University of Southern Indiana
Pott College of Science, Engineering, and Education
Engineering Department
8600 University Boulevard
Evansville, Indiana 47712

Design and Build of a Launching Mechanism for Space Debris Capture

William Choate
Zach Cosby

ENGR491 – Senior Design
Spring 2022

Approved by: ____

Faculty Advisor: Glen Kissel, Ph.D. Date

Approved by: ____

Department Chair: Paul Kuban, Ph.D. Date

Acknowledgments

The Space Debris Capture team would like to show our immense gratitude to the following people. Without them, everything accomplished in this project would not have been possible.

The University of Southern Indiana Engineering Department:

Dr. Glen Kissel

Dr. Todd Nelson

Dr. Paul Kuban

Justin Amos

Jamie Curry

Abstract

In this project a launching mechanism for space debris capture was designed, built, and tested. Space debris capture mechanisms capture space debris and then deorbits with the debris. If the space debris issue is left unchecked, it will spiral out of control and pose a risk to infrastructure and astronauts. This project aims to create a prototype to test centrifugal force for spin deployed nets. This prototype was designed from the inside out starting with the net. Some FEA analysis was conducted to help with the design process. The prototype was then constructed and tested for deployment. The prototype was successful in spin deployment at roughly 12 $\frac{rad}{s}$. All requirements of the project were met except for the actuated linear deployment velocity of 1 $\frac{m}{s}$.

Table of Contents

List of Figures

List of Tables

List of Acronyms/Abbreviations

NASA	National Aeronautics and Space Administration
ESA	European Space Agency
PLA	Polylactic Acid
ELSA-d	End of Life Services by Astroscale (-demonstration)
USI	University of Southern Indiana
LEO	Low Earth Orbit
PMD	Post Mission Disposal

1. Introduction

Space debris is defined by NASA as a man-made object that no longer serves a purpose and is in orbit around the earth. This debris is found floating in many different orbits and must be cleaned up. Capture devices for space debris are used to collect the debris from satellites that have been destroyed or decommissioned. Space debris is most dense in the lower earth orbit region around earth. The distribution of the space debris can be seen in Figure 1. This can be very challenging for all current satellites and future missions to have to avoid. This project aims to create a spin launch device that is capable of capturing space debris with a net. This mechanism would use springs to launch the mechanism forward and centrifugal forces to rotate and deploy the net [17.]

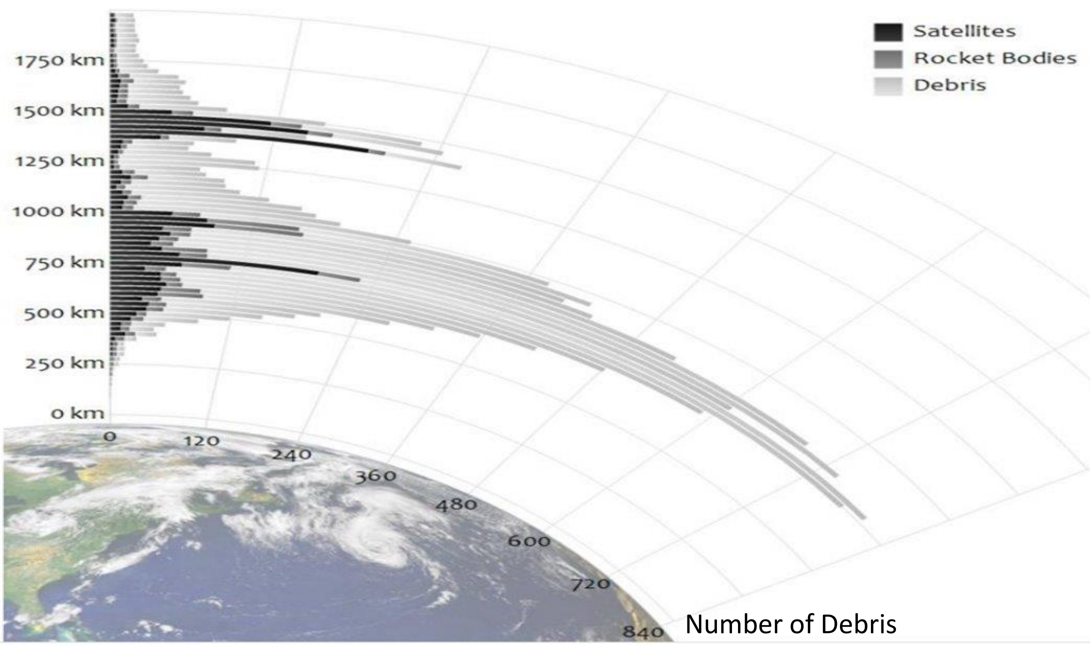

Figure 1 Distribution of Space Debris in Low Earth Orbit [17]

1.1 Objective

The objective for this project is:

The objective of this project is to design a mechanism that spins and launches a net to capture space debris.

This project is needed due to the lack of research describing the deployment system for a spin deployed net. Most available research that discuses spinning nets details the dynamic motion of the net and not how to reliably obtain the spin and deployment. Most research is also dedicated to theoretical studies and do not have a real prototype built and tested. This leaves many questions as to how accurate the theories around nets are. One paper from the Royal Institute of Technology suggests that if a net is small enough than the net would not require a control system for reliable deployment. Except for some quick calculations that suggest the possibility, the author quickly returns to talking about larger nets that require control systems [11].

1.2 Deliverables

The deliverables for this project are.

- Solidworks Model
- Tabletop Prototype
- Presentation, Poster, Report

This project is a prototype for a proof of concept and not as a final design ready for practical use. The scope of the project was simply to prove the concept and let future teams create a more robust end to end design that can be deployed in space. The future works section will go into more detail about what may be required for a final design.

Chapter 2 describes the background of the system. Chapter 3 describes multiple concepts that were considered before the final design was chosen. Chapter 4 goes into details on the final design for the prototype. Chapter 5 will discuss the testing of the prototype. Chapter 6 will talk about the testing of the device. Chapter 7 will discuss the new and reviewed engineering concepts. Chapter 8 discusses the teamwork between the team members. Chapter 9 here we will discuss the lessons that we have learned from this project. Chapter 10 talks about the future projects and things that would need to be accomplished to send this device into space. Chapter 11 is the conclusion of the report and summarizes the rest of the report. In the appendices there is a system hierarchy, mechanical block diagram, budget, mass table, bill of material, and a concept of operations.

2. Background

2.1 Statement of the Problem

Currently there are over 22,000 pieces of tracked debris orbiting earth. Tracked pieces are defined as being 10 centimeters or larger. There are far more pieces of debris that are smaller than this but are difficult to track with equipment on earth but, could be tracked more easily with a satellite. The amount of space debris continues to grow every day as pieces of debris collide into each other splitting larger pieces into smaller pieces, by colliding into existing satellites or free-floating rocket parts. The Iridium 33 and Cosmos 2251 collided in 2009, greatly increasing the amount of space debris in orbit [6]. On November 15, 2021, the Russian government launched an antisatellite missile and destroyed an existing satellite [19]. This caused an estimated 1,500 pieces of tracked space debris at a rough altitude of 482 kilometers. At this orbit the debris threatens the ISS and satellites in similar orbits. The Kessler Syndrome describes this phenomenon and how space debris will increase exponentially over time to an unmanageable amount in LEO. This belief is that as space debris collides into more debris then more pieces will fragment from the collision. This creates an exponential increase in the amount of debris. Thus, causing more collisions and increasing the risk of contacting larger spacecraft and risking the life of astronauts. Below in Figure 2 is a Monte Carlos simulations of space debris showing the predicted amount of space debris until the year 2210 [17].

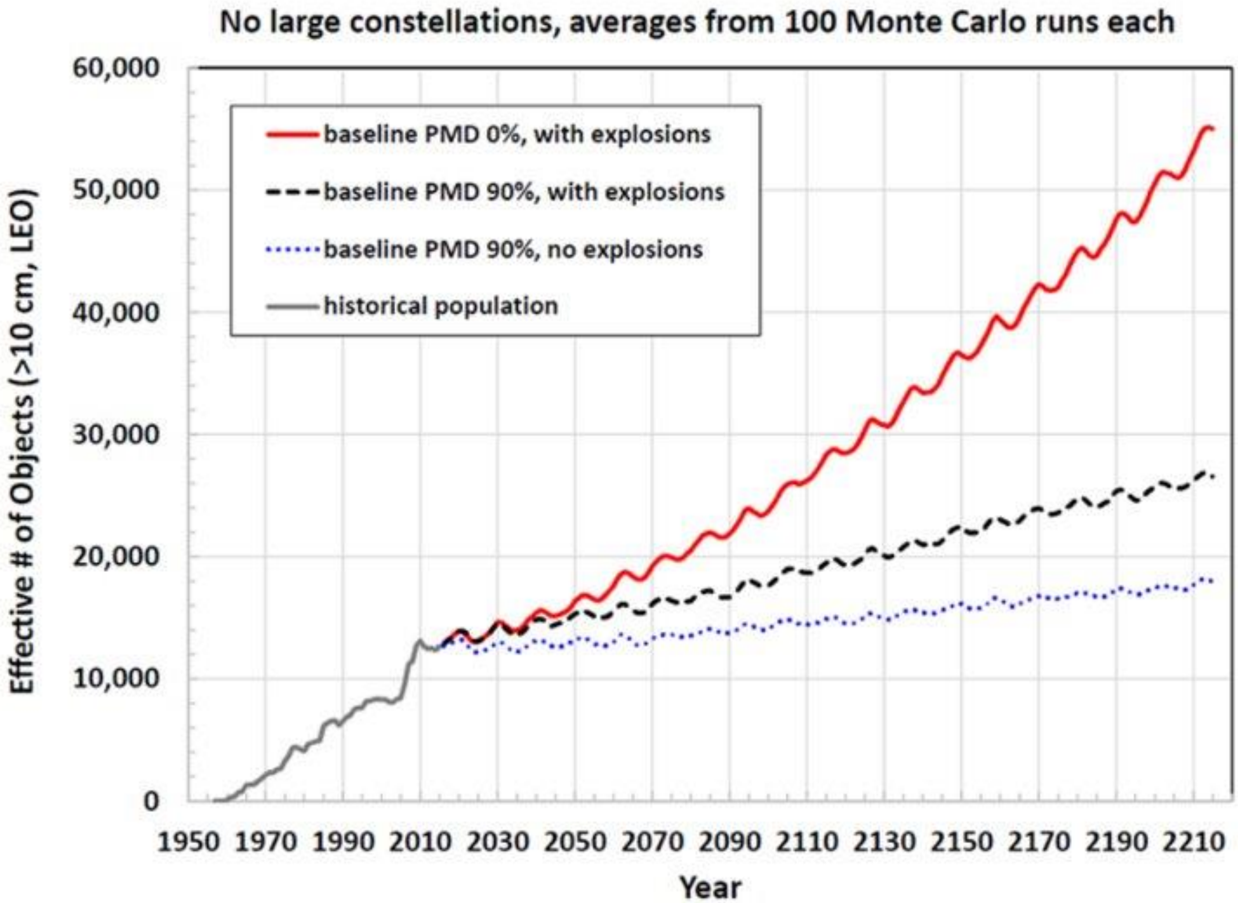

Figure 2 Monte Carlos Simulations of Space Debris in LEO [17]

Current space debris mitigation practices have the satellite float into a graveyard orbit or fall into earth's atmosphere. This is done typically at the end of the mission cycle for newer satellites. Figure 2 shows three different predictions for future space debris in LEO. The different predictions are calculated on Post Mission Disposal (PMD) and if there is an explosion of rocket bodies. This implies that even with mitigation tactics the amount of trackable space debris is set to increase. Current missions require PMD to be approved to go into orbit. Unfortunately, even with 90% post mission disposal the amount of space debris is still set to increase. Other methods that are currently used is simply attempting to track and avoid incoming debris. For example, The International Space Station (ISS) has an imaginary 2-mile boundary box that once breached by a piece of space debris causes the ISS to move into a new orbit. While this is great for not directly increasing the problem it does nothing to reduce the amount of space debris currently in space. This safety measure was triggered shortly after the Russian missile discussed earlier. Thus, the need for space debris capture mechanisms such as the one in the computer render in Figure 3.

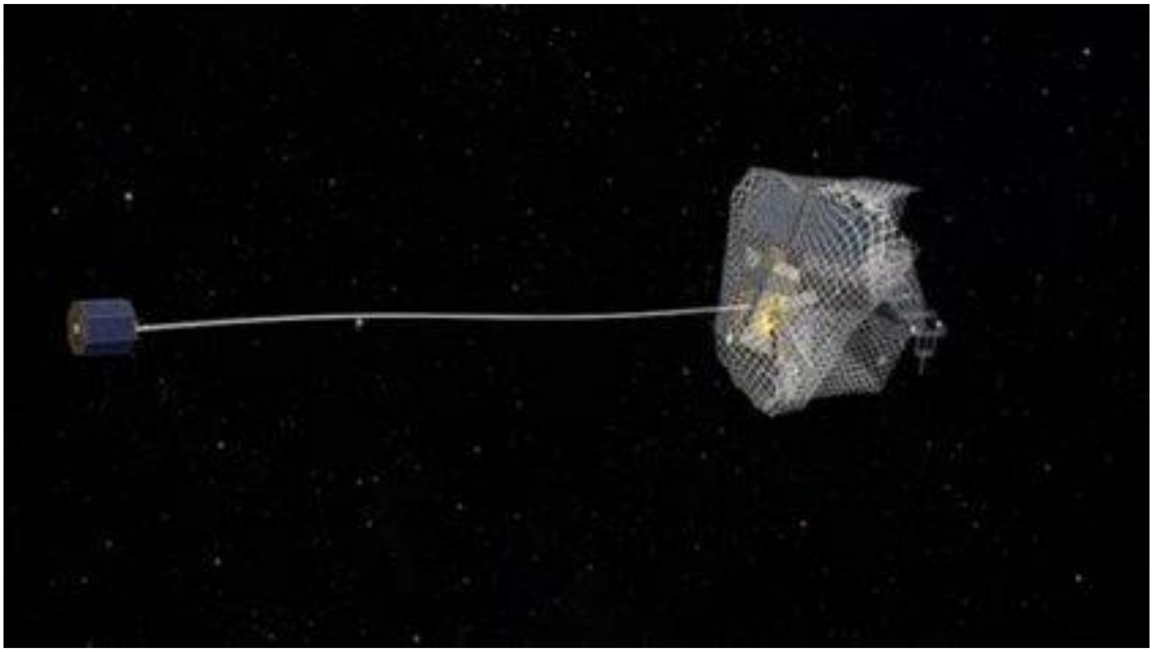

Figure 3 Space Net Capturing Debris [20]

Space debris capture mechanisms can be classified as either passive or active systems. Passive systems are simple systems that wait for the space debris to float into the device and activate the capture mechanism. Active systems use launching mechanisms to deploy the system towards and actively seek out the space debris. Examples of both passive and active will be shown in this paper with the focus being the active deployment systems.

2.2 Relevant Projects and Research

Various agencies and universities across the globe have done research into space debris capture mechanisms. These agencies include NASA and the ESA while various universities include McGill University, Royal Institute of Technology, and Tsinghua University [9],[11],[8],[12],[1] . All these agencies and universities have done research or built a prototype for space debris capture and some of the reports are presented in this section. The issue with space debris has increased so much, that even private companies such as Rubicon started a competition with a cash prize of 100,000 dollars to create a new, unique concept for space debris capture [21].

2.2.1 USI’s Fall 2020 Space Debris Capture System

This first project was done by a USI senior design team in the fall of 2020 [4]. The following design shows a passive system that waits for space debris to enter the trap door that does not allow debris to escape. This system starts as a little box attached to the side of a satellite, then once needed it deploys open with the four telescoping rods. These rods contain a net and trapdoor system on the front face of the system. This system can capture multiple pieces of debris assuming they are clumped together, and they all reach the net at a similar time. The advantage of this system is that it is simple and easy to deploy. It can also be easily scaled up for larger areas or done for smaller areas. Some disadvantages are that it relies on space debris to come close to the satellite it is attached to. This could cause damage to the satellite and potentially cause it to become space debris. Figure 4 shows the final design for the USI Passive Space Debris Capture Mechanism.

