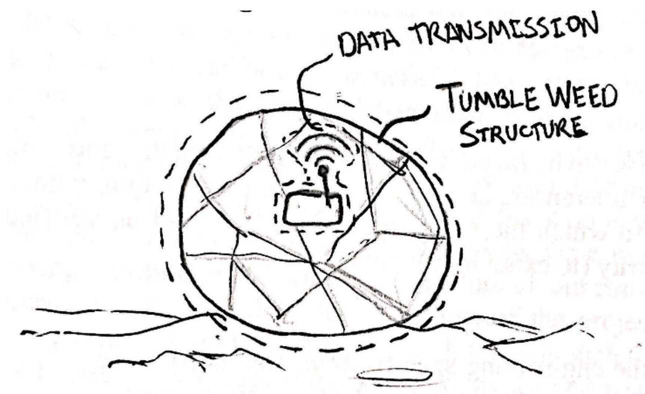


Figure 7. Boundary sketch for Tumble Bot.

3.3 Customer Needs and Wants

After CDR, the problem statement evolved due to the insight that was gained about the Martian environment. Due to the difficulty of this design challenge the top priority was to make the ball roll on the Martian surface.

The line of sight requirements for the onboard camera, withstanding impacts, durability over time, inclusion of a small solar panel, and cost were all re-prioritized from needs to wants. These issues would be resolved before the mission launches but are outside of the scope of this senior project. The focus of the project was focused completely on making a structure that was capable of rolling.

Table 1 outlines the necessary functions of the design and additional features that would improve its performance. This table was generated from interviews with the project sponsors, research, and analysis.

Table 1. JPL Needs and Wants for Tumble Bot.

Needs	Wants
• Passive Locomotion • Roll on 20% of Martian surfaces • 1.5 kg payload • Camera • Communication device • Small solar panel • Roll over 50% of rocks on Mars • Get out of a hole that is 1/8 the diameter of Tumble Bot • Minimum 2-week lifespan • Disposable	• 1-month lifespan • Inter-changeable instrument payload • Collapsible/deployable • Be able to get out of a hole with a rock in it • Low cost • Compatible with current capsule & deployment technology • Withstand a 500-meter drop • Clear line of sight for camera

3.4 Quality Function Deployment (QFD)

The QFD chart, which can be found in Attachment 1, is a visual organizational tool that helps compile what the customer wants, how to determine if those specifications are met in the design, and how those specifications may have been met before in other designs. It is important to consider who is affected the most by the design decisions, and this is shown in the left-most column of the chart. It was determined that manufacturers, scientists in the field, and personnel in charge of launch are affected the most by the design decisions. The next assessment was the correlation of the engineering specification criteria to the customer requirements in the main body of the diagram. Additionally, each specification was compared to the others to determine if they are directly or inversely related, and this is represented by plus and minus signs in the triangular section at the top of the table. The right side of the table contains a numerical rating of how well existing designs have solved the customer's requirements. Conversely, the section at the bottom of the table shows a numerical rating of how well existing designs have met the engineering specifications for Tumble Bot. This helps to highlight possible design ideas that may work for the design.

3.5 Specifications Table

A quick summary of the project specifications can be found in Table 2. Included are the requirements or targets that needed to be met, their tolerances, and how important those requirements were (High, Medium, and Low). The extent to which the specifications are met will be verified by analysis, testing, inspection, and S=similarity to existing designs.

Table 2. Engineering specifications determined by JPL sponsors

Spec. #	Parameter Description	Requirement or Target	Tolerance	Risk	Compliance
1	Not exceed JPL budget	$2000	n/a	M	A
2	Light weight	15 kg	±5 kg	M	I
3	Functional lifespan	2 weeks	Min	H	A, T, I, S
4	Passive locomotion	Powered by Environment	n/a	H	A, T, I, S
5	Impact resistant	Survive 500-meter drop	Min	H	A, T, I, S
6	Carry research payload	1.5 kg	±1 kg	H	A, T, I
7	Overcome obstacles	Pass/Fail	n/a	M	A, T, I, S
8	Reproducible design	Pass/Fail	n/a	H	A, S
9	Ability to get unstuck	Pass/Fail	n/a	H	A

Chapter 4. Concept Design

Brainstorming sessions and technical research helped in developing a better understanding of the target environment and the short history of the passive "tumbleweed" exploration idea. This included prior attempts and the scope of the capabilities of the feasible designs brainstormed. A conscious effort was put towards examining as many abstract ideas as possible, and most of the ideas could not yield a working design. Weight is the most significant limiting factor when it comes to passive locomotion in an environment where energy is not easily harnessed. As a result, weight needed to be considered first in future design iterations.

The next big step was to determine if an open tensegrity ball, which focuses on maximizing drag at the cost of higher rolling resistance, was more beneficial than a closed inflatable ball, which focuses on minimizing rolling resistance at the cost of lower drag. The risk associated with an inflatable design is the sharp rocks on Mars, as they pose a significant threat to the structure. Ideation resulted in the conclusion that an optimal design would have to be a non-inflatable ball. Making these decisions required in depth research of materials, consultations with experts, design iteration, and lots of time spent debating over rough whiteboard sketches.

Ideation yielded two designs: one was a traditional tensegrity structure with a "3 orthogonal planes" sail in the middle and the other, nicknamed "Persimmon-Hotdog", was not a tensegrity structure at all. The value of the traditional tensegrity design is that it allowed for a higher drag sail configuration and gives the payload better visibility of the surroundings than an enclosed ball. The value of the Persimmon-Hotdog is the low number of components, more spherical geometry, and its potential ability to jump out of the way of obstacles.

Traditional tensegrity design was initially pursued because it seemed to match more closely what the sponsors were envisioning as a successful design. This was a semi-arbitrary decision as not enough analysis was done at the time to see the advantages and disadvantages of each of the designs.

4.1 Pugh Matrix

The Pugh matrix is meant to show all the design requirements that need to be met and compare how well each design meets the criteria compared to a 6-bar tensegrity sphere with straight, rigid members. This 6-bar tensegrity was selected as the datum because it is the most basic, spherical tensegrity structure that could effectively be used when considering rolling resistance and manufacturability. The other structures being considered are the maxi-surface, 6-bar with curved members, 12-bar structure, 24-bar structure, 30-bar structure, the Persimmon-Hotdog model, and a thermal balloon (as listed in the above table). The details of each of these designs are discussed in the sections below. The most important design criteria for these structures are their likelihood of rolling and their ability to overcome obstructions. The results for all the concept designs are shown in Table 3.

Table 3. Pugh Matrix for the 5 Concepts Designs Compared to the Datum Design

Criteria	Tensegrity - 6 bar	Maxi Surface	Curved Member 6-bar	Tensegrity - 12 bar	Tensegrity - 24 bar	Tensegrity - 32 bar	Persimmon-Hotdog	Thermal Balloon
	Datum	1	2	3	4	5	6	7
Light Weight		-	-	-	-	-	-	+
Passive Locomotion		+	+	+	+	+	+	+
Small Packaging Footprint		-	-	-	-	-	+	-
Data Retrieval		-	-	+	-	-	+	-
Cost		+	S	-	-	-	-	-
Durability		+	-	+	+	+	-	-
Environmental Impact		-	-	-	-	-	-	-
Manufacturability		-	-	-	-	-	-	-
Line of sight		-	S	+	+	+	-	-
Ability to get unstuck		S	S	S	S	S	+	S
Σ+		3	1	4	3	3	4	2
Σ-		6	6	5	6	6	6	7
ΣS		1	3	1	1	1	0	1

4.2 Helium Balloon

The Helium Balloon, shown in Figure 8 and Figure 9, would be a tensegrity structure that has a loose-fitting membrane around it. The membrane would act as a sail and would help prevent the structure from getting hooked onto a rock. The temperature of the inside of the balloon would be held constant at atmospheric pressure and then helium would inflate the balloon and cause it to float and land at a new destination.

The benefits of this design include the ability to collect data both on the surface and in the atmosphere of Mars. It would also potentially be able to float out of any larger hole or crater that it encounters. The biggest problem with this design is that when the preliminary calculations proved that the balloon would not be able to carry the 1.5 kg payload. Another problem with this design is that since the membrane would enclose the entire structure, there would be no field of view for a camera or solar panel. Calculations have indicated that a design based on buoyancy is not a possible solution due to the incredibly low density of the Martian atmosphere. Basic buoyancy calculations show that even with helium (the second lightest gas) the volume of the gas that is required to just lift a 1.5kg payload is erroneously large, not to mention the mass of the balloon itself. Since overall weight is the largest concern, this design was not viable.

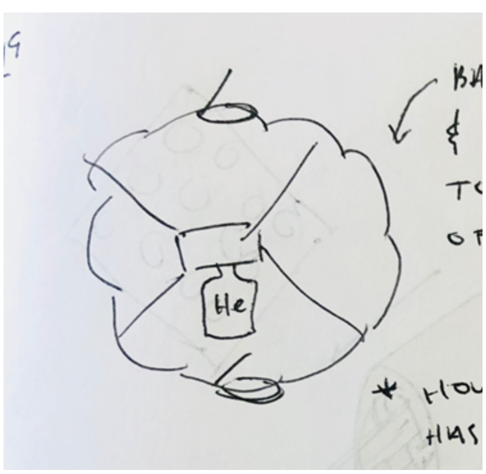


Figure 8. Helium balloon concept sketch.

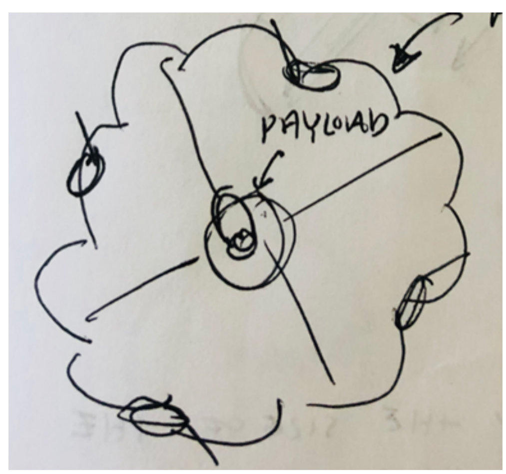


Figure 9. Helium Balloon with payload

4.3 Persimmon-Hotdog

The Persimmon-Hotdog design consists of springy curved members bent between two end caps that were joined with a center cable. The shape of the Persimmon-Hotdog can be changed by modulating the amount of tension that is exerted on the center cable. This design would be able to modulate its shape from a ball to become long and skinny (like a hotdog) or short and fat (like a persimmon). Tension on the center cable could be modulated by a motor and a spooling system mounted in the center of it. The two endcaps that would have space to hold scientific data collection instruments. The different states of the Persimmon-Hotdog are shown in Figure 10. The internal structure of the Persimmon-Hotdog is shown in Figure 11.

The main benefit of this design is that the structure would have a way to potentially get itself unstuck if it were to fall into a shallow hole. The first step of this process is to contract the cable in the center by activating the spooling system, causing the frame of the bot to compress. This energy would be stored as potential via the elastic deformation of the bars. Once contracted the structure would develop flat spots on the top and bottom and would likely fall over onto one of these surfaces. The next step would then be a rapid release of the tension in the cables which would allow for the frame to rapidly spring back into the “hotdog” position. The potential stored in the deformed members would be used launch the ball. Hopefully the jump would be enough to help the ball escape from the obstacle constraining it and if not then it would repeat this process.

The problem with this design is that it would require a motor and a spooling system that could be potentially heavy, and they would have to be incredibly efficient because they would run off such a small power input. The structure would most likely have to be enclosed, as shown in Figure 12, which could cause visibility issues for the cameras unless they were mounted on the exterior of the ball.

One positive aspect of this design is that it still offers a valid solution without the spooling system or any jumping ability. Much later in the project, a version of Persimmon Hotdog that excludes the jumping mechanisms ended up being the design that was determined to be optimal. Analysis of the spooling system and its jumping ability were left out due to a lack of resources and time constraints, but their addition to the final design of this project would be a good thing for future projects to focus on.

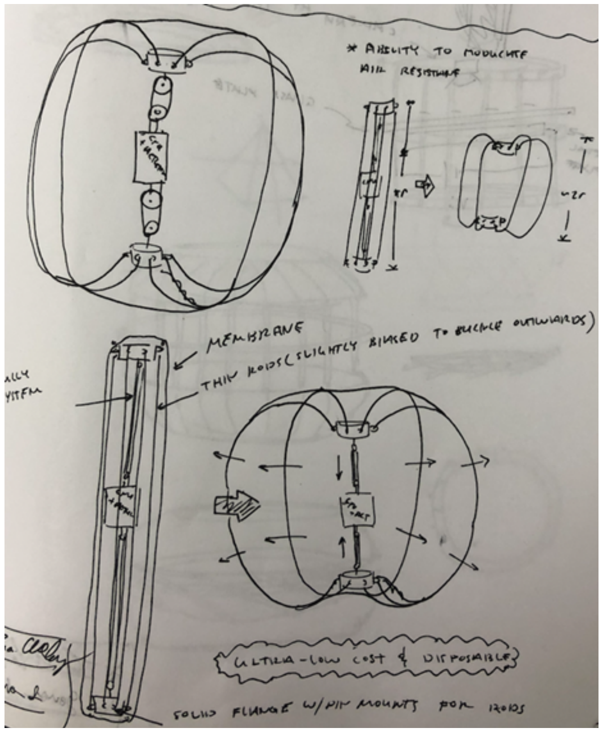


Figure 10. Different geometry states of the Persimmon-Hotdog design.

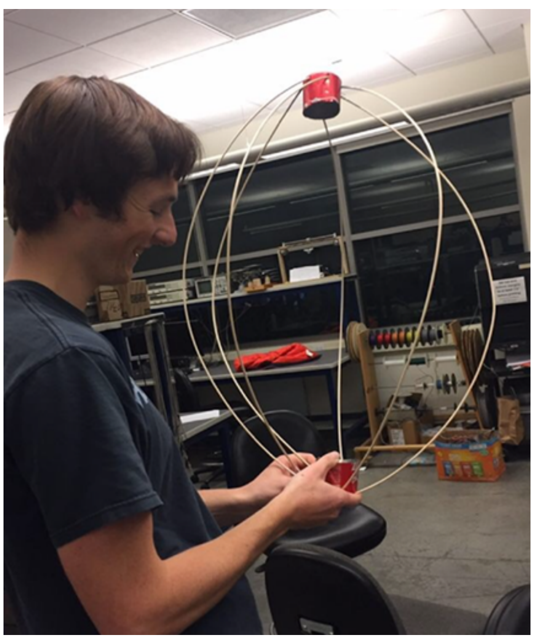


Figure 11. Internal structure of the design.

Figure 12. Structure enclosed in a membrane.

4.4 Tensegrity Spheres

Ideation led to the decision to commit to developing a design based around a tensegrity sphere, which launched an investigation into the advantages and disadvantages of different tensegrity spheres. The basis of this concept design was that a tensegrity sphere would form the main load-bearing skeleton of the Tumble Bot with a high drag sail configuration suspended inside the ball to catch the wind. The payload would also be suspended in the center of this frame.

This process began with experimenting with wooden dowels and rubber bands. The dowels were cut into 4" long pieces with a band saw and a .5" deep slit was cut into the ends of each of the pieces. Then, a rubber band was stretched lengthwise around each piece. The result was a stick with elastic cables running opposite to each other lengthwise down the exterior and this formed the basic building block of the tensegrity structures. Using these building blocks, experimentation began to create as many tensegrity structures as possible, and the best designs were 4 unique tensegrity spheres. They were named based on the number of dowels that they were composed of: 6-bar, 12-bar, 24-bar, and 30-bar. Close observation revealed that the number of bars increased by 6 between each of the configurations.

Once there were physical structures to test, criteria had to be determined to compare them. The best conclusion for a single criterion was based on the free body diagram shown in Figure 13.

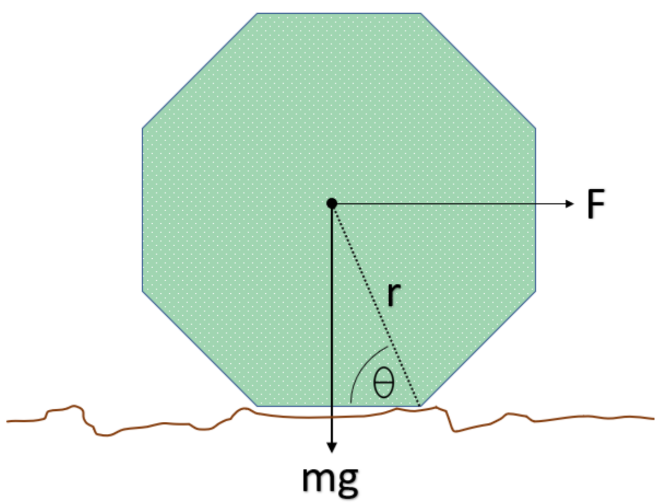


Figure 13. Free body diagram of the static model.

The analysis was based on the idea that rolling would be initiated if a large enough drag force was applied to the ball, such that the it would begin to pivot about one of the edges. Equation (1) was derived from the diagram above. When the statement is true, rolling will be initiated. This equation is as follows:

$$\frac{mg}{\tan\theta} < F \tag{1}$$

where m is the mass of the structure,
g is the gravitational constant,
θ is the angle of tilt,
F is the force of drag on the ball.

It became clear that there were three ways to increase the probability of the ball rolling: decrease rolling resistance, decrease the weight of the ball, or increase the drag force experienced by the ball. These three parameters could be optimized independently to create the optimal ball design.

It was assumed that the drag force on the tensegrity sphere would be negligible compared to the drag of the sail structure that was to be installed inside it, so analysis of the tensegrity spheres focused on determining which configuration had the lowest weight and rolling resistance. An optimum mass/rolling resistance value was determined for each configuration individually. The rolling resistance of the ball had an inverse relationship with the number of members and the mass of the ball was directly related to the number of members, so an optimal ratio was found.

The angle θ shown in the equation above is not the actual angle theta as measured from the geometry because in actuality the structure is flexible. θ is the angle between the horizontal and the point on the part of the structure touching the ground that the center of mass as to move over in order to initiate rolling. By doing some simple trigonometry this angle was determined to be the compliment of the angle to which the structure can tilt before rolling is initiated. This angle was found by placing the models on a flat surface and increasing the incline of that surface until the model began to roll, and then subtracting the tilt angle from 90°. The angle at which rolling occurred was recorded with a level app on a smart phone. Multiple tests were conducted for each structure and the average of these tests was determined to be the (90°-θ) tilt angle for that structure.

The mass of each member was determined using Euler buckling criteria, statics, and some basic data describing the geometry of the models. The load that each member experiences is a linear function of the total mass of the structure, so a number representing the theoretical minimum mass of the structure was calculated as a unitless value. This theoretical mass number only had value relative to the theoretical mass numbers of the members of the other configurations and was used to draw conclusions about which of the 4 configurations could be the lightest even though there was not enough information to calculate the actual minimum mass of any of the structures. The theoretical mass number for each configuration was a function of the diameter of each of the structures, the number of members that were in contact with the ground at a time, the angle off horizontal of these members, and the length of the members used in each of the structures. The overall minimum mass of the structure was determined to increase as the number of members increased. The configuration that had the lowest mass/rolling resistance (m/θ) ratio was said to require the lowest force to initiate rolling. These values can be seen in Table 4.

Table 4. Tilt test results for the final design.

90-θ (degrees)	tan(θ)	Mass number	m/θ
27	1.962611	0.01040	0.00530
23.6	2.28891	0.01199	0.00524
13.7	4.102165	0.01750	0.00427
13.4	4.197561	0.01879	0.00448

A plot showing the relationship between the m/θ value of the four tensegrity structures and the number of members can be found in Figure 31 in Appendix E. Note that these results are independent of the diameter of the tensegrity sphere.

The largest downfall of the procedure was its failure to account for the differences in tension between the different configurations. The structures with more members had lower tensions because the ratio of the length of the members relative to the ball's diameter decreased. This meant there was less distance between members. To optimize this test in the future, strain measurements of all the rubber bands would be taken, and then the members would be resized so that the rubber bands exhibit constant strains. To calculate the scaling factor for the members, a ratio between the desired strain on the rubber bands and the actual strain would be made for each model. Then this ratio would be multiplied by the actual member size to get the desired member size. New dowels would then be cut to yield members of the desired size and these would be used to build new structures that could then be roll tested to yield results that would be independent line tension. Also figuring out how to build an 18-bar model might be worthwhile because the lowest two m/θ ratios are from the 12-bar and the 24-bar, suggesting that if an 18-bar configuration exists it may have an even lower m/θ ratio.

4.4.1 6-Bar Tensegrity Structure

The 6-bar tensegrity structure is composed of six bars which are held together by tensioned cables (rubber bands for the prototype). The geometry of this structure consists of 12 triangular faces that the structure rests on, as can be seen in Figure 14. This model was extremely durable and always easily returned to its original shape. There are two kinds of these triangular faces and they are staggered around the equator of the ball in such a way that it is difficult for it to roll in a straight path. Benefits of this design are that the bars are well spaced so none of the members collide when rolling, and it can be easily flattened in three dimensions. Folding a final design that is based on a 6-bar tensegrity structure for transport would be simple and it would make deployment easy. The main disadvantage of this design is that it is not very spherical, and it resists rolling in a straight line, which severely limits its movement efficiency. The model depicted was calculated to have the lowest theoretical mass number but the highest rolling resistance value.

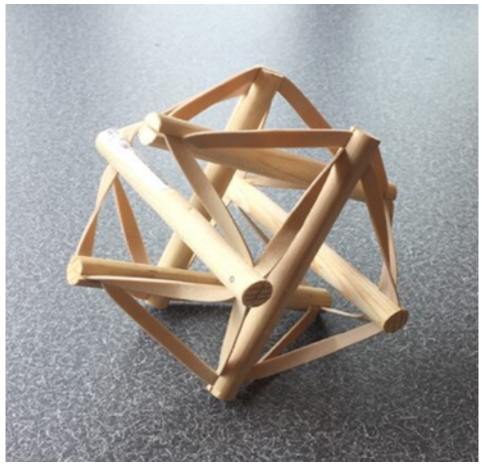


Figure 14. 6-Bar tensegrity structure concept model.

4.4.2 12-Bar Tensegrity

The 12-bar tensegrity model, shown in Figure 15, exhibited a mix of triangular and square faces. The way the faces are positioned around the ball still did not promote the ball rolling in a straight path. Like the 6-bar, the 12-bar exhibits pairs of side opposite to each other that are parallel, but they are more visible in the 12-bar configuration. The model was springy and stable much like the 6-bar. It has a slightly higher theoretical mass number than the 6-bar tensegrity but overall a lower rolling resistance. Surprisingly, it had a negligibly lower m/θ value than the 6-bar model, and this may be at least partially due to the slightly lower tension in the rubber bands. The 12-bar configuration was not really any easier to roll than the 6-bar configuration.

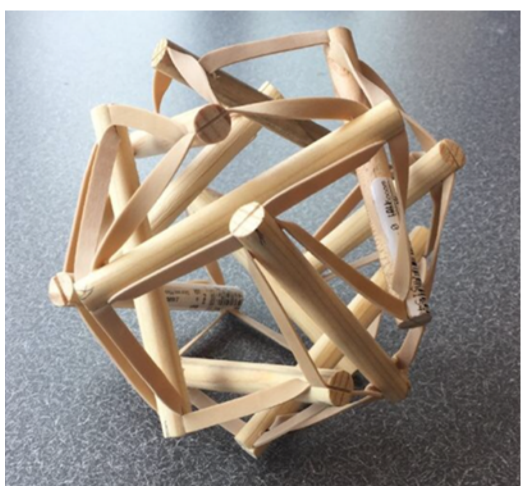


Figure 15. 12-Bar tensegrity structure concept model.

4.4.3 30-Bar Tensegrity

The 30-bar tensegrity structure, shown in Figure 16, has a mixture of triangular and pentagonal faces. Due to its high number of members, member collisions are frequent, and it is unable to collapse. It can easily roll in any direction and because the models low tension gives it a gelatinous quality. It has the highest theoretical mass number a higher m/θ value than the 24-bar tensegrity. The theoretical mass number increases significantly for higher order tensegrity structures. The data collected strongly supports the claim that the optimal tensegrity sphere for this application will not have more than 30 members. This statement is supported further by the fact that it has the lowest tension in its rubber bands and therefore would be able to initiate rolling easier than a properly tensioned test model. The sole benefit of this structure is that it is very round and therefore has the lowest rolling resistance but even that becomes insignificant when it must traverse rough terrain. Investigating higher order tensegrity spheres would most likely be a waste of time.

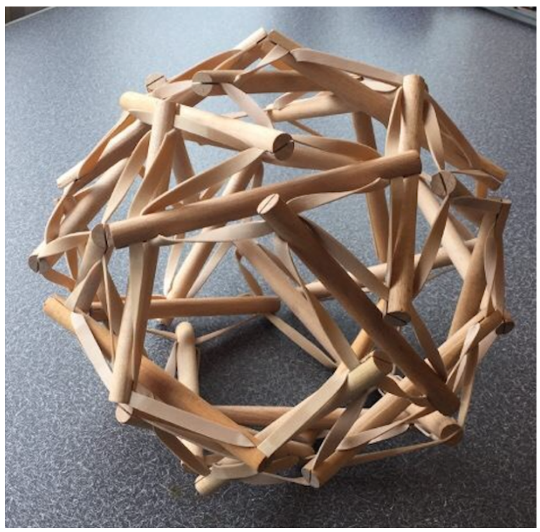


Figure 16. 30-Bar tensegrity structure concept model.

4.4.4 24-Bar Tensegrity

The 24-bar tensegrity structure, shown in Figure 17, consists of three bands of square faces that wrap around the sphere and 8 small triangular faces. The squares mostly meet edge to edge so transitions from face to face are easy for this geometry and it favors rolling in straight lines. This comes at the cost of high member interference and an inability to collapse. Despite having low tension, the 24-bar configuration was still relatively firm due to high amounts of member interference. Of the 4 test configurations it was determined to be the best because it had the lowest m/θ value and favored rolling in straight paths.

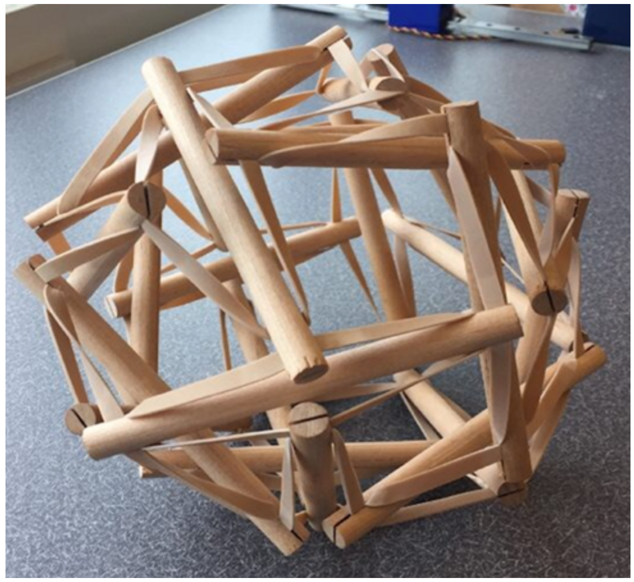


Figure 17. 24-Bar tensegrity structure concept model.

After determining that the 24-bar tensegrity structure had the least rolling resistance, a second model was constructed with skinnier members and higher line tension, as seen in Figure 18. It was used to confirm that member interference would not be an issue on a full-scale prototype version of this design. When this model was tilt tested it was found to have a tilt angle (90°-θ) of 16.7° and a m/θ value of .00525. This alternative m/θ value for the 24-bar sphere indicated a nearly 20% decrease in how easily the structure could initiate rolling that was dependent on cable tension. The m/θ values for the 6-bar and the 12-bar .00530 and .00524 respectively so the effects of tension in this case were enough to call into question whether the 24-bar was truly the optimal configuration. This data clearly indicates that cable tension will play a significant part in determining the rolling resistance of any tensegrity-sphere-based design and is a factor that requires further investigation before these kinds of designs are developed.

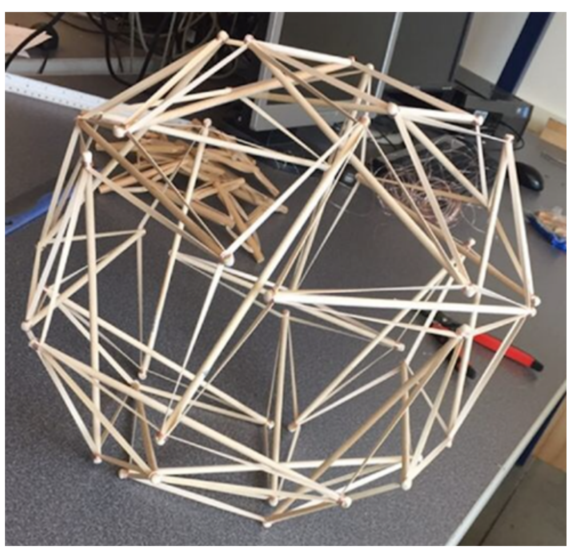


Figure 18. Refined 24-bar tensegrity structure concept model.

The theoretical modeling and test procedures that were developed to acquire the tensegrity sphere data are the most valuable part of this testing. As was mentioned earlier, holding line tension constant across multiple test cases will be a necessity for future testing. At this point of the project plans were being formed to complete this testing and solidly confirm which tensegrity configuration would require the lowest force to initiate rolling. However, this testing was never completed due to a shift in focus to the other parts of the project.

After completing the preliminary stages of roll testing, it was time to start examining ways to capture the wind to maximize drag on the sphere. Several potential membrane shapes were 3D printed, attached to a string, and hung in the wind tunnel. The tunnel was run at a range of wind velocities and the resulting angle of deflection of the string holding the model was recorded for each of these different velocities. The experiment set up is shown in Figure 19. The angle of deflection and the mass of the model were used to calculate the drag force for each of the models. Drag force was then used in combination with standard atmospheric properties and the air velocity to find drag coefficient as a function of Reynolds number for each of the tested geometries. These results can be seen in Figure 36 in Appendix E.