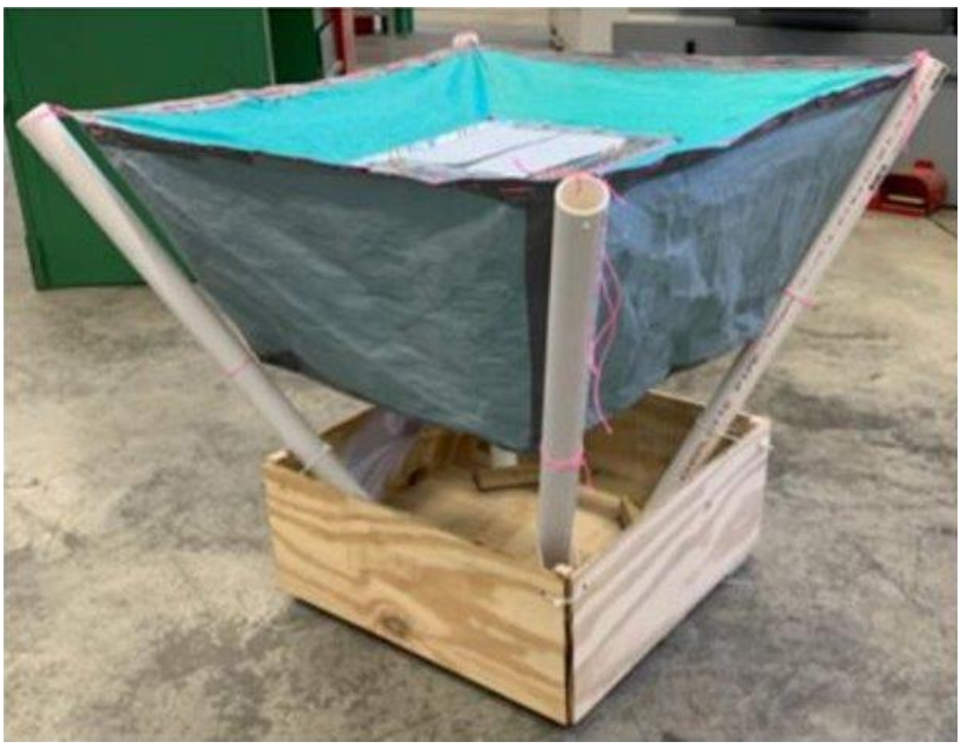

Figure 4 USI's Fall 2020 Space Debris Capture System [4]

2.2.2 Spider Web Space Debris Capture System

The spider web space debris capture system was designed to spin and deploy from a central hub [2]. This spin process can be seen in Figure 6. This paper mostly focused on the deployment dynamics of the net with Finite Element Analysis (FEA) in both the deployment stages and debris collision stages. While their simulations showed promising results for spin deployment and debris collision, they do not detail how to achieve proper deployment and what methods of deployment should be used. While a concept, shown in **Error! Reference source not found.** 5, was given, it was never tested or fully simulated to verify that the mechanism could achieve the desired results. A control system is mentioned but is left for future works, this leaves the idea a little lacking in thought and increases the difficulty of making this work. Thus, more research and testing are required to verify spin deployed nets.

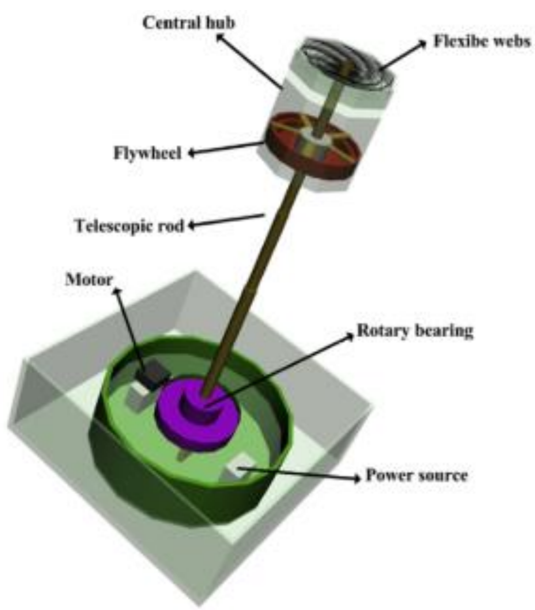

Figure 5 Launching Mechanism of a Spider Web Capture System [2]

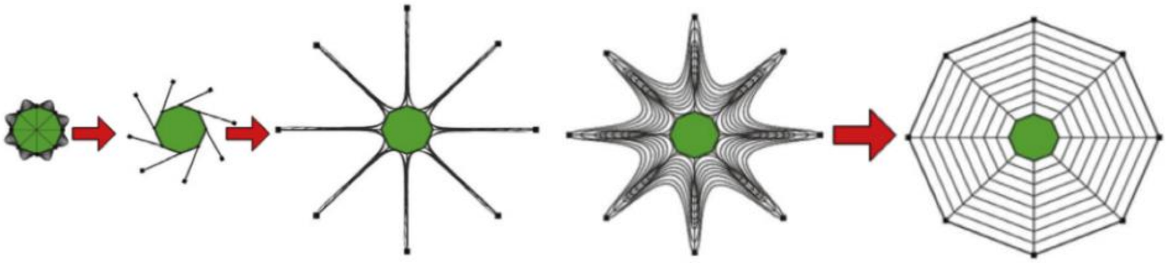

Figure 6 Spinning Web Deployment [2]

2.2.3 Tsinghua Net Deployment Tests

Tsinghua University in China has done many theoretical studies on space nets and eventually tested a prototype and confirmed their computer simulations [1]. This was done by using a small metal device shown in Figure 7 to launch three-point masses at set angles. The net was stored in the center of the device until launch. The launching mechanism was a small dose of black powder. While this is acceptable for a prototype on land it would be extremely difficult, if not impossible, to be approved to go into space on a rocket. They tested their net with different launching speeds and found that their models were extremely accurate. Table 1 shows the results from this experiment [1]. Figure 8 shows the net of the Tsinghua launching mechanism. In the top center of the image is a white net that can be seen bending over as the weights of the net fall back to the ground.

Figure 7 Tsinghua Launching Mechanism [1]

Figure 8 Net of the Tsinghua Launching Mechanism Net [1]

Table 1 Tsinghua Testing Data [1]

	First	Second	Third	Fourth
Powder dosage (g)	7	9	14	20
Ejection angle (°)	60	60	60	60
Range(m)	12	13.75	18.35	22
Ejection velocity (m/s)	11.7	12.5	14.4	15.8
Theoretical velocity (m/s)	12	13	14.5	16

The data in Table 1 shows four trials of the experiment that varied the amount of gunpowder per trial. This was done to test the accuracy of their computer simulations and dynamic analysis. It can be seen in the table that their calculations for ejection velocity had an average error of 3.2%. When comparing the range and video imaging of the deployment with the computer models it can be seen visually to be extremely accurate. Thus, the computer models accurately predicted the location and relative velocities of each node on the net. Where a node is defined as being the intersection of two strands of twine or rope. This indicates a high probability of accurate predictions for a future experiment involving nets in space and how they deploy and capture space debris. Below is Figure 9 this shows the basic concept of their design that would be used in space capturing a piece of space debris.

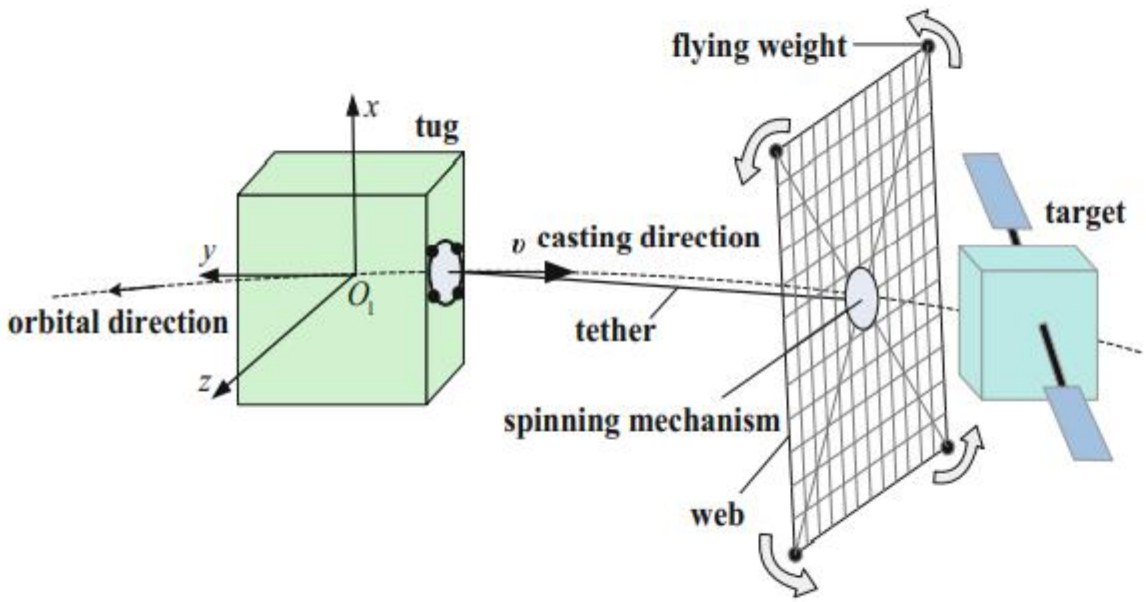

Figure 9 Tsinghua University’s Basic Concept of Space Debris Capture [1]

2.2.3 Suaineadh Space Web Experiment

This design was sent to space as part of a test to help better determine deployment dynamics [12]. This experiment was set up by creating a hub that would hold the net and adding multiple sensors to record deployment speed. This was also combined with cameras to visually determine deployment success. This experiment never included a test for debris capture. While the experiment proved a success at deploying the net, the testing equipment to gather the data on the velocities and accelerations across the deployment time was lost. The significance of this paper shows that centrifugal force can be used to deploy a net in space. Although, the design tested required a control system to help maintain desired velocities throughout the experiment, this increases the cost of the overall system by a large amount while also increasing the overall weight of the system.

Error! Reference source not found. 10 depicts the CHAD mechanism used in the S uaineadh experiment. In this image an orange and black cylindrical figure is shown in the center of a net. At the four corners, the little orange masses are seen. In its prelaunch state the net and masses are wrapped helically around the hub. During deployment the satellite that contained this experiment had an initial angular rotation of 11 $\frac{rad}{s}$. This device was then launched linearly outward from the satellite. Then centrifugal force causes the outer masses to deploy radially outward from the center hub. From here a reaction wheel on the inside of the hub is activated to help ensure good deployment. This is done because the conservation of angular momentum will cause the masses to slow down as they deploy outward, and the hub will continue with its angular momentum. Hence the reaction wheel slows the angular velocity of the central hub to help match the rotation of the masses. The paper also notes great care in the placement of the reaction wheel next to the center of mass [12].

Figure 10 Chad Mechanism for the Suaineadh Experiment [12]

2.2.4 Ideal Linear Velocity of Nets

McGill University did an interesting study on net launching. In this study they looked at different types of nets and tried to determine the best initial velocity [8]. McGill suggest that initial velocity should be 1 m/s. This was specifically for smaller nets. It is important to note this was not for rotating nets, but a lot of the characteristics of the net also describes the net that is made in this paper.

2.2.5 Research by the Royal Institute of Technology

The Royal Institute of Technology research produced the most significant papers that discussed rotating nets [11]. They showed the process that was used to calculate the angular velocity needed to get the net open. These equations were complex and hard to follow. Going through these equations and thoroughly understanding them was not the best use of time, as just a target angular velocity was needed to design the launching mechanism and an end-to-end design of a net was not being done. Instead, Equation 1 was used to find a ratio of initial and final angular velocities (how the equation come about is explained in Appendix M). This equation produces a ratio of the initial and final angular velocity by using the fact that angular momentum is conserved when the net is deploying. Since this was done early in the process, the mass of the hub, m_h, the mass of the net, m_n, and the mass of a hanging mass, m_{hm}, was estimated (These values were not kept since they were very rough estimates). The initial radius r_o, and the length of one side, L, were set to 0.1 and 1 meter respectively by other design parameters (the units for this equation are difficult to see how they cancel and is explained in Appendix M) .

$$\frac{\boldsymbol{\omega_{fin}}}{\boldsymbol{\omega_{init}}} = \frac{\frac{m_h}{2}+m_n+4m_{hm}}{\frac{m_h}{2}(\frac{r_o}{L})^2+\frac{m_n}{6}+2m_{hm}}\left(\frac{r_o}{L}\right)^2 \qquad (1)$$

From there, a ratio of our value could be compared to Royal Institute of Technology values, seen in Equation 2. Their $\frac{\boldsymbol{\omega_{fin}}}{\boldsymbol{\omega_{init}}}$ was 0.0441. Their initial angular velocity was 12.57 $\frac{rad}{s}$. It was found that about 10 $\frac{rad}{s}$ was needed to open the net proposed in this project (plugging in the final masses it ended up being closer to 9 $\frac{rad}{s}$ but 10 was a good target angular velocity). This seemed reasonable comparing to other projects and was used as the target angular velocity.

$$\frac{\frac{\boldsymbol{\omega_{fin}}}{\boldsymbol{\omega_{init}}_{ours}}}{\boldsymbol{\omega_{init}}_{\boldsymbol{ours}}} = \frac{\frac{\boldsymbol{\omega_{fin}}}{\boldsymbol{\omega_{inti}}_{RTI}}}{\boldsymbol{\omega_{inti}}_{\boldsymbol{RTI}}} \qquad (2)$$

While this process worked for this project, this would not be the ideal method if the launching mechanism were being used in space. Before designing the launching mechanism, a thorough design and dynamic analysis of the net, hub, and hanging masses should be done to get the most accurate required angular velocity.

Also, this paper made a case for why a motor should be used to create this angular velocity. Finally, this paper also gave a good background on controls and why smaller nets don't need to use control systems. These are just the most significant take aways for this project, however, this paper provided good information about rotating nets.

2.2.5.1 The LOFT System

The LOFT system was a theoretical radio astronomy facility expanding 1500 feet in diameter. This facility would deploy from a smaller diameter into this larger diameter using centrifugal force. This is the same process as the Suaineadh experiment except the Loft system was never tested. The importance of this system though was the conclusion for the need of a control system to help control the deployment of the system. Figure 11 shows a theoretical concept of how the system would deploy in an uncontrolled state. In the image we can see in the center that the antenna would be fully deployed. Although after some amount of time the antenna begins to ravel back up in the opposite direction. This is a concern for space web technologies for if they deploy fully and then begin to ravel up again this could cause concern for the capture capability. If the net ravels up it could miss the targeted debris or not fully entangle around the debris allowing it to float away [11].