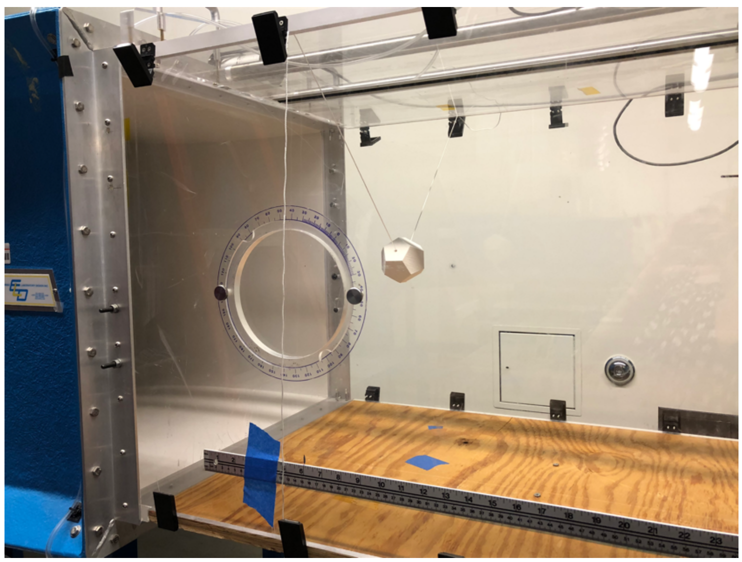


Figure 19. Wind Tunnel Lab Experiment Set Up

4.4.5 Dodecahedron Membrane

One concept for increasing the drag of the tensegrity sphere was adding membranes over each of the sides by stretching fabric around the ball. Since it would require very meticulous CAD work to create a perfectly accurate STL representing the geometry of the tensegrity sphere, it was decided to approximate using a model of a dodecahedron. It also would have been a good idea to cover the concept model tensegrity spheres in a membrane and suspend those in the wind tunnel, but they were determined to be too large for use in the Cal Poly wind tunnel. The 3D printed dodecahedron model used in the wind tunnel testing is shown in Figure 20.

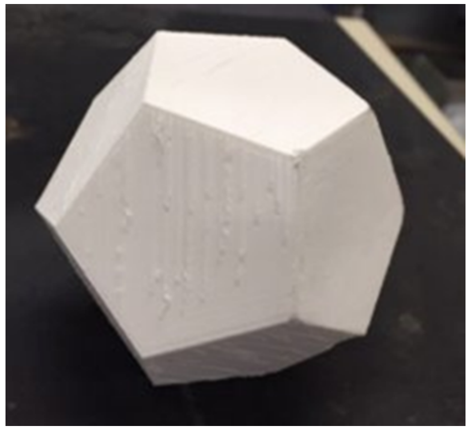


Figure 20. Dodecahedron Model

4.4.6 Orthogonal Planes

The second sail configuration that was tested was a 3D printed structure with three orthogonal planes. The 3 mutually perpendicular sails would be stitched together, and their edges would be fastened to the inside of the tensegrity sphere. This sail configuration has a drag coefficient that is higher than the drag coefficient of the dodecahedron and is marginally higher than the drag coefficient of a sphere. It also required less than 75% of the material that would be needed to cover the entire outside of the structure. Testing indicated that this sail configuration is the most effective for the application, and is the optimal design for Tumble Bot. The 3D printed three-orthogonal-planes model can be seen in Figure 21.

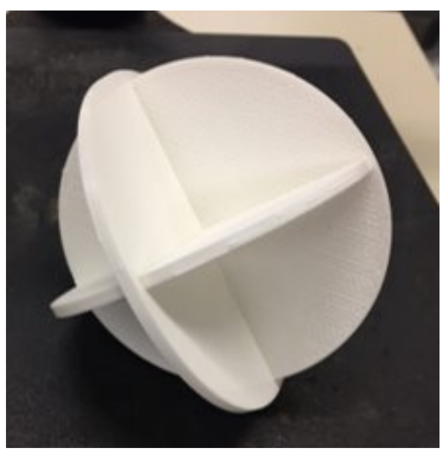


Figure 21. Three-Orthogonal-Planes Model

With a theoretical maximum drag coefficient, the project was refocused on minimizing mass and rolling resistance. From this point it was decided that the best way to proceed was to fix drag force using average wind velocity and atmospheric conditions on Mars and to begin to calculate mass of a 3-meter ball as a function of the rolling resistance alone. This process would then be iterated several times until a geometry with a low enough rolling resistance to output a reasonable mass for a 3-meter ball was discovered.

A preliminary calculation was done using a tilt test angle of 13.7 degrees, the drag coefficient data for the “Orthogonal Planes” sail configuration, a wind speed of 16 m/s, a structure diameter of 3 meters, and an allowable mass of 0.6 kg. However, the payload that the structure would have to carry is 1.5 kg alone. A 3-meter structure is very large and pushes the upper limit of sizing, the drag coefficient is the largest it could feasibly be, and 16 m/s is a very high wind speed for mars so the only thing that could possibly be improved was the rolling resistance. It was clear at this point that the current combination of tensegrity spheres and sail configurations was beyond inadequate and that something radically different needed to be attempted.

4.4.7 6-bar Tensegrity with Bent Members

The efforts of the project this far were founded on the assumption that the members of the tensegrity structure had to be constructed from straight members. The idea was that straight members would minimize the mass of the structure because they would only be subjected to axial loading. It became clear after the calculation described above was completed that the rolling resistance of the current designs was intolerable and that radical improvements would need to be made if this concept were to ever work. The next efforts examined the benefits of curved members. At this point in the project research was done to find epoxies that were able to tolerate low enough pressures to be used in space. This broadened the material selection beyond Aluminum alloys. The potential to use composites led to the exploration of alternative geometries. The first of these alternative geometries was the 6-bar tensegrity concept model, which was made of 3D printed curved members with rectangular cross sections, as shown in Figure 22.

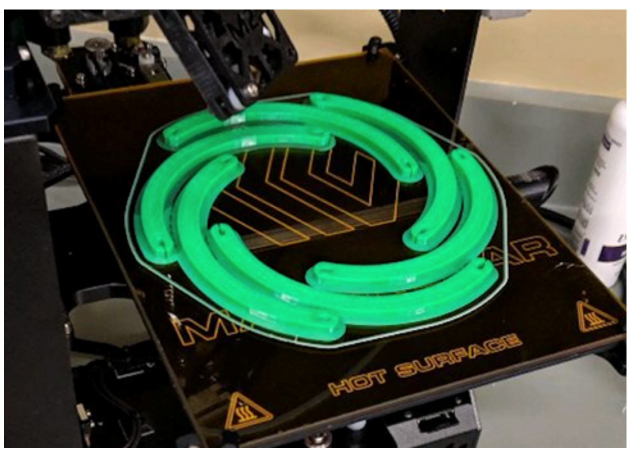


Figure 22. The Individual Curved Members

When assembled, the members created a structure with a spherical shape that still collapsed like the straight-member 6-bar tensegrity investigated earlier. Tilt testing revealed that curved members resulted in lower rolling resistance, but the structure still had significant flat spots. The assembled concept model is shown in Figure 23.

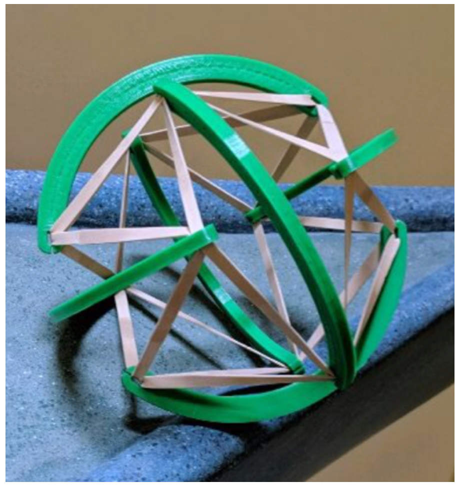


Figure 23. 6-Bar with Bent Members

As expected, the curved members resulted in lower rolling resistance than the pure tensegrity structures. From this experiment it was determined that curved members had the potential to further reduce rolling resistance if the geometry of the curved members created a smooth, spherical surface. Figure 24 shows a concept for a 6-bar tensegrity with curved members to decrease rolling resistance.

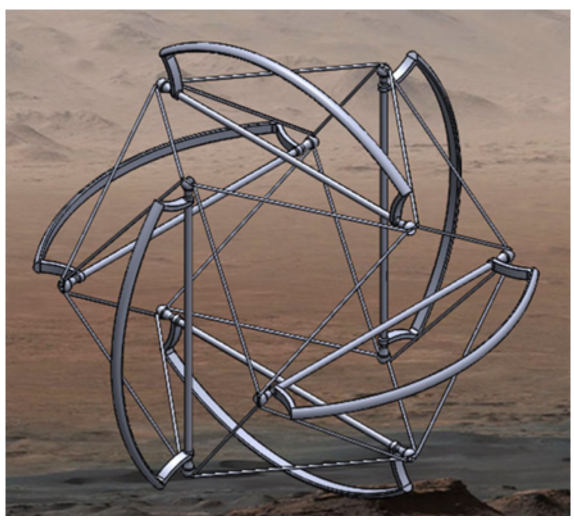


Figure 24. Tensegrity structure with optimized members

4.4.8 Maxi-Surface

The "Maxi-Surface" design is a 6-bar tensegrity structure with members that have been altered to minimize the size of the flat spots on the tensegrity sphere. Rather than using cylindrical beams as the main structural component, non-uniform curved planes that have holes cut in them to reduce weight. This structure is designed to be as spherical as possible while still being a tensegrity structure. The Maxi-Surface design is shown below in Figure 25 with the Orthogonal Planes sail configuration inside to show how they could potentially fit together.

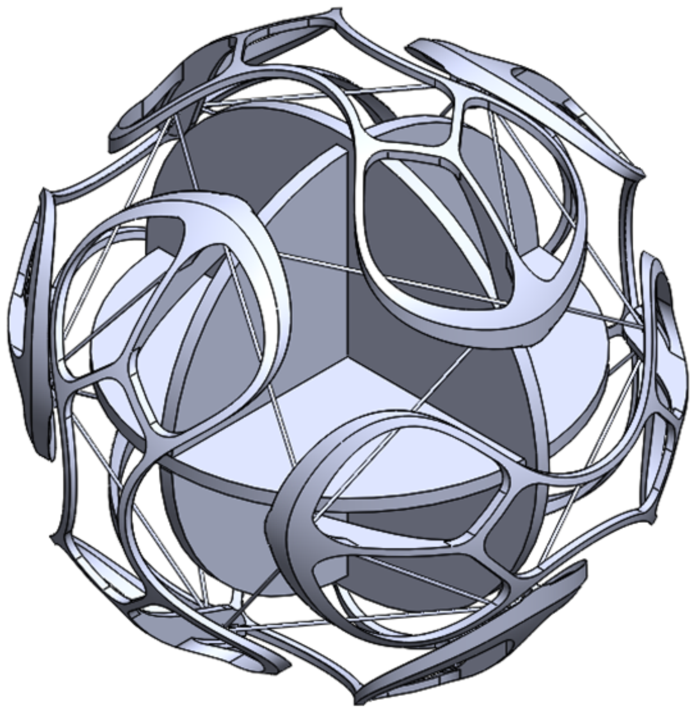


Figure 25. Isometric View of the Maxi-Surface Design

A configuration of this design where each of the members is covered with a sail instead of using the Orthogonal Plane sail in the center. The “maxi pad” shaped geometry of each strut was tested using CFD analysis, shown in Figure 40 in Appendix E. It was shown to have a drag coefficient that was close to the drag coefficient of a sphere simulated with the same software.

4.5 Current Risks

The Design Hazard Checklist, which can be found in Appendix F, notes some of the potential hazards of Tumble Bot. The system will be a large rolling structure which is considered a hazard because it could potentially hit someone during testing, but it is so light that this wouldn’t hurt very much the chances of serios injury would be very low. As rolling is the inherent purpose of Tumble Bot, this is not something that can be restricted.

The Persimmon-Hotdog design poses some actual threats. When the structure is being loaded during testing there is a risk of one of the leaves snapping. A fracture could spray carbon fiber shrapnel and lacerate a person if they were standing within a few feet. At any ranges larger than a few feet a person would probably be safe if a member failed because the carbon fragments would be light enough to be significantly slowed down by air resistance. Tumble Bot would only potentially be a hazard during testing because that is the only time it will be in the presence of humans.

4.6 Challenges

A variety of challenges throughout the design process have been discovered due to the unique nature of the project. A major difference between Tumble Bot and many other senior projects is that there are no currently existing products that solve this problem. There have been a variety of previously existing experiments and prototypes that attempt to solve the same problem, but no clear solution has been identified. The rough idea that was pitched as the concept for this project was shown to be completely inviable after the first quarter of the project and after that point the design process has been run and re-run several times to identify new concepts that could possibly work. A design that is physically possible has not yet presented itself and the project has evolved more into a set of suggestions on future investigations to make and evidence for why many of the obvious solutions to this problem will not work. Each iteration of the design process has provided a better understanding of the problem and narrowed the design space.

The most pressing challenge to creating a viable product is lowering the rolling resistance enough to allow the Tumble Bot to roll when very low forced are applied to it but even this development has a limit. Improvements in rolling resistance only improve performance to a point because the Martian surface itself is so rough. Dramatically increasing the drag is also not viable because the cross-sectional surface area is limited to a circle of the ball's diameter and shapes with drag coefficients that are significantly higher than the drag coefficient of the Orthogonal Planes sail configuration do not exist. Material selection is limited because the system must withstand extreme temperature swings, intense irradiation, sharp objects, and low pressure. Optimization can be accomplished primarily through improving the geometry.

Chapter 5. Final Design

The final proof-of-concept design is a continuation of the Persimmon-Hotdog design discussed in Chapter 4. The design contains twelve carbon fiber members that bend to form a sphere when loaded between two end caps. Unidirectional carbon fiber was selected to construct the members because of its light weight and ability to store high amounts of strain energy. M55J is recommended for the construction of the members because of its history of success in space applications.

The carbon fiber leaves would be attached to the endcaps using sewn fabric connections. The fabric is sewn around the paddle shaped ends of the leaves such that the excess fabric forms a loop that attaches to the ring around the outside of the end cap. This attachment method produces a secure, flexible connection that is easy to manufacture and does not exert any contact stresses on the composite members. There are 24 total fabric connections; one at each end of the twelve leaves.

The endcap was designed to minimize weight, distribute a load evenly, and be easily manufacturable. Since the load that the leaf springs would exert on the end caps is dependent on the manufacturing process of the leaf springs, the exact design specifications of the end cap could not be determined without in depth material testing and a detailed manufacturing procedure. Aluminum Alloy 6061 was chosen for the endcaps because it is lightweight, strong, and easily machined. In order to verify that this component could distribute stress evenly, a Finite Element analysis was performed. The results of this analysis are shown in Chapter 7. The part is made to be easily manufactured from sheet metal and stock aluminum metal with a water jet cutter and a welder. All component specifications can be found in Appendix L Table 8.

The model of PH depicts wrapped in Kevlar 29 parachute material. Kevlar 29 was selected because it is lightweight and puncture resistant. Significant improvements could be made to the design if the Orthogonal Plane sail configuration was used but this was not attempted on this project. Using the Orthogonal Plane sail configuration on the inside of the structure instead of wrapping the entire exterior would result in slightly higher drag and would decrease the overall mass of the structure by about 10%. Connecting this sail configuration to the inside may cause some slight complications but would be worth examining on future projects.

Despite all the time and effort spent studying tensegrity spheres, the Persimmon-Hotdog design was determined to be superior. The structure could be made extremely lightweight with less members than any tensegrity structure could be and with less members. For the PH design all the structure of the ball lays on its exterior, and therefor goes towards improving rolling resistance. because of the lack of flat spots, the roll angle of this structure in a tilt test would be too low to even test. It would be significantly more limited by bumps on the Martian surface than bumps on its own surface so the designs actual viability could only be accurately examined on a location by location basis using data from the actual Martian surface. Simulation results give confidence that it would perform well on large flat planes with sparse rocks and that it would outperform a straight-bar tensegrity structure on any terrain.

The PH was chosen over the Maxi-Ball design because of manufacturability and its potential for jumping. With a short manufacturing timeline and limited resources and manufacturing expertise, it was decided that it would be better to attempt to manufacture the PH than the Maxi Ball. Also, the potential of having a future iteration of this design that can jump to move itself out of a stuck position is significant when the time and energy required to deploy a system on Mars is considered.

One of the largest benefits of the PH design, outside of its low mass and rolling resistance, is its ability to escape undesirable situations by shifting between two geometric states. When in the first state, shown in Figure 26, the structure would have a spherical geometry and would be able to easily utilize the Martian wind to travel the surface of Mars and collect data. This geometry is achieved by increasing tension in the center cable connecting the endcaps by means of the internal winding mechanism until the structure becomes spherical. By increasing the tension of the cables, the leaf springs are forced to elastically compress and store energy. The mechanisms that would allow for jumping were outside of the scope of senior project and were left undeveloped, but this design would be more successful than any tensegrity-based structure even without them.

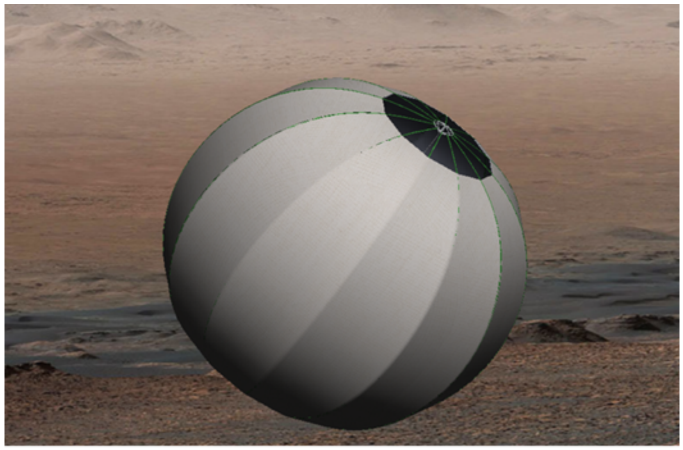


Figure 26. Spherical geometry of the final design

Once the ball becomes stuck it would be able to compress further so that it would take on the shape of a persimmon and flop over onto one side. When the ball is in this position the tension in the lines could be released and the ball would launch itself out of the stuck position with the potential energy that was stored in the loaded members. After the release the structure would be an elongated, cylindrical geometry. An onboard sensor would determine when to activate the described maneuver based how the Tumble Bot's location is changing. If it detects that Tumble Bot has remained static for an extended period, it would be assumed that it is stuck, and the structure would begin to change its shape to free itself. In order to return to the primary geometry, the winding mechanism once again pulls the endcaps toward each other and compresses the leaf springs to form the ball.

The safety, maintenance, and repair considerations for Tumble Bot are unlike those of most design projects. Rather than focusing on reducing potential harm to humans, consideration is taken instead to reducing harm to the Martian environment. This includes minimizing the amount of litter left behind after the product's lifetime, avoiding off gassing due to improper material selection, and contamination due to the introduction of foreign organic matter. Maintenance and repair of Tumble Bot are not applicable since the bot is meant to be deployed on Mars until it breaks down. These considerations can be found summarized in Appendix F.

Since this final design needs to be refined before an actual prototype is manufactured, a cost analysis cannot be determined at this time. Appendix H contains the Bill of Materials which outlines what parts would be needed to construct a complete prototype of the design. This appendix also includes suggested suppliers and an approximate cost estimate for a complete prototype. This estimation was determined based on suppliers with prices readily available, however it is likely that JPL may be able to source cheaper materials from suppliers that they have previously established relationships with. The Bill of Materials only reflects the material cost and does not account for the cost of manufacturing, which is subject to change as the design is modified.

Chapter 6. Manufacturing

The final design for PH is composed of three components: a pair of endcaps, the sail, and the leaf springs. Because the final version of this design would need to have a very large diameter, construction of a full-size prototype was not possible with the limited composites oven space at Cal Poly and the time constraints inherent to the senior project class. A significant amount of time that was allotted for manufacturing was spent waiting for carbon fiber to arrive and access to the composites lab. Once materials and the required permissions were obtained, two attempts were made to produce functional prototype members from pre-preg unidirectional TenCate TC380.

The first attempt used eight layers carbon fiber sheets laid with a symmetric cross-ply fiber orientation [0/0/90/0/0/90/0/0]. The layup was composed mostly of 0° layers because the member was going to be loaded primarily in the longitudinal direction. Each layer was cut as square as possible to ensure that the intended fiber orientation was achieved. Each layer was applied gradually from one side to the other and smoothed down to remove air bubbles using the edge of a credit card, as seen in Figure 27. No significant voids were observed in the composite after it was baked so this was a valid way to manufacture the material that would be used for the next layup. This first attempt produced composite pieces with a severe discontinuity because the two plates that were set on top of the composite while it was cured were not the same thickness and weight. For future layups either a single continuous plate or no plate at all will be used to prevent this defect from happening again.

Figure 27. First Carbon Fiber Lay

For the second carbon fiber layup created another symmetric cross-ply laminate that was made from 11 ply and measured 12” by 36”. The fiber angles used were [0/0/90/0/0/90/0/0/90/0/0]. Like the previous layup, more 0° layers were used than 90° layers because the laminate was to be loaded almost exclusively in the longitudinal direction. The 90° layers were just included to help prevent delamination. The amount of 90° layers could probably be reduced further for future iterations of this component. For this laminate, 11 ply was used because the laminate with 8 layers made previously was too easy to bend.

After an eight-hour cure, the laminate was of generally good quality aside from a few small bumps that were later found to be the result of delamination. From the laminate sheet, 6 test leaf springs were cut using a water jet.

The material data sheet recommended that during the layup process the material should be “debulked” every few layers for 4 hours. This step was skipped because of time constraints and the lack of gum tape required to complete it. In retrospect, skipping the debulking step was the most likely the cause of the delamination.

Chapter 7. Design Verification

The Design Verification Plan, shown in Appendix K, outlines methods to confirm that the final design meets the design specifications. There was no concern that the project would exceed the budget specifications due to the final product being significantly under the initial project budget, as explained in Appendix I.

The non-tangible specifications were verified using software simulations, as this was the only method of verification possible without a physical model.   The geometry of the endcap was created in SolidWorks, as seen in Figure 28, and the solid model was imported into Abaqus CAE to undergo Finite Element analysis. The yield strength of 6061 Aluminum Alloy is 35,000psi, and the maximum stress experienced by the endcap is in the area of 500psi. The FEA results show that the end cap evenly distributes load, but no conclusions can be drawn whether or not this end cap is sufficient for use on a final design because the size of the final design remains indeterminate. The results of this analysis can be seen in Figure 29.

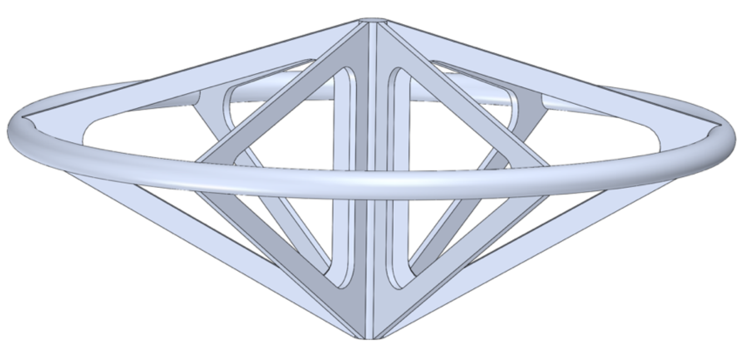


Figure 28. SolidWorks solid model of the top endcap.

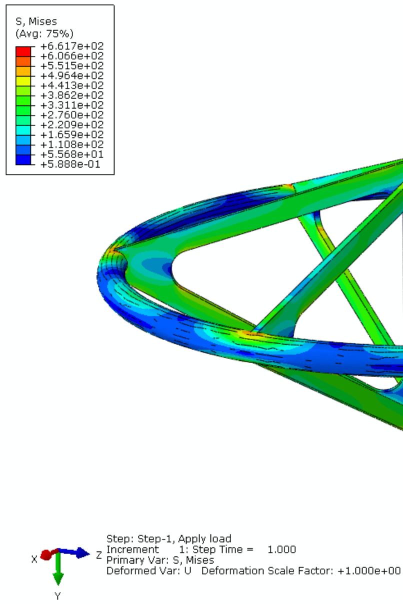


Figure 29. Abaqus FE analysis results for static loading of the top endcap. Units in psi.

A MATLAB script that calculates the probability of the ball rolling at different locations around the Martian surface was developed as a tool to help quantify the problem. The script uses the rolling criteria discussed earlier in this document and locational wind data to generate a 3-dimensional plot that shows the probability of the ball rolling as a function of latitude and longitude. The mass, diameter, drag coefficient, and tilt angle must be input into the code manually. The plot was constructed using weather data over the entire surface of Mars over the course of one year and assumes that the selected year will not have wind data that differs significantly from other years. The 0 to 1.0 scale on the vertical axis represents the percent of days in a year that the ball will roll at each geographic coordinate. Because the tilt test angle is an input in this plot, the results assume Mars to be a smooth surface. This plot can be seen in Figure 30.

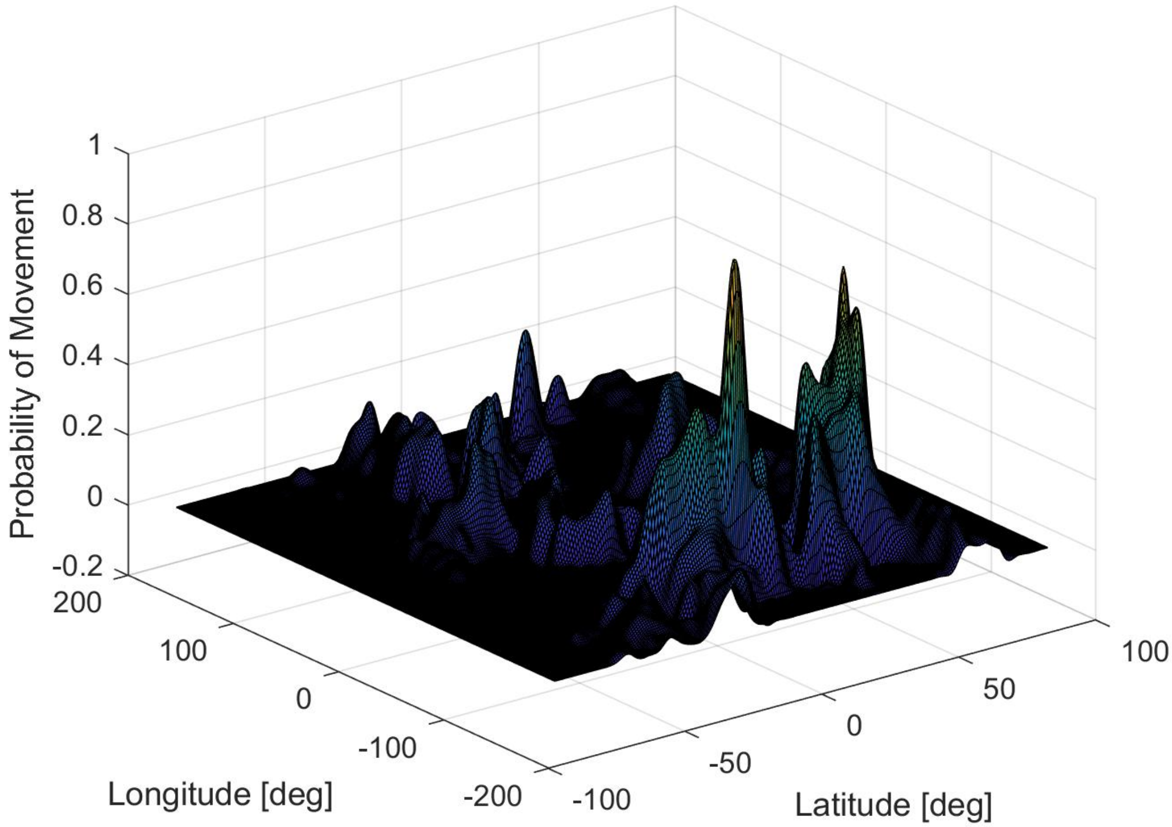


Figure 30. Probability of locomotion in a chosen area on Mars

The members used in the PH design have a unique profile that causes them to bend into a half circle instead of a parabola to promote rolling. The width if the member is varied as a function of length such that curvature remains constant. The basic beam deflection equation that describes deflection as a function of length for a beam with a load applied at its free end was used. Derivatives were taken until the equation for curvature was reached and then curvature was fixed, and width was solved for as a function of length. The resulting profile was input into SolidWorks via an equation and a member was made to match. This model was verified using Abaqus FEA before it was water jet cut out of carbon fiber. Once manufactured the members were manually bent and observed to follow a circular profile.

Chapter 8. Project Management

The design process for Tumble Bot was less structured than the typical design process due to the open-ended nature of the customer needs, as well as the lack of precedent for mechanisms designed to tackle this challenge. The typical process begins with research, interviews, and benchmarking. In contrast, for Tumble Bot it made the most sense to go straight to ideation because a basic design concept was needed to determine what research needed to be done. Extensive research was then completed to investigate or support the designs that resulted from ideation.

The next step in the design process was to quantify the rolling resistance of a straight-bar tensegrity structure and prove that there were no sail configurations that produced greater drag coefficients than the Orthogonal Planes. These tasks were completed through a mix of theory and testing. At this point in the project it was realized that if a viable design exists it would have to have a dramatically lower rolling resistance than the structures that were being tested. There was initially a plan to test how varying the amount of tension in the cables affected the rolling resistance of the structure. Although this testing was anticipated to be completed between the PDR and the CDR, these tests were canceled because the straight-bar tensegrity structures were shown to be inviable and the focus of the project was shifted onto investigating 6-bar tensegrity spheres with curved members. The tension in the 6-member structure does not affect its movement because its rolling resistance is more dependent on the shape of its pads than the sag of the structure, so testing was instead focused on improving rolling resistance.