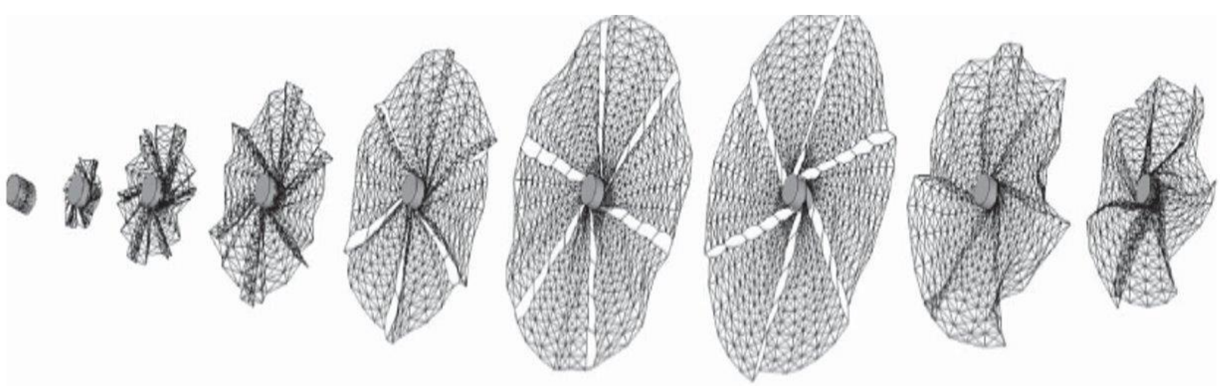

Figure 11 The LOFT System [11]

2.2.5 Star Folding Technique

The Space Webs Final Report gave helpful insight into how to wrap the net around the hub [11]. It is important to have a good wrapping technique as simply stuffing the net into the hub could result in no deployment or only partial deployment. The testing section in this report shows the consequences of improper folding. The Space Webs Final Report gives a few techniques for wrapping the net around hub, but the star folding technique was selected for their design [11]. In Figure 12 and Figure 13 we can see a conceptual section as well as an example from our final build. The final build section will detail how to properly achieve this folding and how to ensure correct deployment.

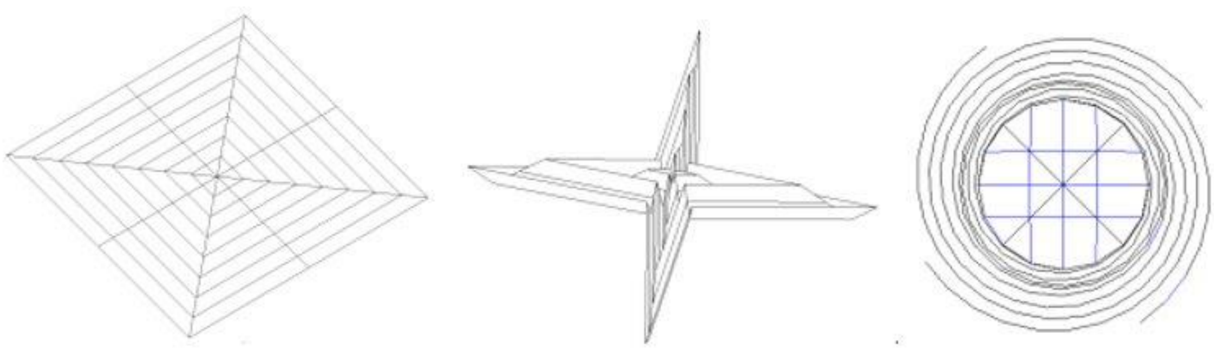

Figure 12 Star Folding Technique [11]

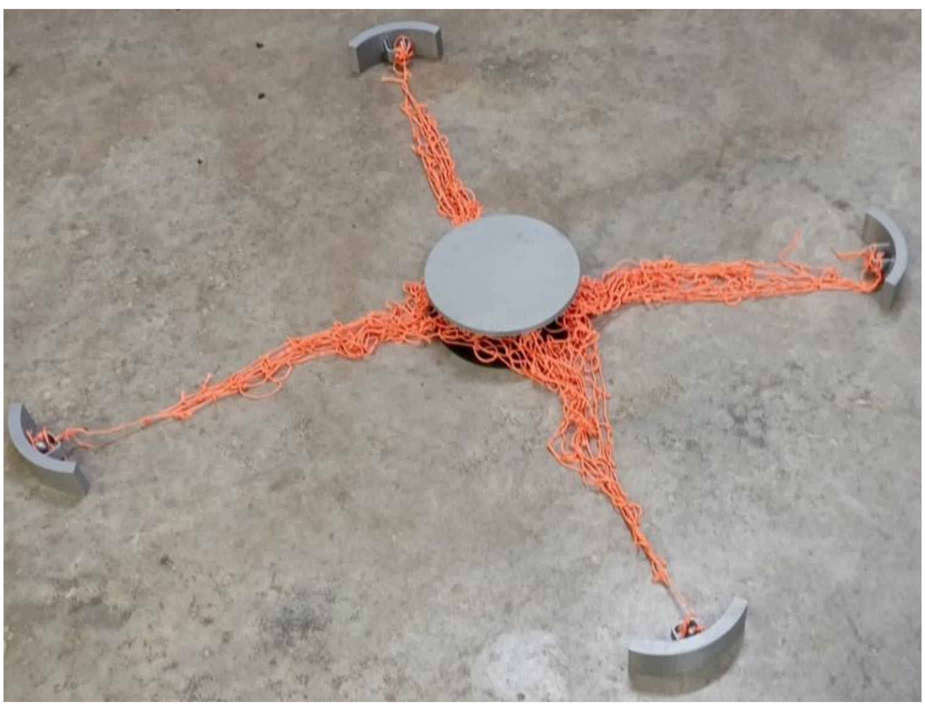

Figure 13 Example of Star Folding Technique

2.2.6 ESA Research

Another good source of information was the ESA. In one of their many papers, it discusses many options for capturing space debris [5]. One of these ideas is the use of a harpoon. The harpoon shoots at space debris and hooks into it. One of the downsides of this, is the potential of breaking the space debris into parts. A drag sail was also discussed in this paper. A drag sail hangs behind the satellite and collects space debris as it goes by. This capture mechanism is limited because it must wait for the space debris to come to it. Additionally, robotic arms were discussed as a method. This way can be either passive or active as the arms could travel towards the debris on a satellite or be attached to a satellite and grab debris as it passes by. The mechanical arms method is extremely expensive as the arms require significant power, precise control systems for movement, and large complex mechanical structures that introduce more points for failure.

A net launching device similar to our project is shown in Figure 14. This shows a rotating net being launched by the hanging masses, corner masses, in the image, at some angle. The hanging masses being launched at an angle causes the net to rotate and open. This design uses springs to launch the hanging masses. This part inspired the design in this project. However, this design was not selected because of the difficulty of controlling the rebounding after the net fully expanded. Finally, a rotating net similar to the one described in sections 2.2.2 and 2.2.3 was described. From their research, the ESA was able to say, “The simulations performed were quite detailed and identified no showstoppers for the concept. On the contrary, it was identified as a very promising capture mechanism” [5]. This was a very promising praise and a good source of recommendation. The one downside of this paper is the fact that it left out detail about the launch or even a concept of design of the launching mechanism.

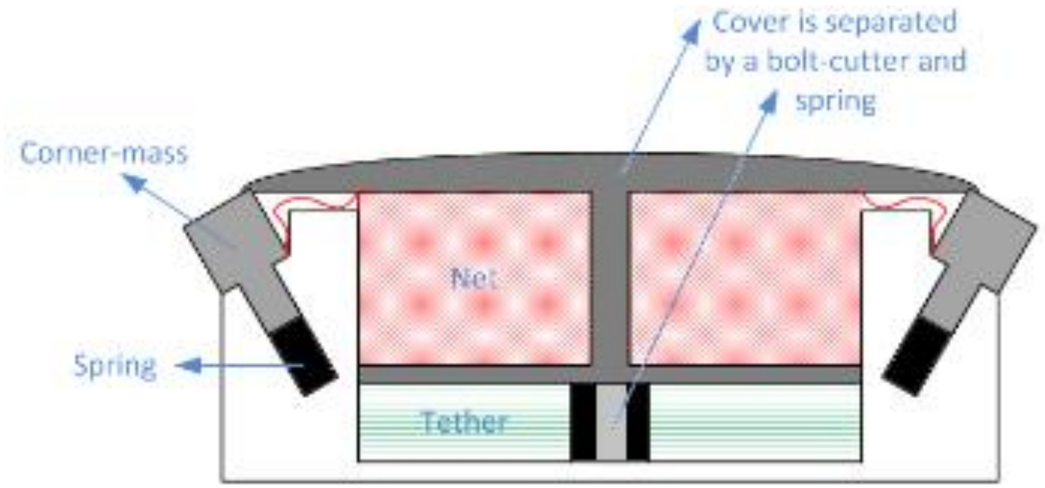

Figure 14 Rotating net launcher from ESA [5]

2.3 Why Rotating Nets

With all these different options, it is important to understand why rotating nets are the chosen space debris removal method for this project are. First, nets are very cheap compared to other space debris removal options [5]. Second, rotating nets generally have a high fault tolerance. Along with this, rotating nets can be compressed into tight spaces and take up less space, even compared to nets launched in linear motion. Additionally, rotating nets work well for a larger variety of space debris [2]. Furthermore, rotating nets allow for easy controlled deployment [11]. An upside of the launching mechanism for these nets is the fact that they generally have a low energy consumption [2].

What these benefits lead to is a low-cost, small, and relatively simple way to remove space debris. This could be significant because this would allow it to be put on smaller satellites. Moreover, a rotating net could be put on satellites whose purpose is not to remove space debris for little cost.

2.4 Why Use Centrifugal Force

It is important to note why centrifugal force is a good choice for deployment. Centrifugal force is already being used in some satellite applications and allows for a larger surface area to be deployed from a smaller volume. The Suaineadh experiment and the LOFT system are both examples of centrifugal deployment. Centrifugal forces are always in the plane of motion therefore so long as these forces are dominating the out of plane motion is negligible allowing for full deployment. Additionally, centrifugal force deployment control is simple. A control system would significantly increase the cost of the project. Along with controlling the deployment, the speed of deployment can also be controlled based on what is needed [10].

2.5 The Need for the Design

2.5.1 The Problem with Past Designs

Most of the papers are proposing a design of the net and not a design of the launching mechanism. This is the most substantial reason for this project. Most research is focused on the nets; the launching mechanism is often either not talked about or is lacking meaningful details. With more focus on a launching mechanism, the launching mechanism can be optimized and more thoroughly looked at. This will lead to more efficient, and better use of the rotating nets to clean up space debris.

The other main reason why this design is needed is that there is an abundant need for different ways to clean up space debris. As discussed above, space debris is a major issue and causing unnecessary problems. NASA and others are actively looking for different methods to clean up space debris [9]. The best example of this is the ELSA-d program. This is a program from NASA dedicated to testing different method of removing space debris. One of the current methods they are currently testing is a magnetic device, but they are looking for many more devices to test [9]. As long as there is a demand for new ways to remove space debris, there will be a need for this project.

2.5.2 Free Deployment Versus Controlled Deployment

The theory and deployment of rotating satellites have been around since the 50's [11]. The Japanese first created and tested a concept satellite that used centrifugal force to deploy [11]. Since then, many papers have expanded upon the idea of rotating satellites. Some of these papers include those from the ESA and Tsinghua University [2],[11],[12]. Some of these designs have been tested but most have been theoretical. This study eventually led to experiments such as the Suaineadh space web like discussed before, but most of these experiments and studies require the use of control systems [11].

The control systems for a spinning satellite are used to control the deployment of the net or membrane (depending on the design). This control is done by either reducing the angular speed of the central satellite or hub or increasing the angular speed. This can be done using a reaction wheel. These wheels can be a single axis design controlling the momentum in one direction or of three axis design and control the momentum in three different planes. These control systems greatly increase the cost of the system, increases the electrical demand, and increases the total mass of the system. They also introduce greater risk in terms of problems arising from a mechanical or electrical failure in the control system [11].

These control systems are needed as the net or membrane begins to deploy the outer edges slow down due to the conservation of angular momentum. Thus, they rotate slower than the central satellite or hub. The control system then reacts to this by creating a counter spin slowing the satellite to better match the angular speed of the outer edges. The reason for this system is stop entanglement of the net/membrane and allow for fully expanded deployment [11].

According to the Royal Institute of Technology in theory free deployment could be accomplished with a small net size [11]. Where a small net is described as one side length L being less than 10 meters in length. The rest of the paper proceeds to talk about larger structures but then quickly discusses the idea of free deployment. From this it was concluded that we would build and test a net launching mechanism to help demonstrate this idea of free deployment as a cheaper and less taxing system than current existing space debris capture systems [11]

3. Iteration of Overall Design

With all that background information and discussion of why the rotating nets were chosen, it is important to note all the designs that were evaluated. The first design was the first iteration of the design that eventually led to design 3. Design 3 was the design that was ultimately chosen while design two was an alternative solution.

3.1 Design 1

The first iteration of the final design can be seen in Figure 15 In this design the rotational mechanism is a motor that is attached by gears off to the side. From here the motor would rotate the shaft causing the mechanism to spin. In the rear of the design there is a pully that winds up a tether. This tether is connected to the back of the hub. This allows for the spring to be compressed and when a release mechanism (not shown) releases the pulley the tether releases and the spring launches the hub forward. The hub would contain a net with hanging masses which would deploy with centrifugal force.

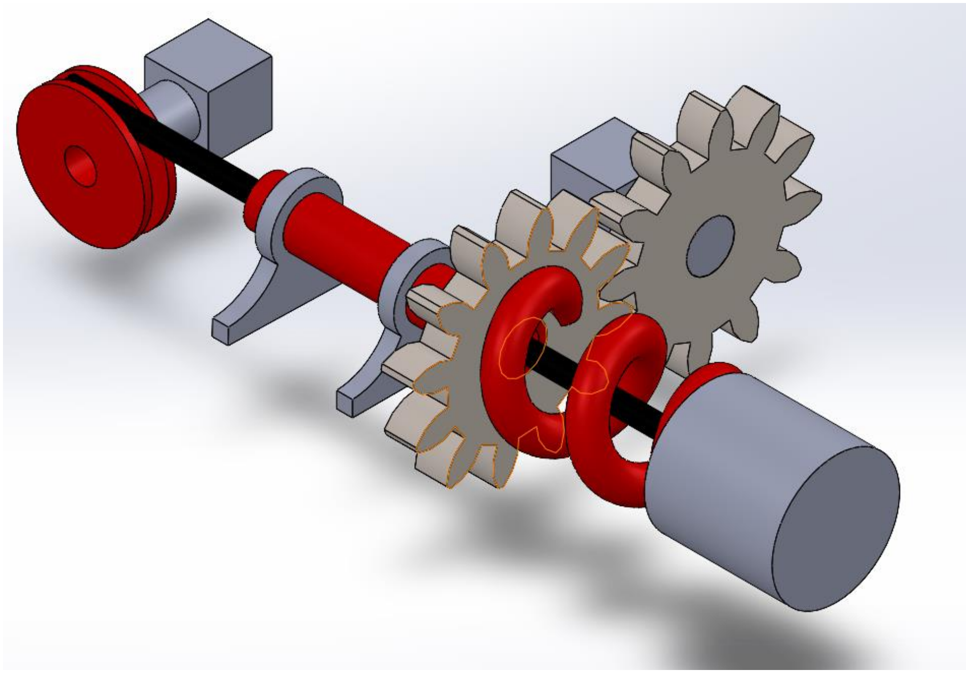

Figure 15 Design Concept 1

This design was evaluated and was determined to be too large and cumbersome and not practical. The idea of using gears and needing bearings over complicated the system and hindered the design. Another issue with this design was the idea of using one spring. It was determined later that more than one spring would be ideal for generating linear velocity.

3.2 Design 2

This design is similar to the final design except it had an attached tether. The tether would be stored behind the hub and a separator would be located between the bottom of the cylinder and the hub. This space is where the tether would have been stored and the springs would have set on the separator. This idea was scrapped due to the extra complexity of adding the tether. This complexity was finding a way for the tether to deploy smoothly and not interfere with the rotation of the hub after ejection and how to pull the tether back into the system. Figure 16 shows a mechanical block diagram of the design with a tether.

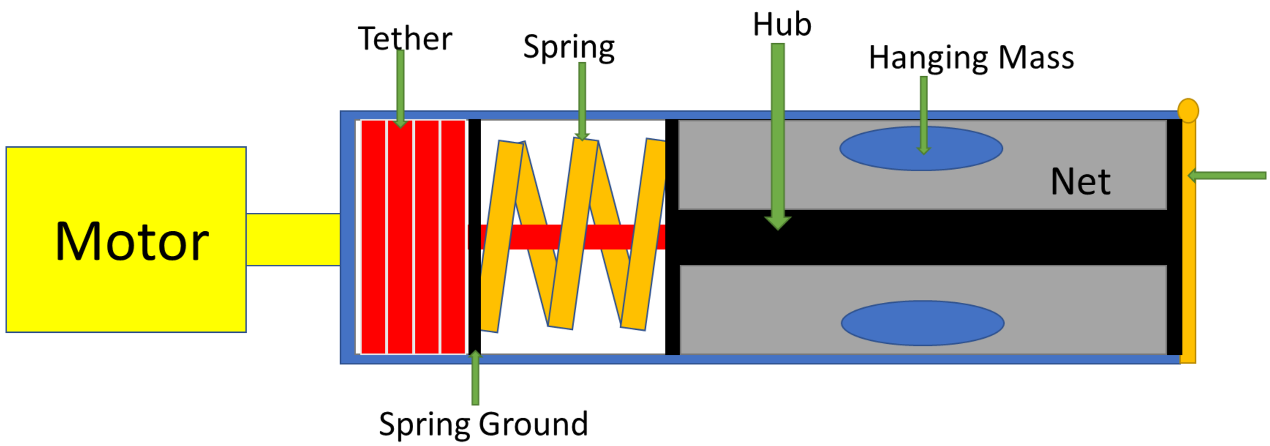

Figure 16 Design Concept 2

3.3 Design 3

Design 3 was selected to take into critical design. The completed design can be seen Figure 13. In this design, a launching mechanism for a rotating net was developed. This design uses a motor to rotate a large cylinder which contains a net, hub, and hanging masses. The net is wrapped around the hub with four hanging masses at the corners. These hanging masses then create a circle that is the same circumference of the hub. This was done so that when the motor turns on and the hub begins to exit the cylinder the hanging masses would keep a uniform orientation relative to the net hub. This keeps the friction consistent and ensures the net stays wrapped correctly. Pins hold the hub in the cylinder until centrifugal force overcomes the static friction holding the pins. Finally, springs are placed between the hub and outer cylinder to create the linear motion.

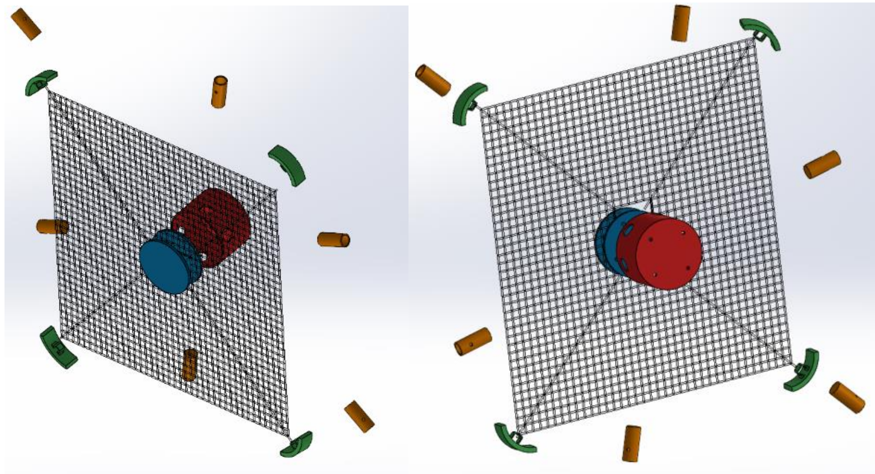

Figure 17 The Final Design of the Launching Mechanism

One of the pros of this design is the fact that there were not a lot of mechanical components needed. Additionally, this design can easily be scaled to fit a smaller satellite. One of the setbacks of the design is it relies of friction, which can be inconsistent (this is further explained in 4.4.6 Pins.)

Ultimately, this design was selected and explored more because of the potential upside of rotating nets. The next section will discuss how the design was made to really maximize those potential upsides. Also, it will explore why and how certain decisions that were made. Then finally, it will explain exactly how the launching mechanism works and functions.

4. Final Design

This section discusses the details of how the final design was built. In Appendix F, a drawing of each part is shown along with FEA images in Appendix L. In this section, the components are discussed in order from how they were designed. Starting with the net as the interior component and then working outward from this point. An overview of how the system should work in theory is given first with a more detailed concept of operations finishing this section. It is important to note that the system was designed in the order the components are discussed such that it was designed from the outside in.

4.1 System Overview

The system was first designed to deploy the net using centrifugal force. It had been decided that a motor would be the best way to get this angular velocity to the net and hub. When the motor was turned on this caused the net to spin. To launch this system forward, springs are used. Thus, the motor provides the angular velocity required while the springs give the linear velocity required. Hence the motor spins the net, and the springs launch the mechanism towards the space debris.

The above paragraph details roughly how the system works the next few paragraphs will show the various components of the system and how they fit together. The system hierarchy in Appendix A may help with understanding how the components fit together. This section will start with the system intact and then show each of the various components and give brief descriptions of their purpose. Section 4.2 will provide a more in depth look into the project and the various components. Figure 18 shows the system fully complete with all six pins in the device and the battery detached. In these images we can see a red and grey cylinder, this was dubbed the outside cylinder and is what holds the hub in the system (The top surface of the hub is seen in white in the left most image of Figure 18). Below this hub is a set of 8 springs that were used for the ejection methods (please note these springs were not used in the testing portion of the system). The pins were then used to hold the hub against the springs. This meant the springs forces were pushing against the hub and into the six pins. Below the outer cylinder is the motor with some other components this will be further explain in a later section.

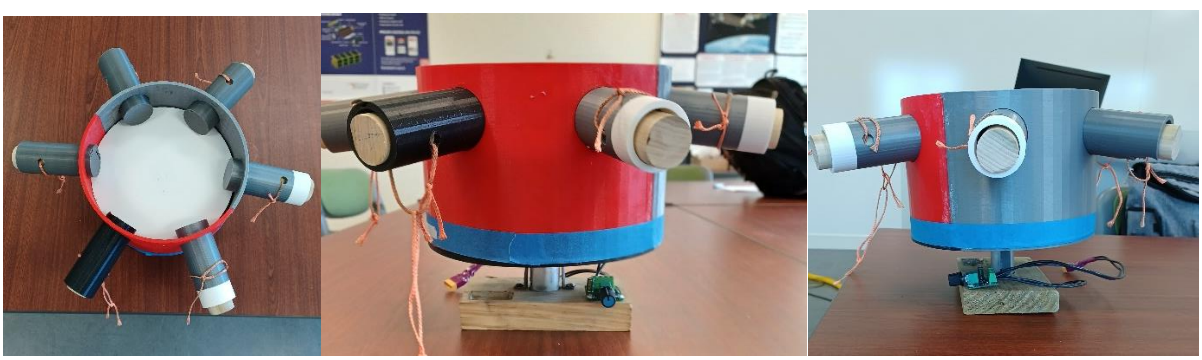

Figure 18 Complete Build Top, Front, Right Side Views

Here, in Figure 19 we can see the hub has been removed from the outer cylinder in the top left image. We can also see the net, hanging masses, and fishing weights having been pulled out from the the hub. The hub is facing downward such that the bottom black plate can be seen. On top of this plate are four pegs that are difficult to see. Figure 35 is a Solidworks model that shows the pegs attached to the bottom plate. The top right image shows the outer cylinder with the eight springs in the bottom of the plate. The bottom left image shows the inside section of the hub. In this image it is possible to vaguely see the hooks where the net is attached. More about the hooks will be discussed in a later section. The bottom right image shows one of the hanging masses with two of the fishing weights attached and where the net is attached.

Figure 19 Separated Components

Figure 20 with the image in the top left corner shows the motor is attached underneath the outer cylinder and attached to a wooden mounting board. It is attached to the wooden mounting board with a motor bracket. The top right image shows the location of the speed controller. It is also important to note that the speed controller is only held down by two screws as seen in the top left image and the top right image. The bottom left image and the bottom right image both show how the system is wired together.

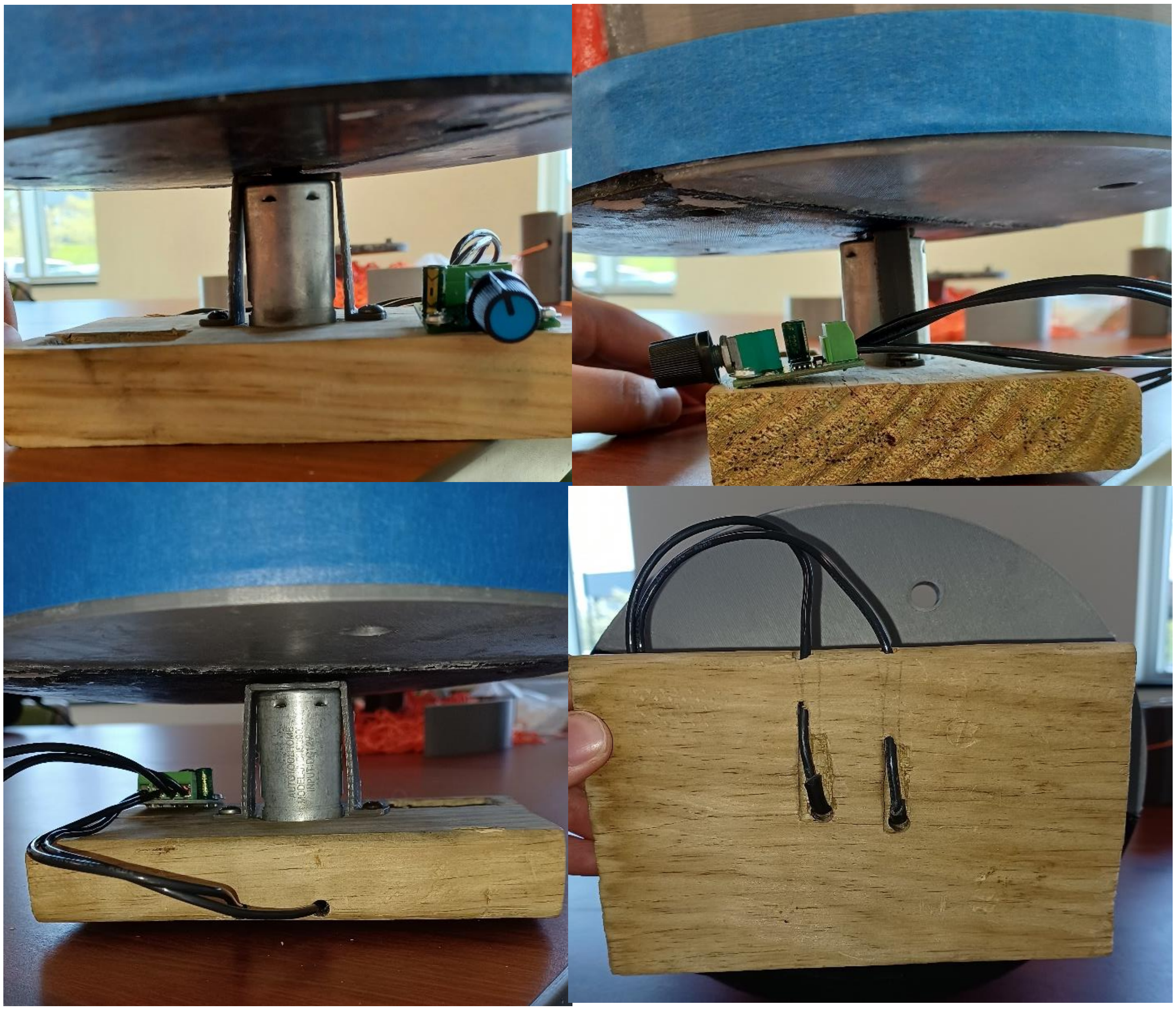

Figure 20 The Wiring the Motor and Speed Controller

4.2 Components

Before getting into the individual components, it is important to see the inside of the system. Figure 21 shows a half cut of the Solidworks model. Additionally, a block diagram in Appendix I shows another view of the inside of the launching mechanism. When designing the launching mechanism, it was important to understand how all the components interested with each other.

Figure 21 shows most of the components in a half cut Solidworks model. The outer cylinder, in red, encircles the parts and holds the hub, hanging masses, springs, and net (not shown). The pins, in orange, sin on top of the hub, in blue, and run through the side of the outer cylinder. The pins force the hub to keep the springs, in yellow, compressed to the bottom of the outer cylinder. A representation of the hanging masses, in green, are sitting in the hub. The net is not in this figure because the net cannot be done practically in Solidworks. The net would connect to the hanging wrapped around the hub and attached at the hooks. The hooks were shown in Figure 19 above and will be shown again. The motor, in yellow, is drawn at the bottom and is inserted into the bottom of the outer cylinder.

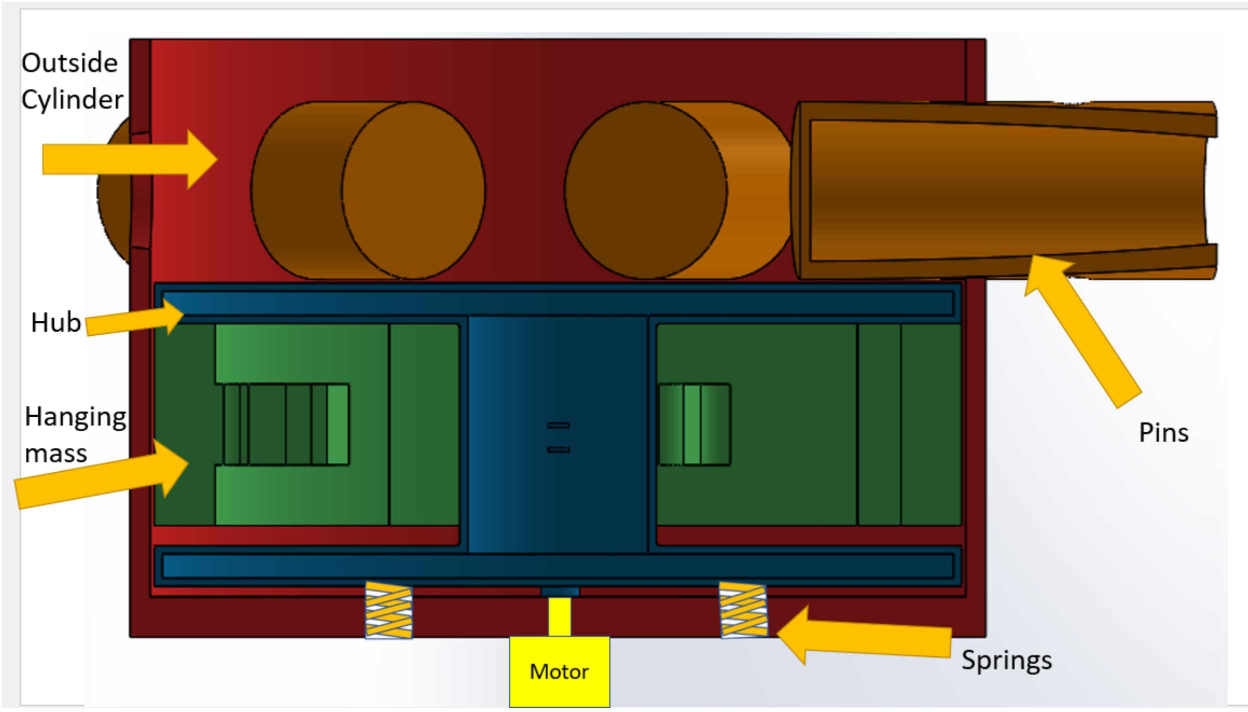

Figure 21 Inside View of the Launching Mechanism

When the angular velocity is met, the centrifugal force will pull the pins out. When the pins pull out, the springs will decompress and launch the hub forward. From there, the lack of a normal force will cause the hanging masses to expand outward and would then pull the net out. This process can be hard to seen in one image Section 4.2 is a concept of operations that explains how the device works.