Further modeling revealed that minor improvements to rolling resistance could result in a significantly more viable design. This change inspired the use of curved members, which in turn allowed the total number of members in the structure to be reduced back down to 6. The purpose of having a higher order tensegrity was to make a more spherical structure but with curved members you can build a structure that is nearly a perfect sphere out of just 6 members and higher order configurations become obsolete. As a result, the focus of the team was then shifted to optimizing the members of the Maxi Ball 6-bar tensegrity-inspired structure to reduce weight while maintaining structural integrity.

The CDR presented the Maxi Ball as a "final design" that met the locomotion design specifications. It was decided after the CDR that the Maxi Surface design should be abandoned for the Persimmon-Hotdog design because the PH design offered the ability to jump, lower rolling resistance, was easier to analyze, and would be significantly easier to manufacture.

Letting go of the Maxi-Ball design was a difficult decision since so much work had been put towards developing this design but the PH was clearly the superior design. The difficulty of manufacturing the Maxi Ball alone outweighed the efficacy of the design. While optimizing the curved member 6-bar design, the Persimmon-Hotdog was being developed in parallel just in case the Maxi-Ball hit a dead end in its developmental process, which it did. Just after the CDR was completed, the project changed dramatically, and the Persimmon-Hotdog became the primary focus for the final proof-of-concept design. Extensive analysis and simulations were performed on the components of this design to verify the concept. Due to time restrictions, only preliminary concept models of the components were made to demonstrate proof-of-concept.

Chapter 9. Conclusions & Recommendations

The majority of the value of this project is in the way that is narrows the design space for passive locomotion on Mars. The research and development that this project completed decisively shows how the majority of the propositions for passive locomotion on Mars would fail and makes the assertion that if a viable design were to exist, it would have to closely resemble the proof-of-concept design proposed in this document.

JPL presented the challenge of creating a structure capable of passively traversing the surface of Mars with a small payload containing scientific measurement equipment. The goal of this project was to present a proof-of-concept design that met the design requirements. The Persimmon-Hotdog design was chosen because it met the design requirements while being easier to manufacture. It also possessed the potential to develop the capability to escape from holes on the surface of Mars, which gives the PH as significant advantage over other designs. Although tangible testing of the system as a whole was not performed, the results of the simulations that were performed on its components supports the claim that the design would perform successfully on Mars. That being said, the "final design" presented in this document is still far from finished. From this point the design criteria need to be revaluated and a new project should be pitched to concretely prove the viability of this design.

It has been established that bending members between two end caps is a viable way to make a sphere that is large enough and light enough traverse the Martian surface but many of the details of this design need more information to be specified correctly. The optimal number of members must be determined based on the roughness of the terrain that the ball is expected to encounter. Using more members will decrease rolling resistance and make the structure more spherical at the cost of increasing weight and cost. Increasing the number of members will only increase the performance so long as the majority of the rolling resistance that the ball is encountering is due to its shape and not the shape of the terrain. These is a point where the terrain is so rough that having a more spherical structure will not benefit performance. This design problem is also interconnected to the overall diameter of the ball. The optimal width and thickness of the members also needs to be determined. This is dependent on the strength of the central winding system (if one is even to be installed) and maximum force that the ball can jump with without damaging itself. The possibility of using members that are not all the same size makes this an even more complex problem. The design of the end caps would need to be modified after the amount of energy that is to be stored in the members is determined.

The susceptibility of carbon fiber to contact stress should be examined as well. The PH structure could possibly fail due to a member impacting a sharp rock and fracturing. The members should probably be shielded from impacts with a puncture resistant material.

The costs and benefits of outfitting the ball with a central winding system to enable jumping needs to be examined. This would be very dependent on how light of a winding mechanism could be manufactured and the sources of power for this winding mechanism.

The design cannot be developed further without detailed data about the kind of terrain that it is to be designed for. The overall diameter of the sphere needs to be determined based on the size of the rocks that it is expected to navigate over and the capsule that it is to be deployed from. The PH design gets better at rolling the larger that it is to the optimal design could be indefinitely large.

The questions posed above would be a good starting point of any number of future projects focused on Martian passive locomotion. Overall, we believe this project to be successful because tackled the first portion of a very large and complex problem and paved the way for future investigations so that someday passive locomotion on mars can become a reality.

References

[1] Fabino, L., Gamarra, P., & Kimball, H. (2018). Energy-Storing Tensegrity Structure Rover. Retrieved January 28, 2019.

[2] Koizumi, Y., Shibata, M., & Hirai, S. (2012). Rolling tensegrity driven by pneumatic soft actuators. *IEEE Xplore Digital Library*. Retrieved January 16, 2019, from https://ieeexplore.ieee.org/document/6224834.

[3] Shibata, M., & Hirai, S. (2009). Rolling Locomotion of Deformable Tensegrity Structure. Retrieved January 16, 2019, from http://www.hirailab.com/pub-conferences/09/CLAWAR2009.pdf

[4] Hall, L. (Ed.). (2017, August 6). Super Ball Bot. Retrieved January 27, 2019, from https://www.nasa.gov/content/super-ball-bot

[5] Floating through the Martian Air. (n.d.). *NASA Mars Mobile.* Retrieved January 24, 2019, from https://marsmobile.jpl.nasa.gov/programmissions/missions/missiontypes/balloons/

[6] Sager, Christian (2013, August 7). The Flying Cities of Buckminster Fuller. Retrieved February 2, 2019.

[7] Walker, Robert (2014, January 12). Will We Build Colonies That Float Over Venus Like Buckminster Fuller's "Cloud Nine"?. Retrieved February 2, 2019.

[8] Bayard, D. S., Conway, D. T., Brockers, R., Delaune, J. H., Matthies, L. H., Grip, H. F., . . . Martin, A. M. (2019). Vision-Based Navigation for the NASA Mars Helicopter. *AIAA Scitech 2019 Forum*. doi:10.2514/6.2019-1411

[9] Balaram, B., Canham, T., Duncan, C., Grip, H. F., Johnson, W., Maki, J., . . . Zhu, D. (2018). Mars Helicopter Technology Demonstrator. *2018 AIAA Atmospheric Flight Mechanics Conference*. doi:10.2514/6.2018-0023

Appendix A. QFD House of Quality

Correlations	
Positive	+
Negative	−
No Correlation	

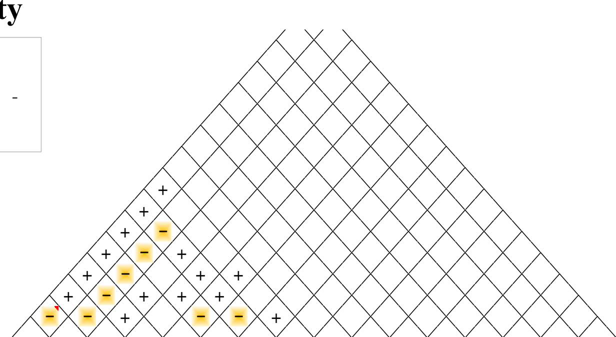
Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼

QFD House of Quality

Project: Tumble Bot

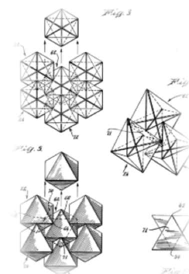
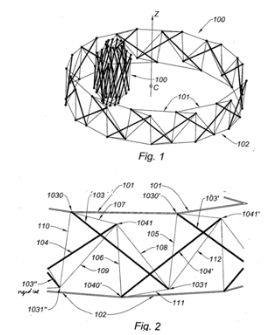
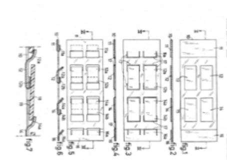
Revision Date 3/6/2019



								Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16						
	WHO: Customers							Direction of Improvement	▼	▼	▲	▲	▲	▲	▲	▲									NOW: Curr. Products					
Row #	Weight Chart	Relative Weight	Manufacturers	Scientists	Launch		Maximum Relationship	HOW: Engineering Specifications (Tests) / WHAT: Customer Requirements (Needs/Wants)	Cost	Weight	Device lifetime	Conversion of wind to KE	Impact Resistance	Max Payload	Ability to overcome obstacles	Reliability of deployment									Tumble Bot	*Ultra Long Duration Balloon*	Solar Montgolfiere	Super Ball Bot	PUFFER	Row #
1		10%	1	8	8		9	Light weight	○	●	●	●	●	●	●	○										4	4	5	5	1
2		10%	1	8	8		9	Passive locomotion	○	●	●	●	▽	○	●	▽										5	4	1	1	2
3		13%	4	7	9		9	Small packing footprint	○	○	▽	▽	▽	▽	▽	●										4	4	5	5	3
4		9%	1	10	5		9	Data retrieval	●	▽	▽	●	●	●	●	●										2	2	2	1	4
5		17%	10	5	7		9	Cost	●	●	●	○	●	●	●	●										3	3	5	4	5
6		12%	3	7	9		9	Durability	●	●	●	▽	●	○	●	●										4	4	5	4	6
7		12%	4	10	5		9	Environmental impact	▽	▽	●	▽	○	▽	○	●										2	3	4	3	7
8		16%	10	8	3		9	Reproducability	●	▽	▽	▽	○	○	▽	▽										4	4	5	5	8
9		0%																												9
10		0%																												10
11		0%																												11
12		0%																												12
13		0%																												13
14		0%																												14
15		0%																												15
16		0%																												16

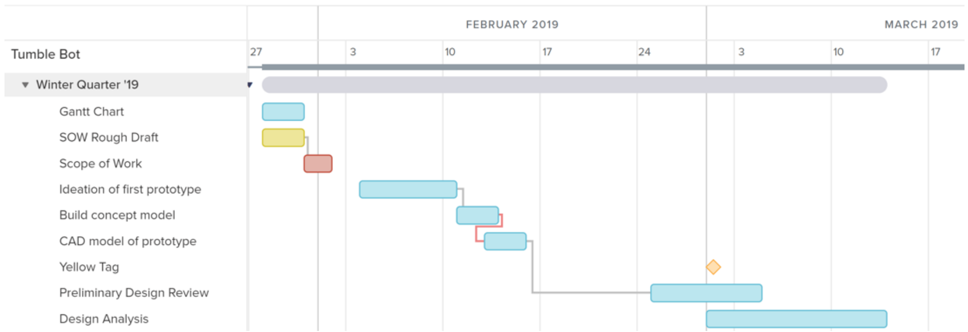
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	HOW MUCH: Target Values	$2 Billion	4 kg rover	1 month lifespan	Wind-driven motion	Survive surface landing	1.5 kg payload	Small to medium rocks	90% deployment success								
	Max Relationship	9	9	9	9	9	9	9	9								
	Technical Importance Rating	600.7	520.6	592.6	370.8	544.2	466.7	593.7	630.8	0	0	0	0	0	0	0	0
	Relative Weight	14%	12%	14%	9%	13%	11%	14%	15%	0%	0%	0%	0%	0%	0%	0%	0%
Curr. Products	Tumble Bot																
	Ultra Long Duration Balloon	3	2	5	5	4	5	5	3								
	Solar Montgolfiere	4	1	4	5	5	5	5	3								
	Super Ball Bot	4	5	3	1	5	4	3	4								
	PUFFER	4	5	3	1	4	1	3	4								
	Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

Appendix B. Relevant Patents

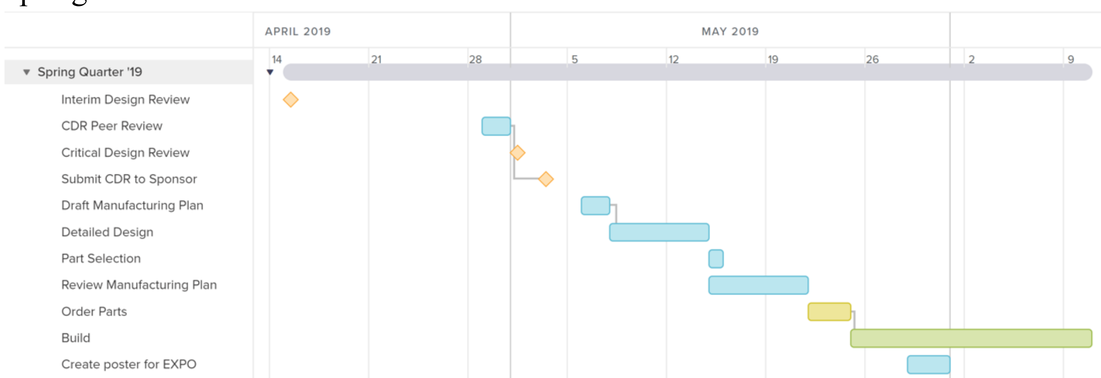
Patent Number	Title	Description	Picture
US4207715A	Tensegrity module structure and method of interconnecting the modules	System of interlocking tensegrity structures that can be used to make a membrane. Good for making a chain male like sheet of tensegrity structures.	
US20150151854A1	A deployable tensegrity structure, especially for space applications	A deployable tensegrity structure comprising, in the deployed state, a support structure	
CN102087528A	Passively driven exploration robot based on tumbleweed bionics	Novel spherical robot that uses air bags mounted on its surface to catch the wind and travel. Actively controls the aeration states of the air bags.	No picture
CN105862443B	The balloon material for hot air balloons and preparation method	Describes the materials used in making the membrane for a hot air balloon and how to correctly manufacture it	No picture
US3553030A	Radiation-sensitive semiconductor device	Semiconductor device that can convert radiation into electricity. Compact and can be formed onto curved surfaces. Requires batteries.	
WO1997025239A1	Ball robot and method for determining position thereof	Spherical robot comprising of at least one actuator, means for controlling operation, at least one programmable module	No pictures

Appendix C. Gantt Chart

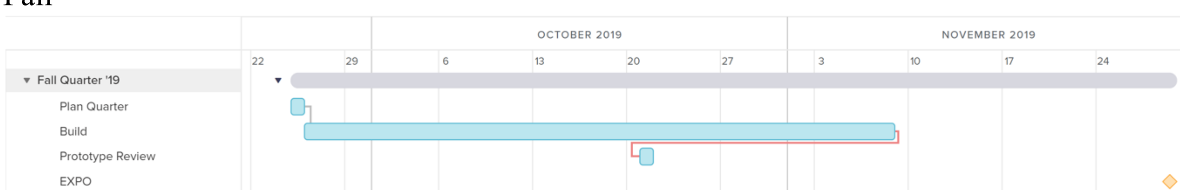
Winter



Spring



Fall



Appendix D. Weighted Decision Matrix

Table 5 contains the current weighted decision matrix. The final values displayed are out of a maximum total of 530 based on the weight of each criterion. The weighted decision matrix shows that the Persimmon-Hotdog concept best meets the design criteria. Although the design only totals 401 points out of a possible 530, this design meets the necessary requirements for the project. A lot of the design criteria are listed as wants and not needs due to the complex nature of the project. The most important design criterion listed on the Weighted Decision Matrix is passive locomotion and light weight. The Persimmon-Hotdog design was chosen because it scored well in both of these areas and had the highest overall score.

Table 5. Weighted decision matrix.