4.2 Concept of Operations

The concept of operating the device is easy. Figure 22 below shows the basic concept from start to finish. The con ops below shows 11 stages in short descriptions. This section will go further in detail with a visual concept of operations.

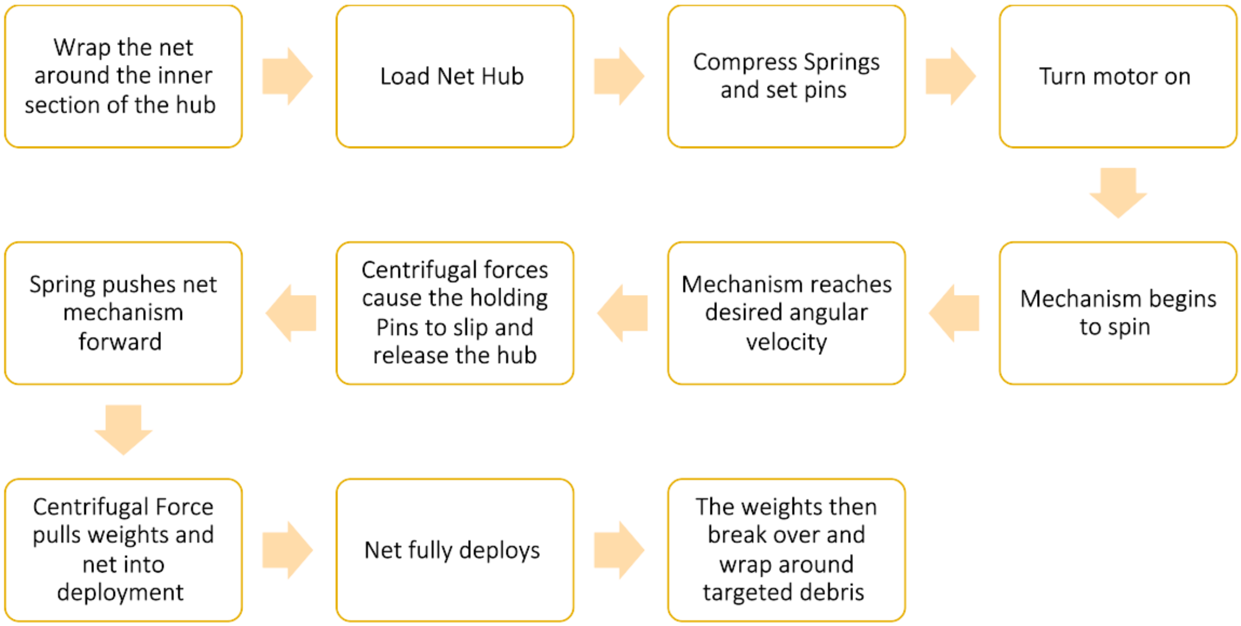

Figure 22 Concept of Operations

The system first requires the net to be wound around the inner section of the hub in the star pattern. There are two methods for achieving this with both ways having pros and cons. The first is to grab all four hanging masses and rotate them around the hub keeping the net tight as it goes around. This is difficult with one or two people as the hub most be held firmly, and the masses must rotate together as consistently as possible. The second option is to create the star pattern with the net and hanging masses and then twist the central hub. Doing this until the hanging masses are siting flush on the outer edge of the hub. This method is simple and easy for one person to accomplish, but it does not allow for the net to be pulled tightly. This was the selected method. How the net was wrapped up is shown in Appendix J.

The next step is to load the hub with the net and hanging masses inside of it. This is easily accomplished by turning the outer cylinder upside down and placing the mechanism on top of the hub.

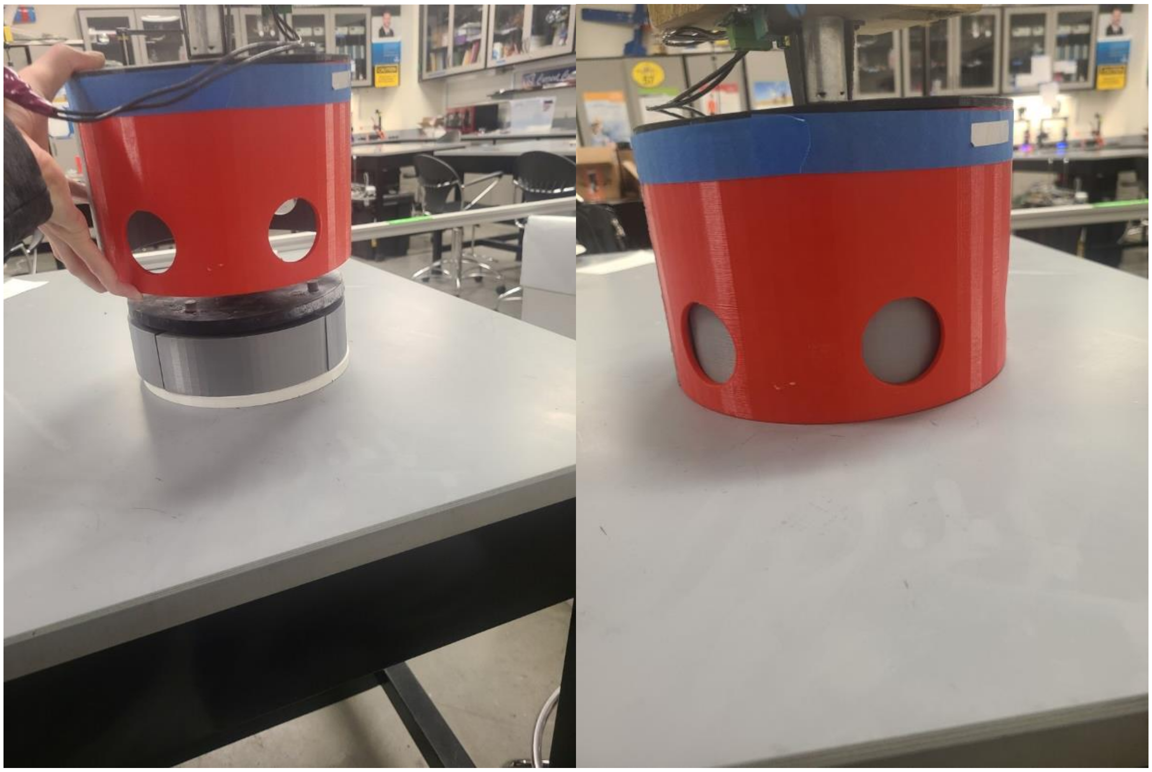

Figure 23 The Outside Cylinder Being Put on the Hub

After the hub is in the outside cylinder, the outside cylinder must be spun in order to line up the hub pegs with the holes in the outside cylinder. This had to be done as the pegs should have been printed directly to the hub, but they were not for this project causing them to be in a location that forced the hub and outer cylinder to only be able to fit at one angle. Next, the hub needs be pushed into the springs to compress the springs.

Figure 24 The Hub is Pushed into the Springs

Right after that the pins need to be put in quickly in order to keep the springs compressed.

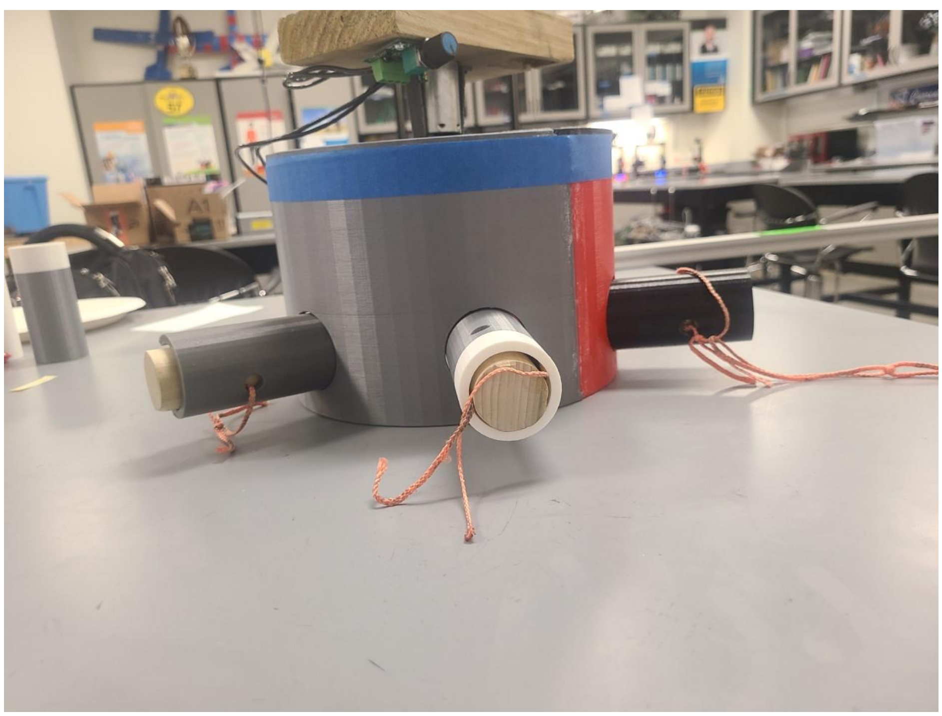

Figure 25 The Pins in the Outside Cylinder

Then the mechanism is ready to launch. This begins by choosing a target and turning on the motor by rotating the dial on the speed controller until the desired angular velocity is obtained. The outside cylinder begins to spin.

Figure 26 The Outside Cylinder Begins to Spin

Once the mechanism reaches the desired angular velocity the centrifugal forces will cause the pins to release. These pins will then fly outward radially, and the hub will be free to move in a linear direction.

Figure 27 The Pins Fly Out (there was only one for this test)

At this stage the hub is spinning with the rest of the system and is now capable of moving in the direction of where the device is pointed (in this case the hub is pointed in the direction of the camera, or down). This is done by the springs, that had been compressed due to the pins (please note for this project the springs were not added as they were the incorrect springs for the project).

Figure 28 The Outside Cylinder Begins Moving in the Direction it is Pointed

Once the hub has passed the outer edges of the outer cylinder, the lack of a normal force will allow the hanging masses to move outward.

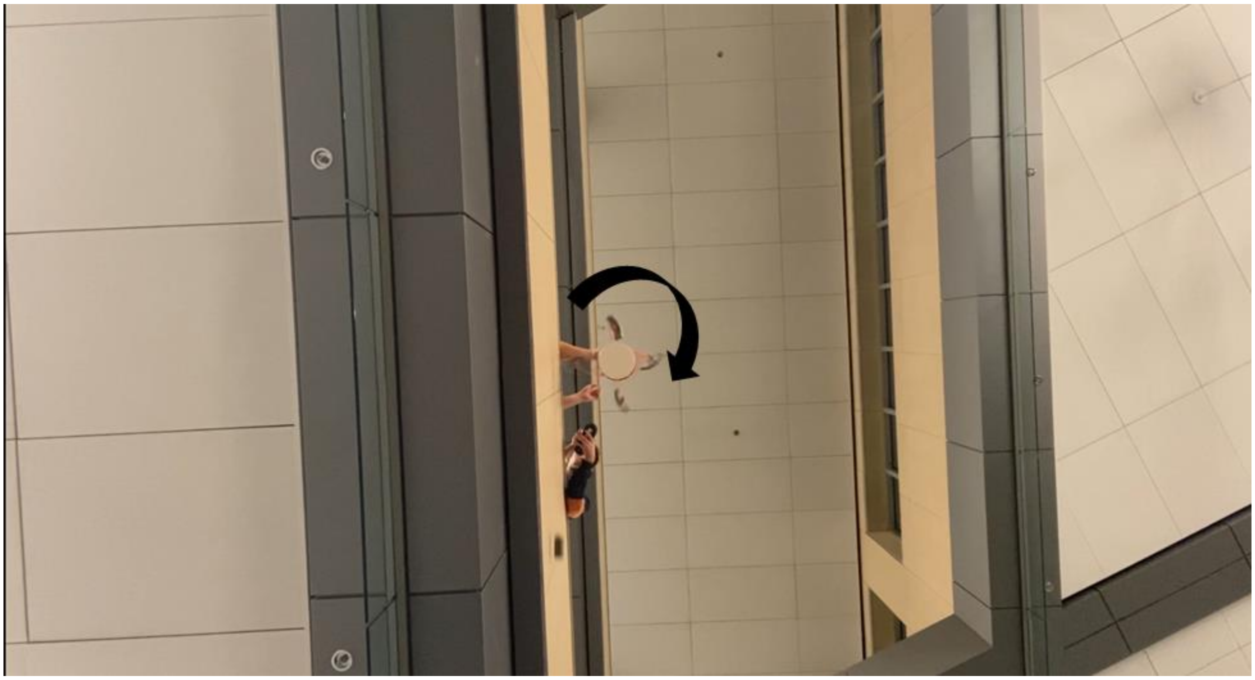

Figure 29 Hanging Masses begins to Pull Out the Net

This then causes the net to be pulled with the masses allowing it to deploy. As the net is pulled out further the angular velocity of the hub will slow down because of conservation of angular momentum.

Figure 30 The Net is Pulled out Further by the Hanging Masses

Finally, the net opens all the way up and reaches its biggest point.

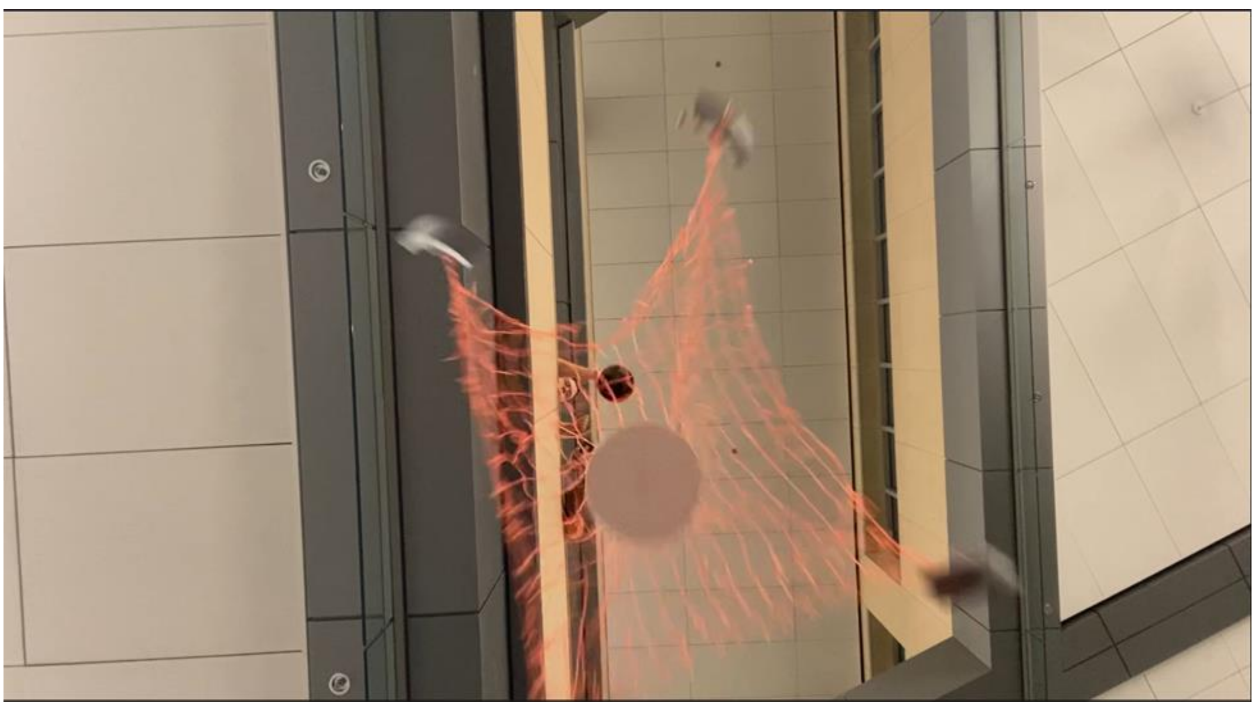

Figure 31 The Net is Fully Deployed

In a real application for this system the time to fully deploy will need to be calculated to do the best job at capturing space debris. When it is launched at space debris, the net would hit the space debris, causing the hanging masses which were traveling linearly at 1 m/s to continue doing so but, due to the resulting impact will cause for the masses to break over and wrap themselves around the object. This ensures a full entrapment of the object to be deorbited or stored for later deorbit. The size of debris should be approximately 8 cm to 30 cm. Further analysis on the capture capability of the net should be conducted to further understand the size of space debris that could be captured.

4.3 Components

4.3.1 Requirements

The requirements are shown in **Error! Reference source not found.**. The following r equirements were all determined though the literature review except the first requirement. This was simply a total size requirement to keep the project constrained for a tabletop prototype. The net size was justified early from the Royal Institute paper determining that a net under 10 meters in length could be deployed using free deployment [11]. The mass was determined from the Saundih space experiment as their total mass was approximately 12 kg. Thus, a choice of a mass slightly over half of theirs as we know that particular system had a lot of testing equipment that this project could do without [12]. The angular velocity was calculated from the Royal Institute of Technology's paper discussing theoretical approaches to the problem [11]. Finally, the needed linear velocity was determined to be around 1 m/s from the McGill University research [8].

Table 2 Requirements

Prototype Size	At most 50 cm x 50 cm x 50 cm
Net Size	At least 1 m x 1 m
Mass of Prototype	At most 6.5 kg
Initial Angular Velocity of the Net	Between 9 rad/s and 11 rad/s [11]
Initial Linear Velocity of the Net	Between .8 m/s and 1.2 m/s [8]

4.3.2 Net

The net size was chosen based on a paper detailing how a smaller net could be used to achieve a controlled deployment. According to this paper a net with a size less than 10 meters in length would be able to achieve this. Thus, the chosen net size was 1 meter by 1 meter to be reasonable for a prototype. The meshing size was then chosen based on the desired debris capture size which was chosen to be 10 centimeters as that is the smallest tracked debris. From this the meshing size was then chosen to be 5 centimeters as this would be able sufficient to catch the desired size. Figure 32 shows the net after being completed.

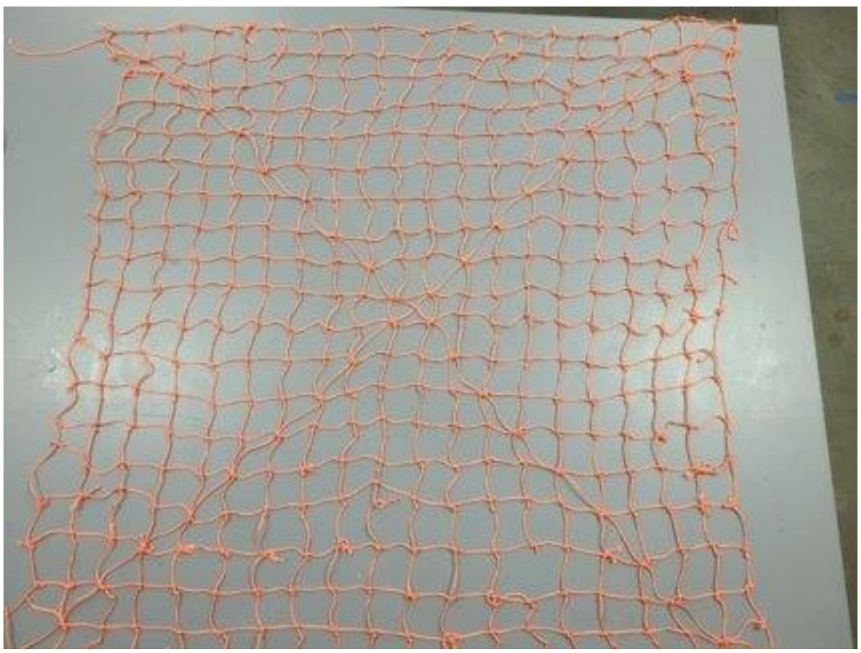

Figure 32 Net After Completion

The net was chosen to be a square net with a square mesh. This was determined as square nets can undergo large deformations while maintaining their shape. This also helps to increase the rigidity of the net allowing for a better deployment. The square net also allows for better vibrational damping through the net. This is accomplished by have a string attached to the corner of the net and then connecting in the center of the net in a diagonal pattern. Other possible patterns and meshes were triangular and octahedral. The problem with triangular nets is that the potential capture area is smaller as well as the net is less rigid. The octahedral net also has similar issues of less rigidity. Appendix H, shows examples of the different web shapes and meshing shapes that had been studied.

Another area of interest for the net is the folding technique as talked about earlier. The chosen folding technique is a star shaped design that allows for easy folding of the net. This is achieved by folding the square's edges into the diagonal thread on the net this can be seen better in Appendix J. Once the four-star points are created the net can be twirled around a center axis allowing for it to wrap around it helically. This design will help the net deploy in a more controlled manner than other designs. This also helps maximize the volume in the inner section of the hub by allowing for the net to fold and sit neatly in an organized pattern. How the net in this project was folded can be seen best in Appendix J.

Table 3 shows a list of different materials that could be used for the net material. From this chart and other details given in the article, Zylon would be the best choice for a space application [11]. Since this is merely a prototype meant for testing on earth, Zylon is overkill for this initial prototype. For this prototype braided nylon was chosen for its tensile strength of 160 pounds in its axial direction and low density.

Table 3 Different Net Materials [11]

Trade name	Generic name	Type	σ_u (GPa)	E (GPa)	ε_u (%)	ρ (g/cm^3)	$\sigma_u/\rho g$ (km)
Zylon	PBO	AS	5.8	180	3.5	1.54	384
Dyneema	HPPE	SK76	3.7	116	3.8	0.97	389
Kevlar	Aramid	49	3.6	130	2.8	1.44	255
Vectran	TLCP	HS	2.9	65	3.3	1.40	211

4.3.3 Hanging Masses

The hanging masses are the essential component that allows for the net to deploy. Four hanging masses are required as each corner of the net must have a mass attached. This system when spun allows centrifugal forces to pull upon the masses causing them to move outward radially. This then causes the net to be pulled with it allowing for full deployment. The only two issues with hanging masses are storage and strength at the connection to the net. Figure 33 shows one of the hanging masses.

Figure 33 Hanging Mass

The hanging masses were designed to fit the curvature of the hub. When all four hanging masses are placed into the hub, they align with the outer most edge. Each hanging mass has a mass of 81 grams. Although, this is not enough weight for the design as demonstrated by the Saundih Space Web Experiment it seems reasonable that a mass ratio of 8 from hanging mass to net is desirable [11]. The mass ratio is the ratio of the mass of the hanging masses to the mass of the net. It was determined that if the Saundih space web had this ratio and was successful than it should also work for this prototype. While the desired ratio was 8 the actual ratio was 7.029. This was calculated from the following equation.

$$\zeta = \frac{4*m_{Hanging\ mass} + 8*m_{Fishing\ Weights}}{m_{Net\ Mass}} \tag{3}$$

Henceforth, to reach this mass two, three-quarter ounce fishing weights were attached to the hanging masses. For the fishing weights to be secured a larger loop was created to hold both weights side by side. From here both fishing weights are tied together using the nylon twine from the net with a pretzel knot on either side of the fishing weights to ensure they will not move. From here the weights are set into the loop and the left-over string on the edge of the fishing weights was used to secure them to the hanging masses. Gorilla glue was then used to help secure this connection further.

FEA analysis was also conducted on the loop to ensure the masses would not break, shown in Appendix L. This was determined by using the highest possible angular velocity with the largest distance it could be from the center point. Thus, the centrifugal force would be the largest and also would not be possible as the initial angular velocity is the largest velocity and as the masses would move outward, they would slow down due to the conservation of angular momentum.

4.3.4 Hub

The hub in Figure 34 is needed to keep the net together till it is launched. The hub can be pushed into the springs, while the net cannot because of its shape. Without the hub, the net would not be able to be launched. The inside volume of the hub had to be bigger than the nets total volume so the net would fit in the hub. When doing this, margin of error was intentionally added because the net would not fill the volume ideally due to its irregular solid shape and natural inability to lie correctly around the hub. This led to the dimension shown in Appendix F. The 1 cm thickness of the top and bottom pieces (shown in Figure 66) was decided so the hub would be able to take the forces of the springs without a doubt. The final mass can be seen in Appendix D.

Two more interesting parts are the hooks on the inside, and the pegs on the bottom of the hub. The hooks are for the net to be tied to (best seen in Figure 19Figure). These are identified in Figure 34 by the orange arrow (pointing left). The pegs sit into the peg holes in the outside cylinder. This allows the hub to spin with the outside cylinder and are identified by a blue arrow in Figure 34 (pointing right).

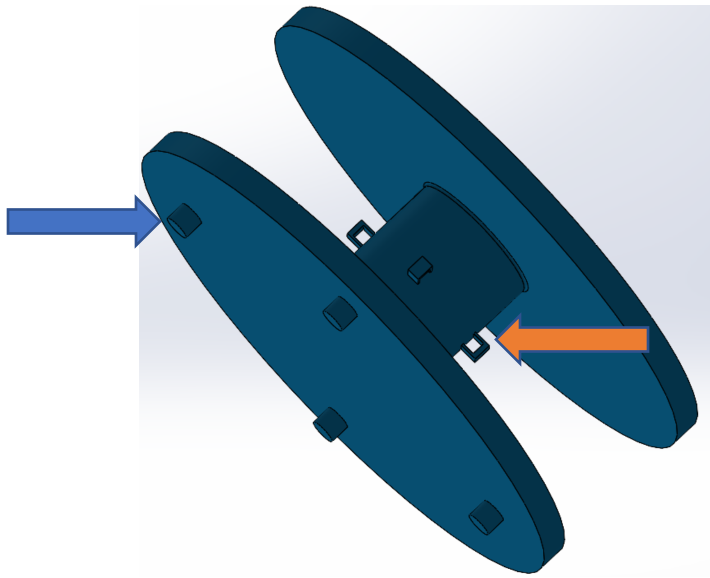

Figure 34 Hub

4.3.5 Outer Cylinder

The outside cylinder's job is to keep everything together before launch and provide the support for everything to launch. In Figure 35, the most left of the images, there can be shown multiple holes on the plate. The 4 outside holes are the hub peg holes indicated by the blue arrow (the dimensions can be seen in Appendix F). This allows to hub to sit into the cylinder and spin with it. The 8 inside holes are for the springs to sit as indicated by the orange arrow. The spring can be seen to sit in the plate in Figure 53. The last hole in the center is for the motor. In the right image of Figure 35, the holes of the pins can be seen. These dimensions of the outside cylinder were designed so everything could fit nicely and be allowed to move as needed. The exact dimensions can be seen in Appendix F.

Figure 35 Outer Cylinder: Bottom Plate and Shell

4.3.6 Springs

The springs are needed to provide a linear velocity of 1 m/s to eject the hub Equation 4 was used to calculate this.

$$\frac{1}{2}mv^2 = N\frac{1}{2}k \quad (4)$$

On the left side of the equation the mass, m, of everything that is being launched (the hanging masses, the net, and the hub) and the desired velocity, v, are known. N, the number of springs, k, the spring constant, and x, the displacement of the spring, were all left to decide. In order to decide everything on the right side of Equation 4, an excel spread sheet was set up. This was done to make the calculations quicker and gave the ability to look at many different springs quickly. While looking through springs, the spring constant was plugged in, and the deflection was solved for. Once the deflection was solved for, it was important to make sure the spring can deflect as far as needed. If the spring cannot deflect as far as needed, a new spring would have to be looked at.

While looking through springs, it was important to keep in mind the supposed benefits of rotating nets. The most significant idea in spring selection is trying to keep the size of the launching mechanism as small as possible. Keeping this in mind, it was decided multiple springs would work better than just one spring. The more springs in the system deceased the deflection needed. The idea of trying to keep as small as possible also led to using some unique springs.

Smalley wave springs, according to their website, reduce the spring height by 50% [18]. Looking through many springs, it was found their springs are in fact smaller than comparable springs with the same spring constant.

It was calculated that 8, N in equation 4, springs were needed of CM15-H1 (specs are shown in Appendix G) would work. These springs are from Smalley and is shown in Figure 36. These springs will deflect at 2.7 mm with a loading mass of 1.1 kg (an over estimation of the mass). This ensures the springs in parallel will produce at least a velocity of 1 m/s.

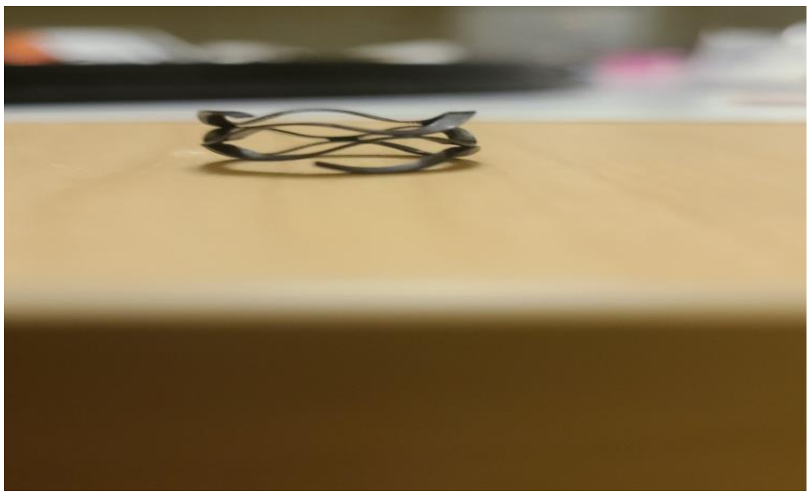

Figure 36 Image of CM15-H1 Spring

4.3.7 Pins

The pins were one of the more difficult components to design and a final build can be seen in Figure 41. The pins sit in holes of the outer cylinder right above the hub, as seen in the Figure 38 (the pins are in orange.) Figure 38 shows where the pins sit before the outside cylinder spins. As the outside cylinder spins the pins will be pulled by the centrifugal force. Once the pins are ejected, the hub with the net is spring ejected and deploys. This deployed version is shown in Figure 37. The pins, in Figure 37, are shown to be pulled out by the lack of a normal force.