Criteria	Weighing	6 bar - curved members		6 bar - hourglass curved members		6 bar		12 bar		24 bar		32 bar		24 bar+ decahedron		24 bar+ 3 orthogonal planes		Helium balloon		Persimmon-Hotdog	
Line of sight	9	4	36	2	18	8	72	8	72	6	54	6	54	3	27	6	54	3	27	4	36
Light weight	9	6	54	7	63	9	81	9	81	8	72	8	72	7	63	7	63	10	90	9	81
Passive locomotion	10	10	100	10	100	1	10	1	10	3	30	2	20	7	70	8	80	8	80	10	100
Data retrieval	9	9	81	9	81	9	81	9	81	9	81	9	81	5	45	9	81	9	81	8	72
Cost	5	7	35	8	40	9	45	9	45	9	45	9	45	8	40	8	40	6	30	7	35
Durability	4	7	28	7	28	9	36	9	36	9	36	9	36	7	28	8	32	5	20	7	28
Manufacturability	7	3	21	4	28	9	63	9	63	8	56	8	56	7	49	7	49	5	35	7	49
			355		358		388		388		374		364		322		399		363		401

Appendix E. Preliminary Test Data

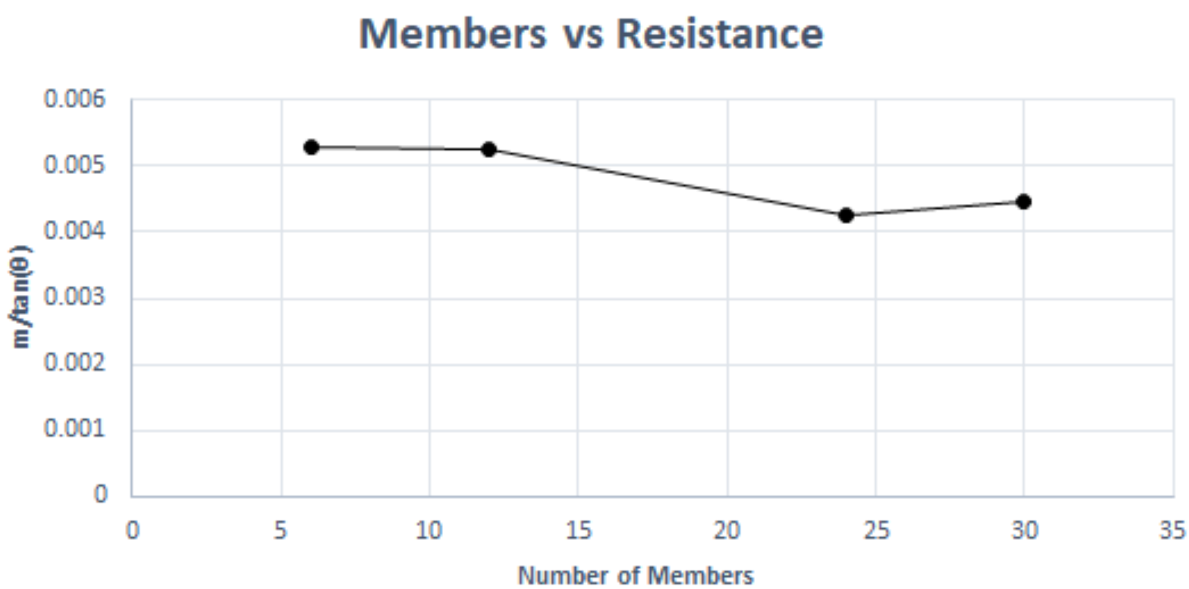


Figure 31. Tilt test results.

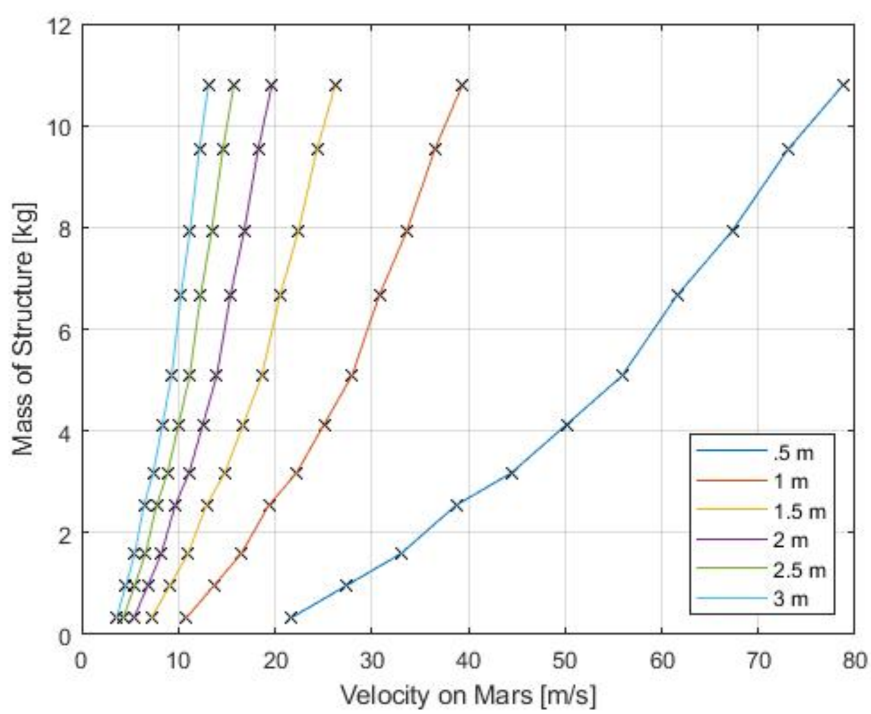


Figure 32. Sphere similitude test results.

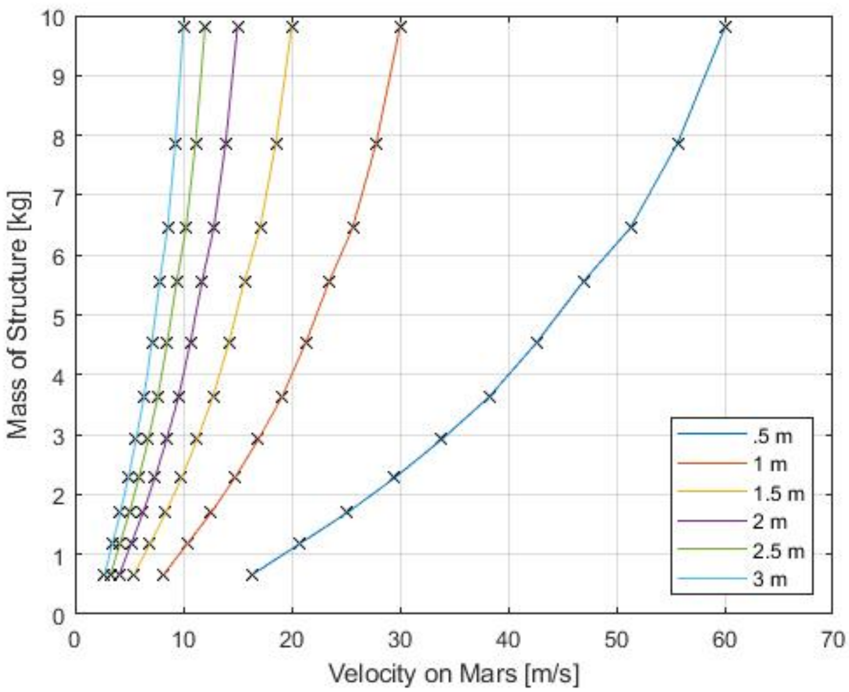


Figure 33. 3 Three-orthogonal-planes similitude test results.

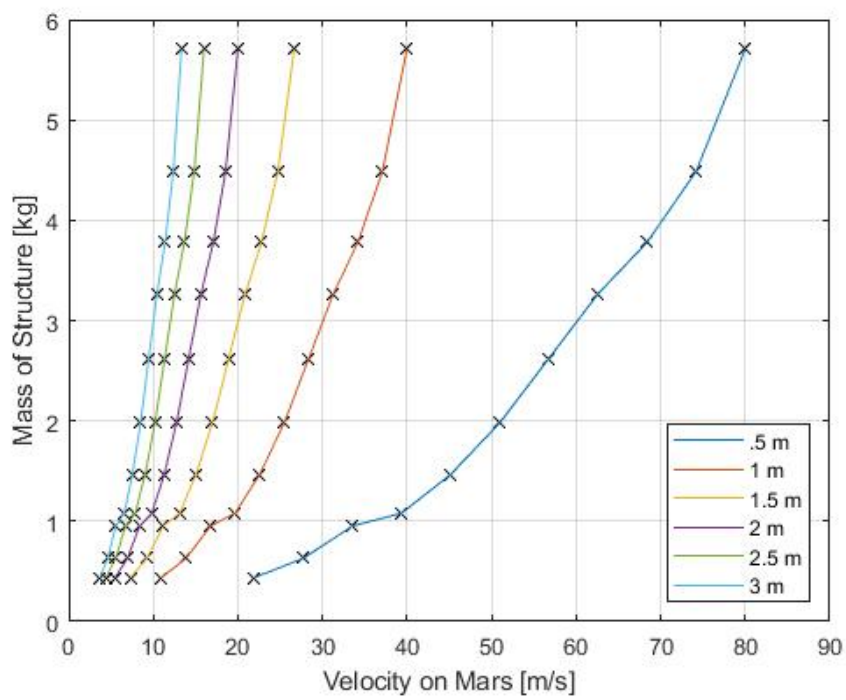


Figure 34. Dodecahedron similitude test results.

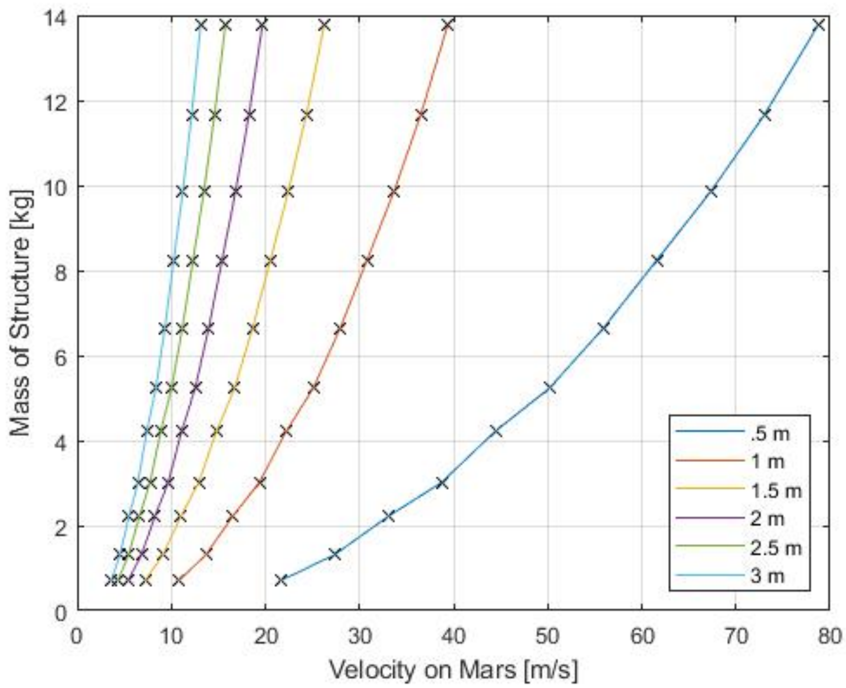


Figure 35. Tumbleweed similitude test results.

Table 6. Experimental drag coefficients for all shapes with constant Reynold's numbers.

Design	Reynolds Number	Cd
Sphere	7473	0.32
3 Orthogonal Planes	7473	0.695
Maxi Surface	7473	0.495

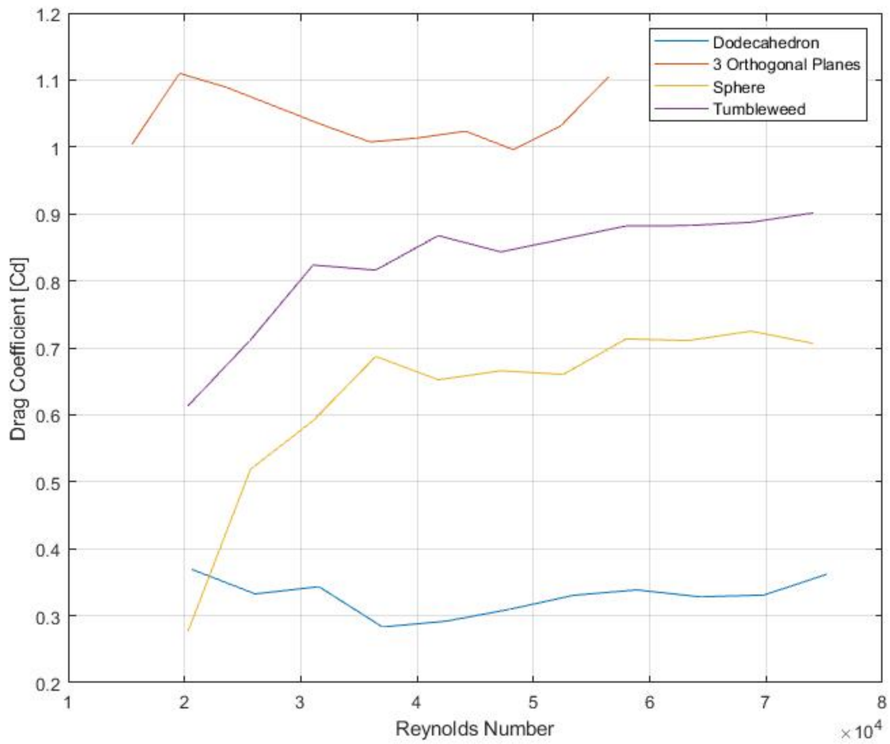


Figure 36. Experimental drag coefficients for all experimental shapes.

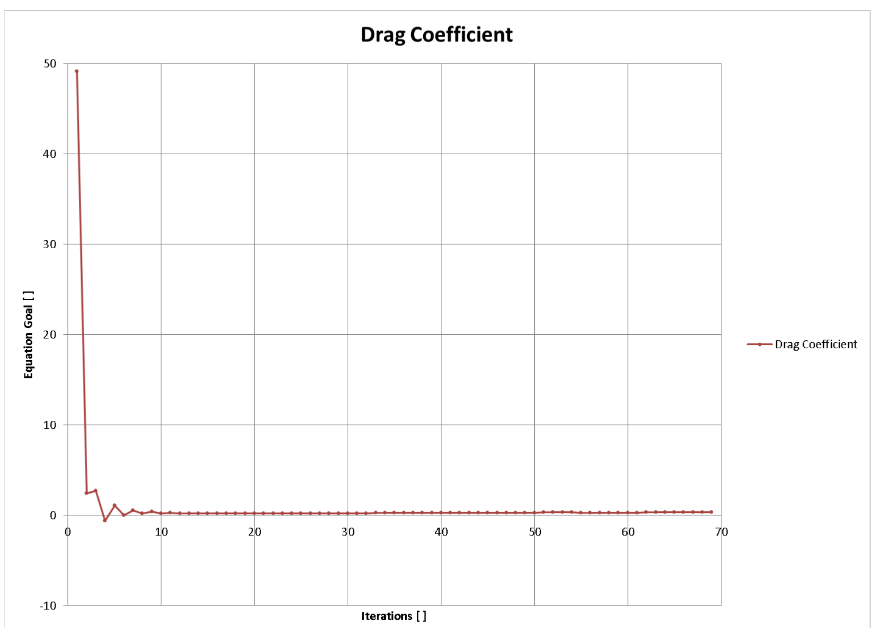


Figure 37. Drag coefficient results from CFD analysis for a sphere.