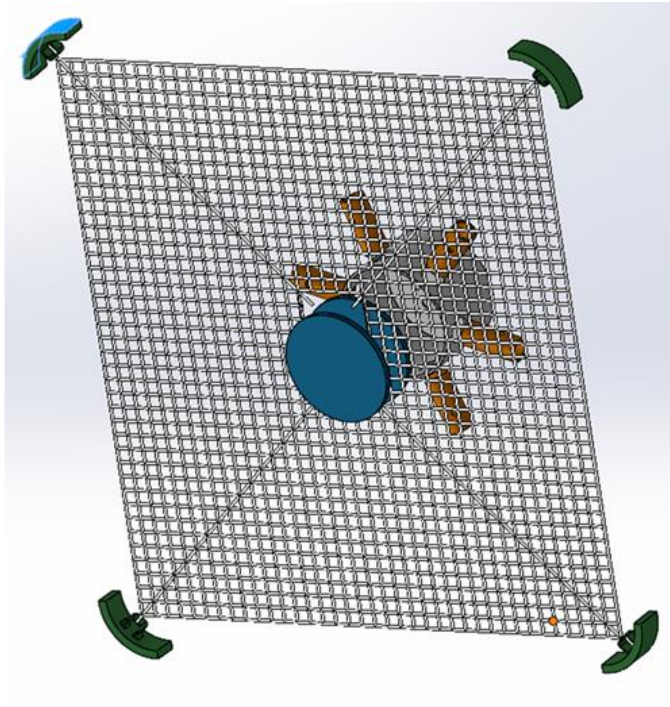

Figure 37 Solidworks of Net Deployed

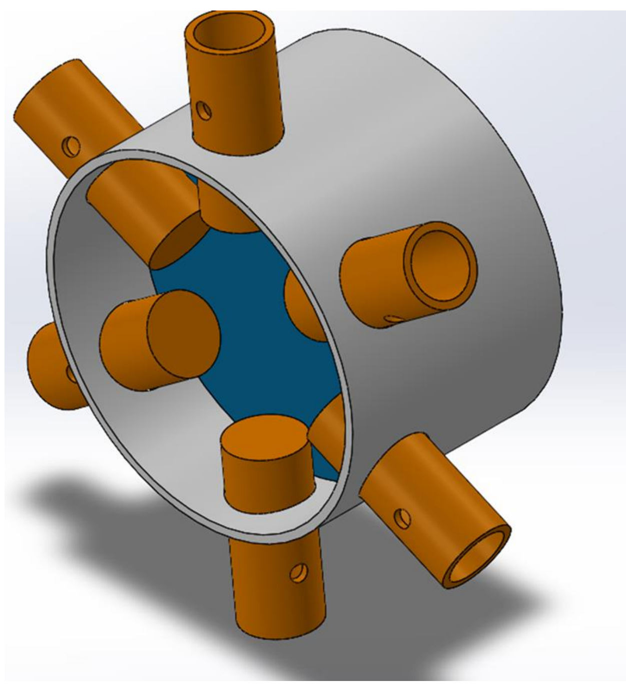

Figure 38 Solidworks Rendering of Pin Release Mechanism

Designing the pins is difficult because the use of friction and the moment caused by the hub being pushed up by the springs. Figure 39 is a diagram showing how the pins fit in and what forces are acting on each pin. The force of the hub (in orange) is pushed up on the pin (in grey). This caused reaction forces on each end of the pin to resist the force and the moment produced by the hub. Because the pin is so tight in the outside cylinder (shown in blue), all forces on the pin inside the outside cylinder are equal and opposite except in the x direction. This means that friction is just resisting the centrifugal force. The weight and normal force are considered negligible.

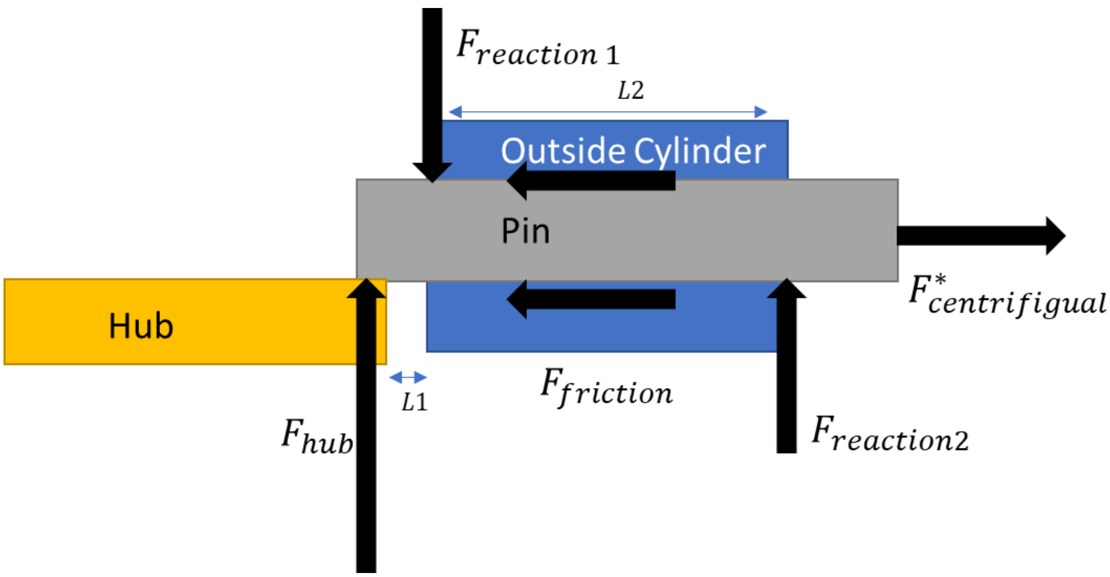

Figure 39 Diagram of a Pin

Figure 39 leads to the free body diagram shown if Figure 40. Equation 5 and 6 are the summation of the moments about $F_{reaction\ 2}$, and a summation of the vertical forces.

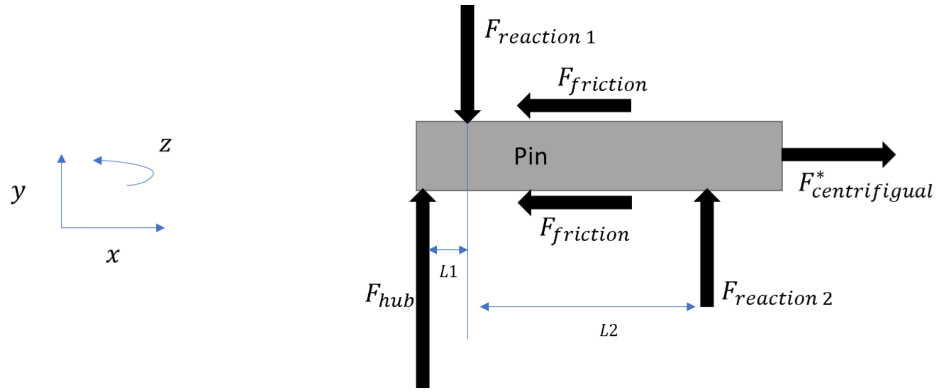

Figure 40 Free Body Diagram of the Pin

$$\sum M = 0 = F_1 L_2 - F_{hub}(L_1 + L_2) \tag{5}$$

$$\sum F_y = 0 = -F_{reaction\ 1} + F_{reaction\ 2} + F_{hub} \tag{6}$$

From there $F_{reaction\ 2}$ and $F_{reaction\ 1}$ can be written in terms of the lengths and as F_{hub}. This is shown in Equation 6 and 7.

$$F_{reaction\ 1} = \frac{F_{hub}(L_1 + L_2)}{L_2} \tag{6}$$

$$F_{reaction\ 2} = \frac{F_{hub} L_1}{L_2} \tag{7}$$

With those implications now the forces in the x direction can be looked at. Equation 8 is equating the forces in the x direction. Then Equation 9 is the simplification of Equation 8 by subbing in Equation 6 and 7.

$$F^{*}_{centrifugal} = \mu(F_{reaction\ 1} + F_{reaction\ 2} + F_{hub}) \tag{8}$$

$$F^{*}_{centrifugal} = 2\mu F_{hub} \left(\frac{L_1 + L_2}{L_2}\right) \tag{9}$$

Equation 10 shows the force produced by the lack of a normal force. M is the mass of the pin. r is the distance from the center of the hub to the center of mass of the pin. This value was set to 0.1 m. $F^{*}_{centrifugal}$ is the centrifugal force.

$$F^{*}_{centrifugal} = mr\omega^2 \tag{10}$$

Finally, equation 10 can be plugged into equation 9. Then the mass can be solved for by plugging in values for the equation. L_2, in figure 23, is the distance the pins sit in the outer cylinder. L_1, in figure 23 is the distance between the outside cylinder and the hub. The angular velocity was set a 10 $\frac{rad}{s}$.

$$m=\frac{2}{r\omega 2}\mu F_{hub}\left(\frac{L_1+L_2}{L_2}\right) \tag{11}$$

After solving for the mass, the shape of the pin was determined. When the calculations were first done, the mass needed was large, relative to the mass of the rest of the launching mechanism. Thus, it was decided to use 6 pins to have smaller pins and distribute that high mass. It was also determined that a piece of steel was needed because of the high mass needed (0.47 kg).

The hole pins were not made from steel because the friction factor between PLA and PLA were lower (μ is roughly 0.1). Additionally, it was thought that trying different materials, such as wood, would confirm the need for that mass. The outside shell was designed to be able to house wood (as well as the needed steel), as seen in Figure 41. The dimensions of the pin are best seen in Appendix F. From there, a hole was left at the end of the pins. This was done so they can be tied to the outside cylinder, so it does not fly away. This was not done in testing. This can be seen in Appendix I.

Figure 41 Pin Design with Interchangeable Masses

4.3.8 Motor

Sizing the motor was simplified to only a torque and air resistance which is assumed negligible in this scenario. Thus, it reduces to the diagram shown in Figure 42. This then reduced the requirements on the motor from how much torque is required to how fast should it reach the desired velocity. From here as seen in equations 12 and 13 where a time of 5 seconds was chosen for the desired time and the angular acceleration of 2 was chosen. The motor was then chosen on this basis and was the prime restriction on the rest of the electrical systems. J was calculated to be 0.0303 $kg * m^2$. This gave a torque required of 0.0606 $kg * m$

$$\tau = J\alpha \quad (12)$$

$$\omega = \alpha t \quad (13)$$

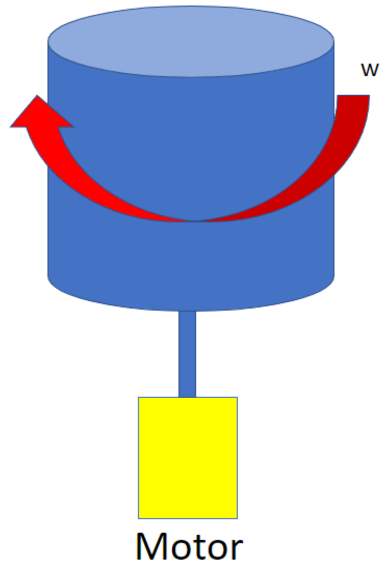

Figure 42 Diagram for Sizing the Motor

A motor was chosen for the need to adjust the angular velocity of the mechanism to test different deployment speeds. This would allow for us to see how accurate the equations were that we used to determine the angular velocity and to visually identify the best deployment speed. Another option could have been a torsional spring. The issue with the torsional spring is that it would only be able to provide angular acceleration for a set value. Thus, it would have a maximum speed that could not be exceeded, and it would be difficult to set the spring at different displacements to obtain lesser velocities. This would have required a lot of thought and design to achieve these different displacements.

Originally a micro dc gear motor was chosen as it was cheap and extremely small. After a few short tests the gear box had started to allow play in between the gears causing the output shaft to have some play. This caused the whole apparatus to rotate unevenly and disturbed the release mechanism. This caused the whole system to fail, and a new motor had to be ordered. This motor also created difficulties in mounting the mechanism to a base plate due to its tiny size. This motor is shown in Figure 43.

Figure 43 Micro Gear Motor

The final motor was a direct drive 12-volt dc motor that was significantly bigger in overall size. This allowed for easier attachment to a mounting plate. The motor having a direct drive instead of a gear box lowered the risk of a wobble in the final build. The overall length of the motor was two inches with the output shaft being 2.3 mm in diameter. This motor is depicted in Figure 44.

Figure 44 Direct Drive DC Motor

4.3.9 DC Motor Controller

The speed controller was needed for the project so that we could vary the angular velocity for different tests. This is important to help determine the accuracy of the research and quality of the build. If the research is correct then the calculated 10 radians per second should lead to the best deployment but, it is important to test a range of values around this velocity to determine which speed gives the best deployment.

The speed controller chosen was one that could be used on DC brushless motors and that were simple to implement. The chosen controller has one dial that allows for the user to adjust the speed of the motor. This controller is rated at 30 watts and 18 volts. As the motor is rated for 12 volts this was a good choice as it can withstand the voltage and maximum power from the two 9-volt batteries that are placed in series with the speed controller. The speed controller is shown in Figure 45.

Figure 45 DC Motor Speed Controller

4.3.10 Batteries

The power source for this project just needed enough voltage to power the motor. This was the only criteria as we were not concerned with long term use and wanted something portable. Two 9-volt batteries were used in series to obtain a total of 18 volts. This gives the system enough available voltage to operate the motor above its rated abilities. Although, this can be controlled with the speed controller to ensure proper operating range. The 9-volt batteries chosen were two Duracell 9-volt batteries.

Figure 46 Duracell Battery

While two 9-volt batteries were thought to be ideal after some initial testing of the release mechanism it was determined that this did not produce the required angular velocity. The power output to the motor simply was not high enough. A voltmeter was used to determine that the current being drawn from the Duracell batteries was too low, even though the voltage was 18 volts. This was fixed by using a 11.1-volt Lipo battery as shown in figure 30. The advantage of this battery was that it allowed for a higher current to be achieved. Testing showed this battery was able to supply currents larger than 3 amps. Although the speed controller was only rated for 2 amps. This caused the speed controller to shut off once the maximum power of 24 watts was reached. The 24 watts was enough to deploy the device with one or two pins.

Figure 47 3 cell Lipo Battery

4.3.11 Motor Bracket

The motor bracket was 3D printed out of PLA. It was designed to slide over the top of the output shaft of the motor and rests along the sides of the motor and screws into the wooden mounting board. FEA was conducted on the bracket assuming the maximum force that would be applied to the bracket would come from the weight of the space debris launching mechanism. From this a total mass of 8 kg was assumed and the orientation of the device was 90 degrees so the bracket would be at its highest stress. This was done in the direction of where the legs were and the direction of where the legs were not. Appendix L shows an example of the FEA analysis on the bracket. The legs are the two pieces on either side of the bracket that run along on the side of the motor. An image of the bracket is shown in Figure 48. From here the top whole was created to fit around the little raise in the motor just below the output shaft. From here the legs were constructed to reach the base of the mounting board and then holes were left for two wood screws to be attached to secure the motor. Figure 49 shows the motor mounted onto the mounting board with the screws.

Figure 48 Motor Bracket

Figure 49 Motor with Motor Bracket

4.4 Final construction

4.4.1 3D Printed Parts

A large portion of the project was 3D printed and used PLA. This was because 3D printers and PLA were readily available. This made the construction of certain parts very easy to construct as they were built over night. The team was not picky on what colors the parts were so this process could be quickly. This is why many of the parts are different colors because the team used whatever color was available. The pins, hub, outside cylinder, motor bracket, and hanging masses were all 3d printed. The hub was printed into 2 parts, as shown in Figure . The smaller black circle, on the left of Figure 50, goes into the hole, on the right of Figure 50.

Before inserting the black piece, Gorilla glue was place on the edge of the pieces where there is contact. Then the pieces were put together and were allowed to dry. The hub pegs were also printed separately. The spot where each peg needs to go was measured and glued on the flat side of the black hub part, shown in the left of the Figure 50. This was not the ideal way to put the pegs on the hub but having them printed on the hub would have caused an excessive amount of PLA filament to be wasted on support structures. Holes should have been left to indicate where the pegs go, making locating where the pegs go easier.

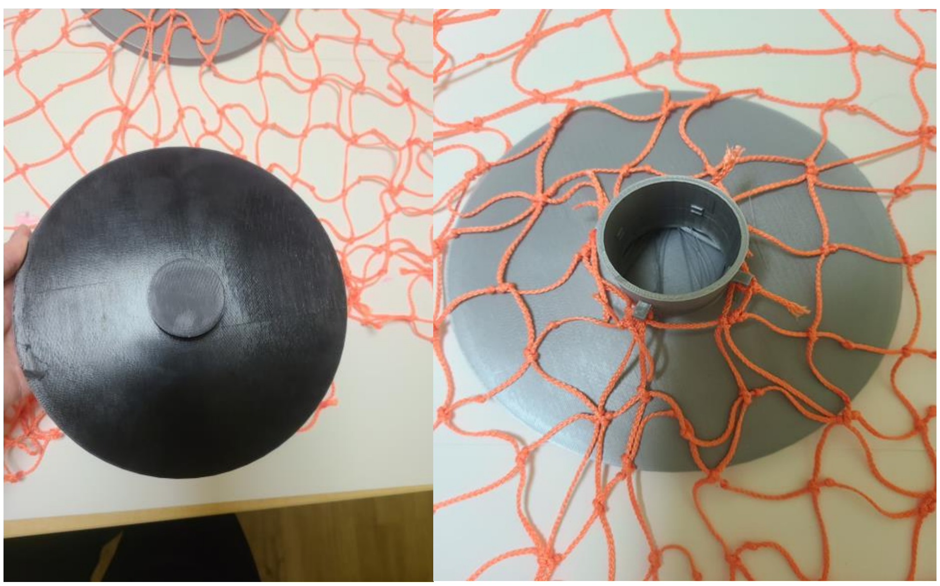

Figure 50 The Hub Printed in 2 Parts

The outside cylinder was printed into 4 parts, shown in Figure 51 and put together using the same glue. Each part can be seen in a different color. A Solidworks drawing in Appendix F shows the part dimension of the separated 3D Printed parts and shows where the parts would be put together.