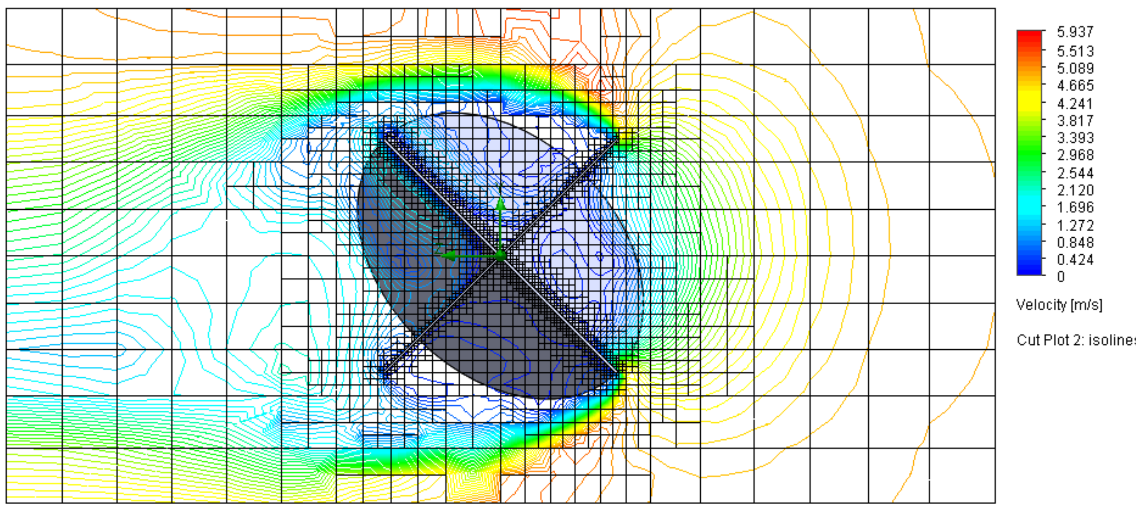


Figure 38. CFD results for the orthogonal plane geometry.

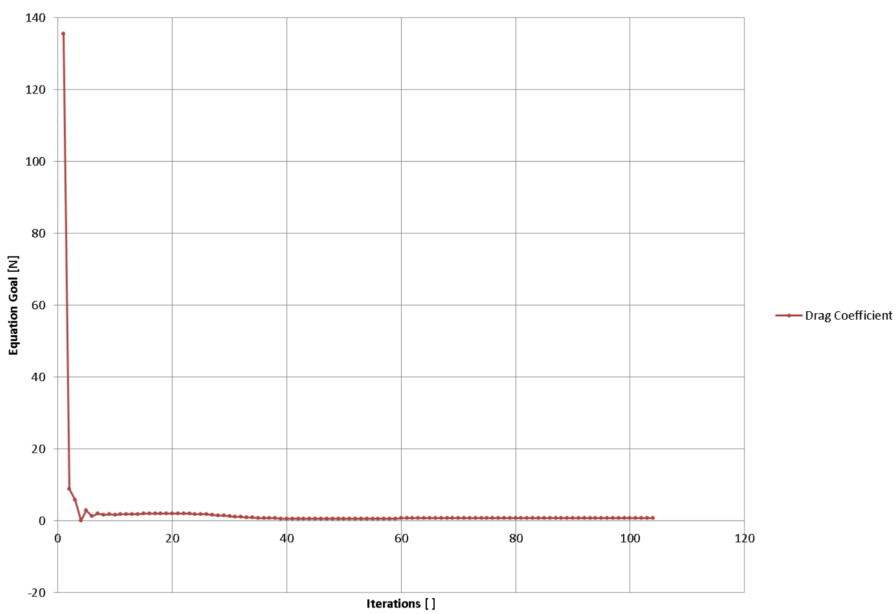


Figure 39. Drag coefficient results from CFD analysis for the orthogonal plane geometry.

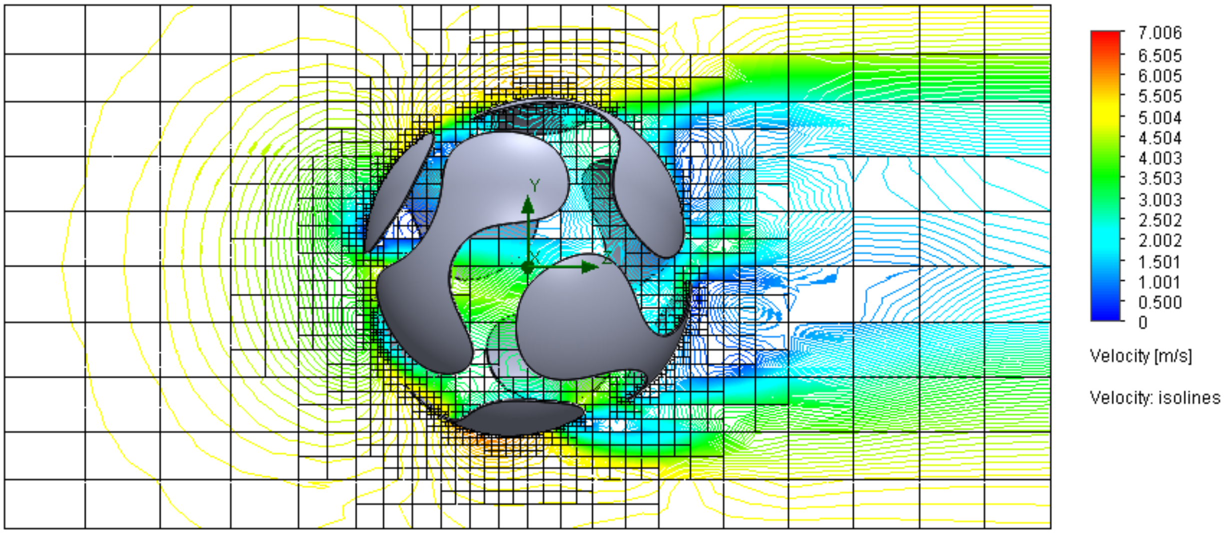


Figure 40. CFD results for the maxi surface.

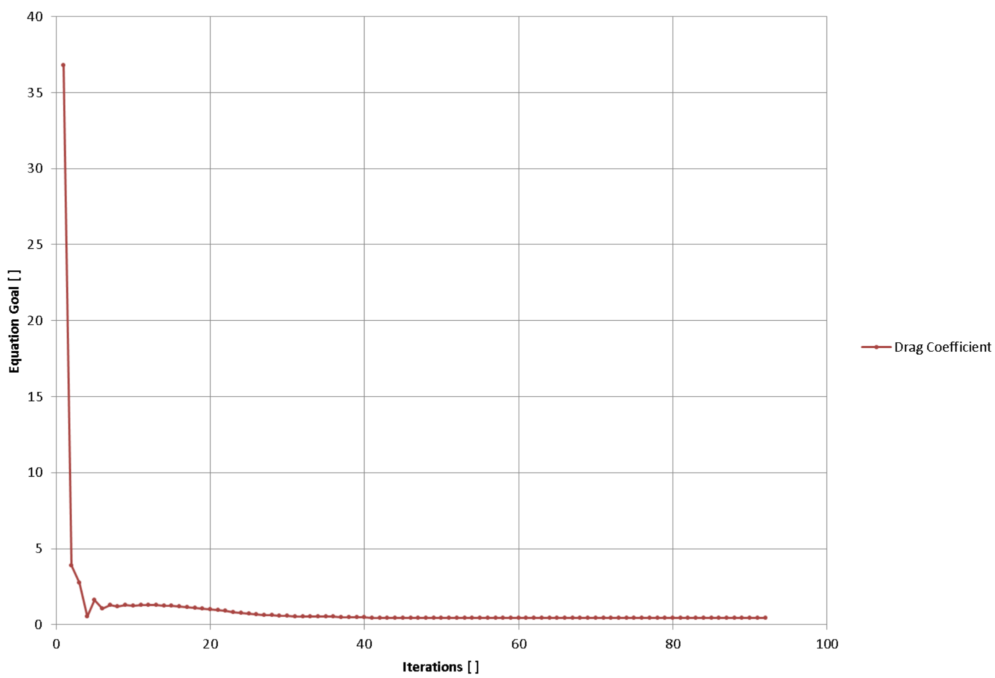


Figure 41. Drag coefficient results from CFD analysis for the maxi surface.

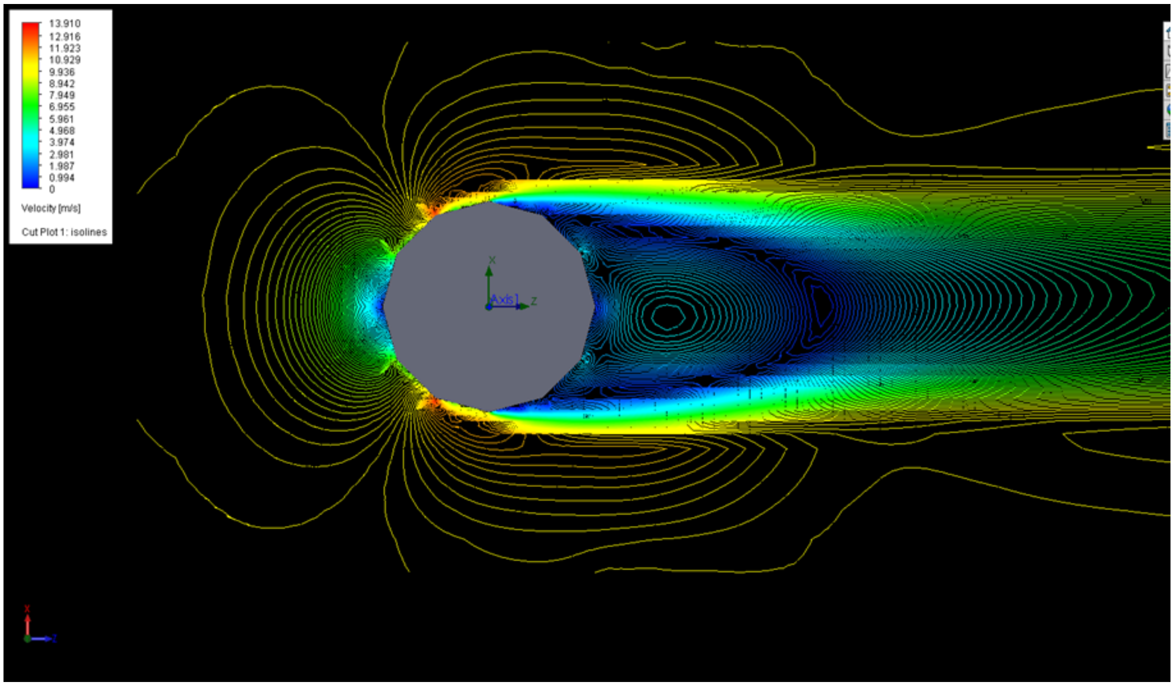


Figure 42. CFD results for the Persimmon-Hotdog final design.

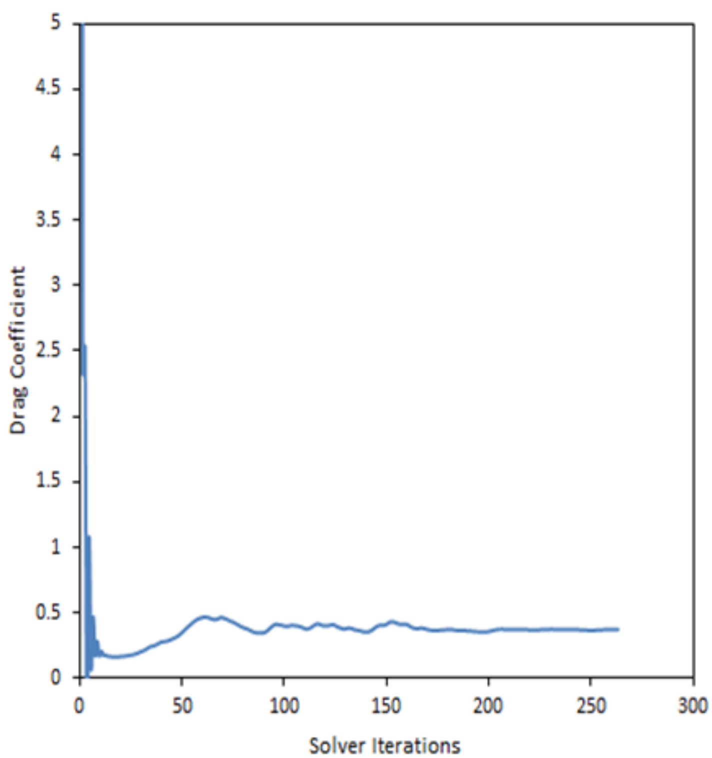


Figure 43. Drag coefficient results from CFD analysis for the final design.

Appendix F. Hazard Checklist

DESIGN HAZARD CHECKLIST

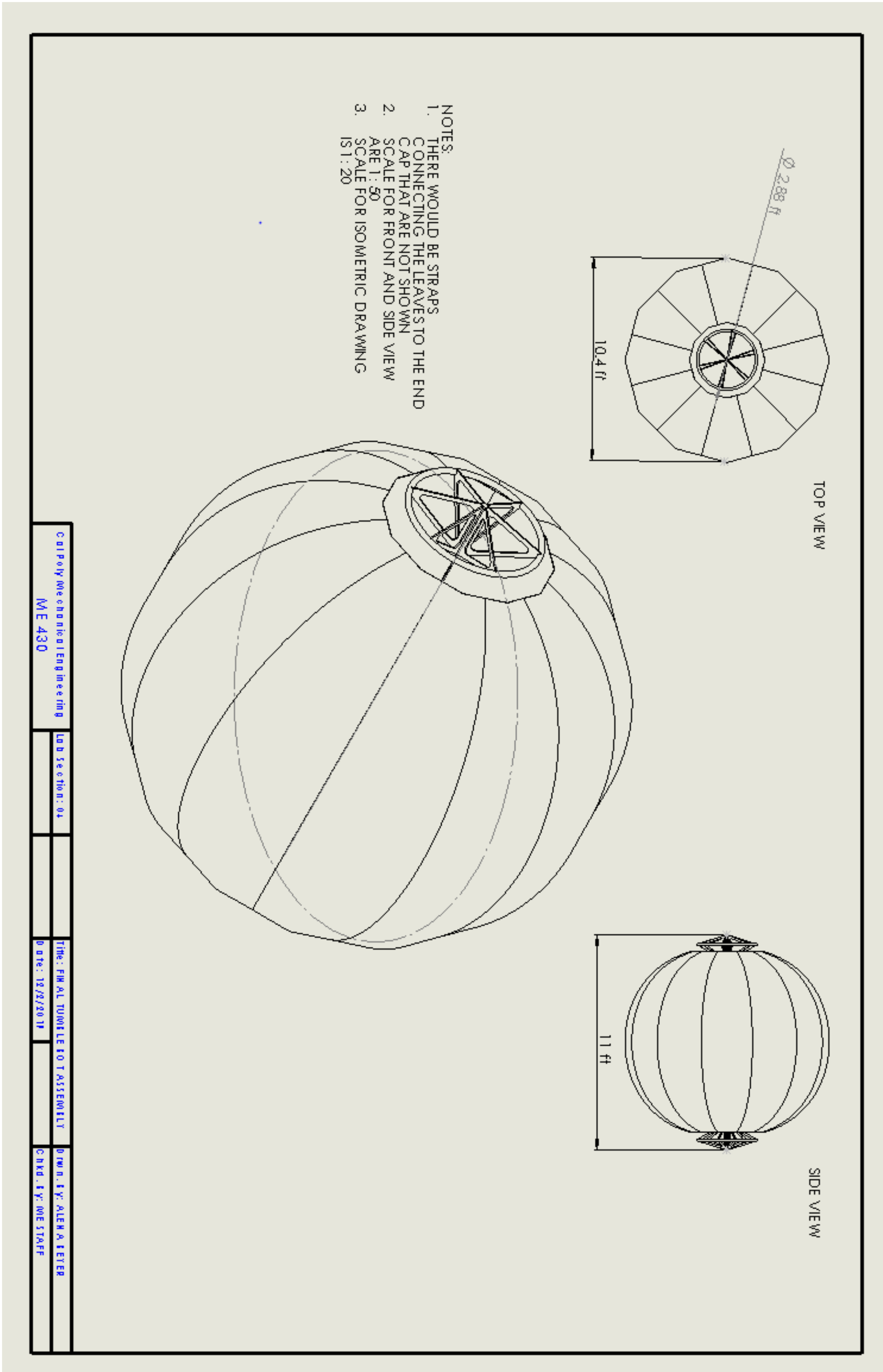
Team: Tumble Bot Advisor: Lee McFarland Date: 2/28/19

Y	N	
☒	☐	1. Will the system include hazardous revolving, running, rolling, or mixing actions?
☐	☒	2. Will the system include hazardous reciprocating, shearing, punching, pressing, squeezing, drawing, or cutting actions?
☐	☒	3. Will any part of the design undergo high accelerations/decelerations?
?	☐	4. Will the system have any large (>5 kg) moving masses or large (>250 N) forces?
☐	☒	5. Could the system produce a projectile?
☐	☒	6. Could the system fall (due to gravity), creating injury?
☐	☒	7. Will a user be exposed to overhanging weights as part of the design?
☐	☒	8. Will the system have any burrs, sharp edges, shear points, or pinch points?
☐	☒	9. Will any part of the electrical systems not be grounded?
☐	☒	10. Will there be any large batteries (over 30 V)?
☐	☒	11. Will there be any exposed electrical connections in the system (over 40 V)?
☐	☒	12. Will there be any stored energy in the system such as flywheels, hanging weights or pressurized fluids/gases?
☐	☒	13. Will there be any explosive or flammable liquids, gases, or small particle fuel as part of the system?
☐	☒	14. Will the user be required to exert any abnormal effort or experience any abnormal physical posture during the use of the design?
☐	☒	15. Will there be any materials known to be hazardous to humans involved in either the design or its manufacturing?
☐	☒	16. Could the system generate high levels (>90 dBA) of noise?
☒	☐	17. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, or cold/high temperatures, during normal use?
☐	☒	18. Is it possible for the system to be used in an unsafe manner?
☐	☒	19. For powered systems, is there an emergency stop button?
☐	☒	20. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

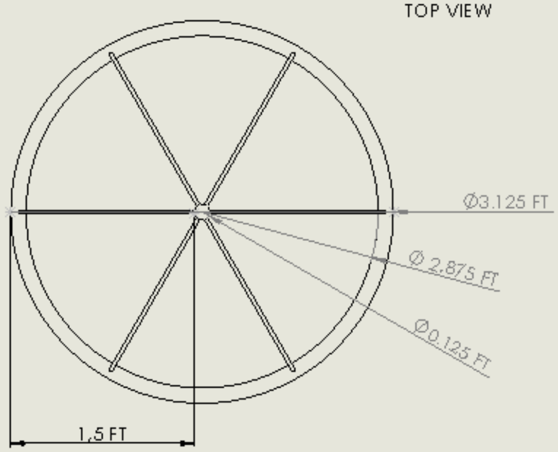
For any "Y" responses, add (1) a complete description, (2) a list of corrective actions to be taken, and (3) date to be completed on the reverse side.

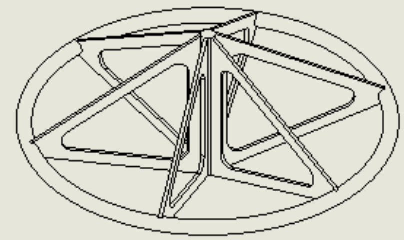
All "Y" responses are explained in Section 4.10 (Current Risks) of the PDR

Appendix G. Parts and Assembly Drawings



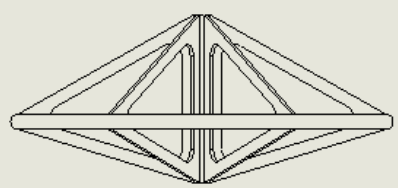
TOP VIEW



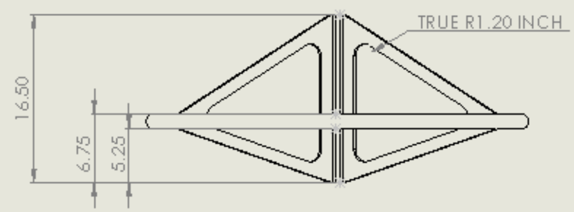


NOTES:
1. ALL THE INTERIOR RADII ARE 1.2 INCHES
2. TOLERANCES ARE UNKNOWN AS OF NOW, FINAL TOLERANCES WILL BE DETERMINED BASED OFF OF CHOSEN MANUFACTURING PROCESS

FRONT VIEW



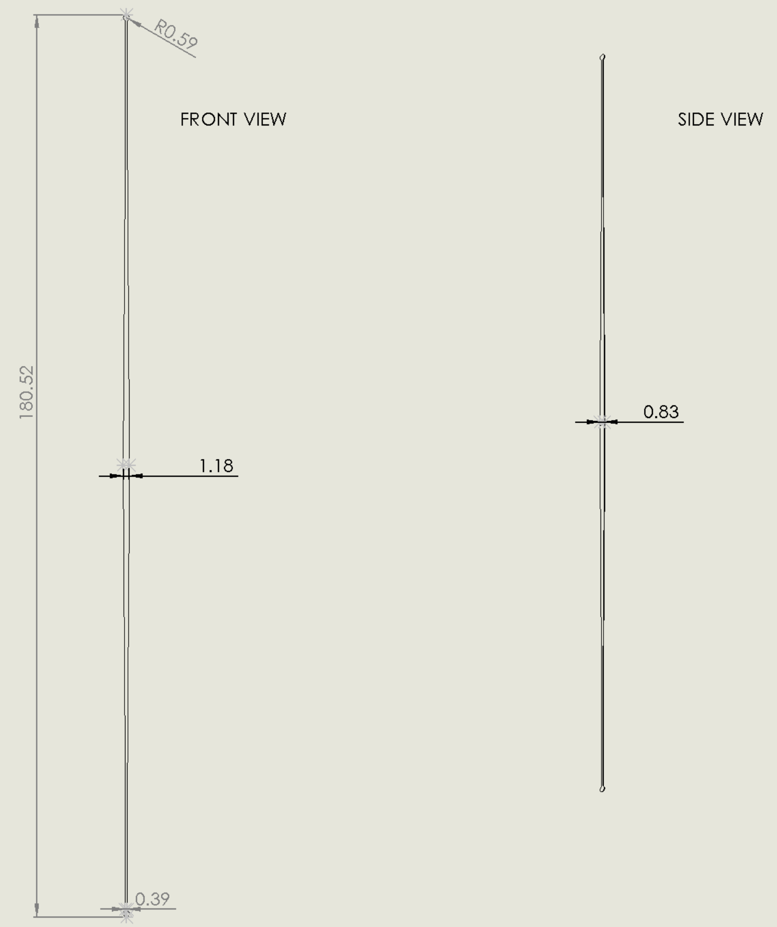
SIDE VIEW



Cal Poly Mechanical Engineering ME 430	Lab Section: 04		Title: TUMBLEBOT END CAP	Drwn. By: ALEN A BEYER
			Date: / Scale: 1:10	Chkd. By: ME STAFF

NOTES:

1. THE WIDTH OF THE LEAVES ARE NONLINEAR AND RANGE FROM 0.39 INCHES TO 1.18 INCHES
2. THE WIDTH OF THE LEAVES IS UNIFORMLY 0.83 INCHES
3. THERE ARE 12 LEAVES IN THE FINAL ASSEMBLY



Cal Poly Mechanical Engineering ME 430	Lab Section: 04		Title: TUMBLE BOT LEAVES	Drwn. By: ALENA BEYER
			Date: 12/2/2019	Chkd. By: ME STAFF

Appendix H. Bill of Materials

Since the final deliverable was a proof-of-concept design, there was not much of a focus on sourcing and purchasing materials. The indented Bill of Material below contains an accurate description of the assembly levels as well as some possible vendors and prices per quantity. The quantity needed of each material is dependent on the final dimensions of the

					Indented Bill of Material (BOM)				
					Tumble Bot				
Assembly	**Part**		**Description**			**Vendor**	**Qty**	**Cost**	**Ttl Cost**
Level	**Number**								
		Lvl0	Lvl1	Lvl2	Lvl3				
0		Final Assembly				------			
1			Structural Assembly			------			
2				Carbon Fiber (M55J)		TORAY	unknown	$23/kg	
2				Kevlar		US Composites	unknown	$24.50/yard	
2				Fabric Joint					
3					Kevlar	US Composites	unknown	$24.50/yard	
3					Bonded Nylon Sewing Thread	Polystar	1500 yards	$17.24/1500 yard	17.24
3									
1			Payload Assembly						
2				Solar Panel					
2				Communication Device	Electronics				
2				Camera	Heaters				
2				Payload Mounting Assembly					
3					Mounting Plate				
3					Screws				
3					etc				
	Total Parts						**0**		**17.24**

Appendix I. Project Budget

The initial budget specified by JPL was $2,000. As the project progressed the scope changed from building a scaled down model to instead delivering a proof-of-concept design with analysis that validates that the final design meets the project specifications. The majority of the analysis was done using FEA and CFD software, so it was not necessary to procure many physical materials. The total amount that was expensed to JPL over the course of the project was $34.99 for a Hoberman Sphere during the initial brainstorming process. All of the materials that were used for the final design verification were obtained at no cost. The concept models were printed for free in a Cal Poly lab, and the carbon fiber sheets were donated to help with the project and support the Cal Poly composites lab.

Appendix J. Failure Mode & Effects Analysis (FMEA)

Design Failure Mode and Effects Analysis

Product: Mars Tumbleweed

Prepared by: Team 43

Team: Tumble Bot

Date: 03/13/19 (orig)

System / Function	Potential Failure Mode	Potential Effects of the Failure Mode	Severity	Potential Causes of the Failure Mode	Current Preventative Activities	Occurence	Current Detection Activities	Detection	Priority	Recommended Action(s)	Responsibility & Target Completion Date	Action Results: Actions Taken	Severity	Occurence	Criticality
Rolling structure / not buckling	Euler buckling	structure collapses	9	1) break under impact loading 2) member deflecting on a rock	1) delfection analysis 2) Euler buckling hand calculations 3) experimenting with different geometries	6	FEA	1	54						
Rolling structure / maintain round shape	Cables lose tension required to keep shape	structure will not roll	6	1) members deforming 2) members breaking 3) tension cables break 4) joints break	1) ideation to determine best, round structure 2) measuring rolling the structure with different tensions 3) designing joints to maintain constant tension	8	Concept Models	4	192						
Rolling structure / have enough drag	Sails don't move the structure with only wind force	not enough drag to induce movement of structure	9	1) not enough exposed surface area 2) sails tear 3) sails weigh down structure	1) Testing different sail configurations in the wind tunnel	10	Concept Models	1	90						
Internal Payload / record clear images	a) No line of sight for camera b) Images are blurry	will not collect acceptable data	7	1) sails obstruct camera view 2) camera gets damaged 3) camera disconnects from structure	1) Using the least amount of sail surface area possible 2) designing sail configuration to allow for significant line of sight	9		1	63						
Internal Payload / effective solar panel	Solar panel is not exposed to enough sun	Not enough electricity to power the camera, communication device or heat the electronics	8	1) sails shade panel 2) panels get damages	1) Using the least amount of sail surface area possible 2) designing sail configuration to allow for sunlight to rach the panel in all directions	9		2	144						
Internal Payload / communicate	Payload cannot communicate with Master	unable to communicate wih satellite	7	1) not powered by solar panel 2) electronics can't maintain connection	1) modeling electronics after designs that have been proven to be effective	9		1	63						
General / joint integrity	joints break	structure's shape will deform or collapse	8	1) joints shear 2) joints get caught on rocks	1) Stress analysis 2) Reinforcing joints	8	FEA	2	128						
General / appropriate material selection	Material is too heavy or off-gasses	material will make the design less effective	6	1) chemical reactions with environment 2) makes structure too heavy	1) Being conscious of our material choices 2) designing with materials that will survive a vacuum	2	Existing vacuum chamber data	5	60						

Appendix K. Design Verification

Table 7. Design verification criteria and evaluations.

Specification #	Test Description	Acceptance Criterion	Data Type	Pass/Fail
1	Project Budget	<$2,000	Quantitative	P
2	Mass estimation of each component	Less than/equal to 15 kg	Quantitative	P
3	Cannot be tested on Earth	Can roll for 2 weeks on Mars	Qualitative	Inconclusive
4	Tilt Testing, CFD	Will move in wind speeds of 5 m/s	Quantitative	P
5	Abaqus FEA	Withstand static loading	Quantitative	Inconclusive
6	Meets specification #2	Carry 1.5 kg payload	Quantitative	P
7	Cannot be tested on Earth	Can roll over 50% of rocks	Qualitative	P
8	Manufacturability, Cost	Very reproducible	Quantitative	P
9	Ability to get unstuck	Escape hole 1/8 of its diameter	Quantitative	P

Appendix L. Component Specifications

Component level breakdown for the mass of a 3-meter diameter ball. All masses can be scaled as a function of diameter to find the theoretical masses for systems with different diameters.

Table 8. Specifications of all components.

Component	Ball Diameter [mm]	Component volume [mm^3]	Density [g/mm^3]	Mass [g]	Mass [kg]
Sail (kevlar 29)	3000	2.70E+06	1.44E-03	3.89E+03	3.89
Endcap (6061)	3000	done in SW	done in SW	1.22E+03	1.22
Member (TC380)	3000	4.04E+06	1.18E-03	4.77E+03	4.77
Payload (kg)	1.5				
Total				9.87E+03	11.4