Figure 51 Outer Cylinder: Bottom Plate and Shell

The reason the outside cylinder and the hub were printed in parts was because they were quicker to print in parts and the 3D printers had a size constraint. Additionally, there were more 3D printers available that could print smaller parts than larger parts. The final part to be printed from the 3D printer was the motor bracket. This was quicker than making it out of metal and printed in only 40 minutes. In general, 3D printing allowed many our parts to be made quickly and easily.

4.4.2 Net

The net was constructed by hand using #18 nylon mason twine. The twine was pulled from the spool in lengths of 1.4 meters. They were then laid out in a grid like fashion to match the 5-centimeter meshing requirement. A node in this case is defined as being where the strings cross over each. The extra length of string was needed as every node on the net requires a knot and the knots on the edges use more string than those in the center nodes. The knots on the edges are square knots while the ones in the center are pretzel knots. The issue with using pretzel knots is that they only lock motion in one direction when trying to tie two strings together. Thus, small amounts of glue were applied as the various nodes to help insure the proper meshing size of the net. The diagonal strings were approximately 2 meters in length as some extra string was required on the end corners to attach the hanging masses. This net took about 20 hours in total to complete from start to finish across about four days. This time of 20 hours does not include time spent researching net making, knot tying, and topology (The study of nets).

After the net was built, the center was cut out and it was tied to the hub, seen in Figure 52. Then each corner of the net was tied to each to the hook on the hanging mass. This is shown in Figure 52.

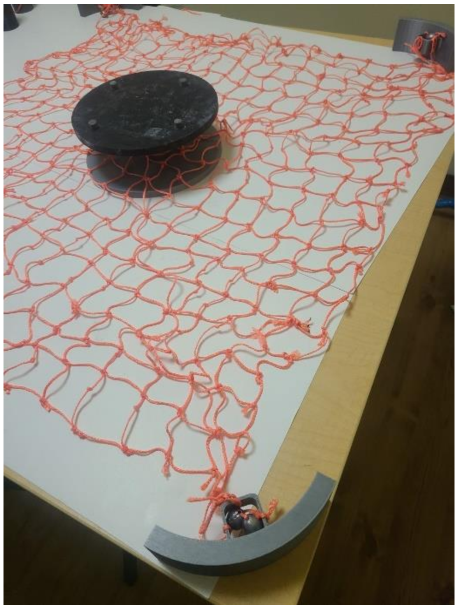

Figure 52 The Net, Hub, and Hanging Masses Connected

4.4.3 Purchased Parts

All the bought parts were easily integrated into the rest of the launching mechanism. The springs were slotted into the 8 holes in the bottom plate of the outside cylinder (the plate in Figure 53 is part of the outside cylinder; the whole part can be seen in Appendix F) and could be glued into their holes, as seen in Figure 53.

Figure 53 Springs in the Bottom Plate of the Outer Cylinder

Next, a block of wood was used to mount the speed controller, motor, and batteries. The motor mount then slides over the top of the motor and is screwed down to the wood. This is seen in Figure 54. The speed controller is also screwed down to the wood. From there, the motor can be slotted right into the outside cylinder and glued down.

Figure 54 Motor in the Outside Cylinder

4.4.4 Complete Build

Figure 55 shows the build put all together. In general, everything fits well together. The different colors are due to different printers being used. Also, through the project some parts changed color do to the fact that some parts broke when testing and they had to be reprinted. The only change that was noted and eventually made was making the peg holes hollow. This just made it easier to put the hub into the outer cylinder (in Appendix F this is shown.) This was not detrimental to the project but just makes it easier to align the pegs and the respective holes.

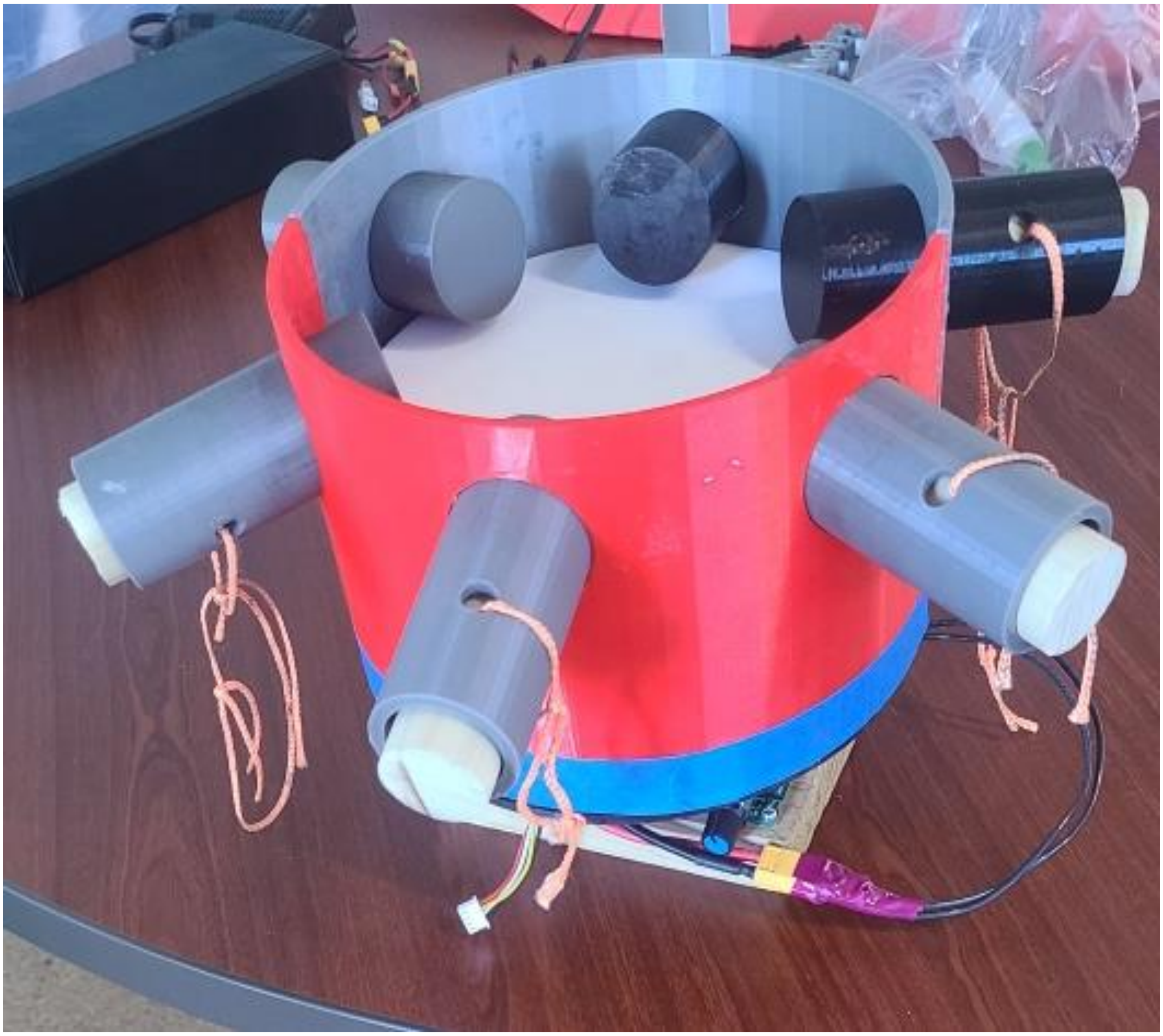

Figure 55 Complete Build of the Launching Mechanism

In Figure 55, the string in the pins was meant to be attached to be attached to the outside cylinder so that the pins would not fly away and cause space debris. This was not done for testing as it made seeing how the pins worked easier.

5. Testing

It was important to test pieces in increments to be able to best address problems. After everything was put together, it was important to test the motor first and make sure it works. The motor was inserted and was initially working fine. Yet, after a couple of tests the motor started to wobble because the force on the shaft from the outside cylinder. From there a new motor was ordered.

While a new motor was being ordered, the old motor was being used to test the pins and see if they work. The motor was held by hand and kept close to the ground to limit the wobble. Additionally, instead of starting with steel in the pins, dowl rods were tested with no spring force. This way it can be seen if it is possible to get the pins to come out all at once. Initially, all the pins came out at once in the first trial. In the second trial only half came out. Then in a third trial 2 came out and the rest stayed in. After that, some lube was added to see its effects. The results did not differ much, as only 2 came out the next time. The trials were then put on hold as the wobble became too much to manage and get meaningful results.

When the new motor came in, tests could be resumed. The hub was put in and one pin was used. For the first test, no springs were used. This made it more clear what problems the springs may add when implemented into the system. Additionally, this makes it easier to make sure the net deploys. Instead of springs, gravity is used to pull the hub and net out. The test site was about 10 feet up from the ground. The outside cylinder was pointed down at the ground, as shown in Figure 56. The arrow shows the direction the hub drops.

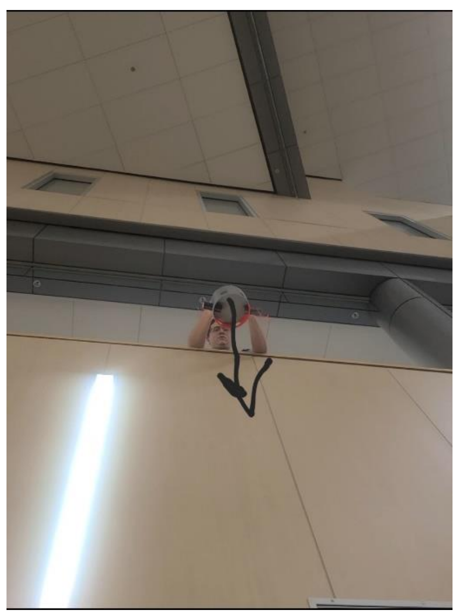

Figure 56 Orientation of Testing

When the pin slid out the net began to open but stopped because how close it was to the ground. Because the ground was hard the hub broke as shown in Figure 57.

Figure 57 Broken Hub from Testing

After a night of putting parts back together, testing could resume. For the next set of testing, a higher location was selected. Additionally, soft cushions were put underneath where the hub would hit. This prevented the hub from breaking and allowed for consecutive testing. The number of pins was changed to two, as it was easier to get two pins out than getting all six at once. Getting one pin out was hard and very inconsistent. These inconsistencies could have been caused by a few issues and was predicted in the FMEA in Appendix N. The first was inconsistent printing that caused rougher surfaces or misshaped as the printer cannot create perfect circles. Secondly, the hub pressing on one edge of the pin caused the pins to have a moment around the hole in the outer cylinder. This equates to trying to shove a square peg into a round hole as the circular pin is no longer in line with the circular hole. Still using gravity to launch the hub, the results were produced in table 4.

Table 4 Launching the Net at Different Angular Velocities

Test	rpm	rad/s	Did it open?	Number of Pins
1	81	8.4823	No	1
2	137	14.34661	Yes	1
3	138	14.45133	No	2
4	102	10.68142	Yes	2
5	121	12.67109	Yes	2
6	107	11.20501	Yes	2
7	139	14.55605	Yes	2
8	108	11.30973	Yes	2

This data was gathered by using a tachometer that measured the rpms and then were converted to rad/s. In test 1, the net did not open up because it did not meet the angular velocity. It is also important to note that it does not have to meet an exact value for the net to open up. The net opened for a large range of angular velocity. However, the ideal angular velocity would allow the net to open up for the longest amount of time without the net bouncing back. Unfortunately, this set up is not the best way to see because of the test setting.

Another significant outcome from the set of testing, is the importance of net folding. In test 3, an acceptable angular velocity was met. However, the net was not folded up correctly which causes the net not to open. More about the net folding is seen in Appendix J.

The springs acquire from Smalley failed to produce the desired initial velocity for the hub to eject. Although, the calculation showed the desired velocity during the initial testing of the springs it was noticed that they did not spring back quickly. This was predicted in the FMEA in Appendix N. A few theories were developed as to why this lack of springiness occurred. The amount of deflection that was required was approximately 2.7 mm this was extremely small and not practical. The error in the 3D printer during the manufacturing was enough to change this significantly. Another possible reason these springs did not work was potentially from the unique design of the springs. These are springs as seen in Figure 36 are not the conventual style of spring and may function differently.

The last big take away from set of testing was the fact that the pins were not the ideal release mechanism. It is hard to get all 6 pins to release all at once consistently. Even getting two pins to release was hit or miss. This confirmed that a different release mechanism needed to be used.

5.1 Net Folding

The folding technique was tested to determine if it would allow the net to deploy open. The star folding pattern as described earlier was used. It was determined that the orientation of the folding was important. The net launching device was set to rotate counterclockwise, and the net was folded counterclockwise also. During testing this caused the net not to deploy from the hub at all. Some movement from the hanging masses was observed but this is due to slack in the net and not the device deploying. It was determined from this that the net can only be folder opposite of the direction of motion to fully deploy.

5.2 Tachometer

The angular velocity data was collected by using a tachometer. The tachometer had been tested for accuracy with the system before the launching mechanism was tested. This was done by simply turning the launching mechanism on and letting it spin and then measuring the angular velocity. Initial testing gave results of over 2000 rpms. This was determined to be incorrect as the motor should not have been able to create this amount of angular velocity with the load. It was then concluded since tachometers work via infrared light being bounced off the surface of the object that the PLA was too reflective and was causing bad readings. This was fixed by adding blue masking tape around the bottom edge. Blue masking tape was readily available and appeared to be dull and less reflective than the PLA. A small strip of reflective tape that came with the tachometer was then placed onto this strip of masking tape. Figure 58 shows the masking tape and reflective tape on the outer cylinder.

Figure 58 Final Testing Setup for Tachometer

Figure 59 shows the tachometer used in the testing phase. It works by simply pointing the front face towards the object that is spinning and pressing a button. A red laser light then shines on the object and reflects into the tachometer. As mentioned above it is best to have a dull nonreflective material around the spinning object with a small strip of reflective tape on the dull surface to achieve the best results. The tachometer then records the highest speed achieved during that trail and stores that information while also displaying the current speed. A history button allows the user to see the last maximum result of the previous trail.

Figure 59 Tachometer with Readout

6. New and Reviewed Engineering Concepts

For this project there was plenty of engineering material that had to be reviewed. For starters, using energy equations and force equations was important when designing springs. Conservation of momentum also was reviewed to understand how the nets work. Additionally, understanding angular velocity was significant to try to design the pins.

A lot of new concepts had to be learned to do this project. To start off with, a lot had to be learned about space debris capture, what methods are available to remove space debris and how do those method work. Going off that, an understanding how the net works was incredibly important to be able to design the rest of the project. Likewise, how to size a motor was an important skill needed to do this project. Another skill that was learned for the project was how to 3D print parts in a manner where they were quick and easy to assemble. When designing the pins, more detail about modeling friction and linkages had to be learned.

7. Teamwork

Teamwork was incredibly important to this project. A lot of new knowledge was needed to craft this design. Splitting up who focused on what made the amount of new information needed more manageable. Additionally, splitting up who designed what and who did which task was important for the project and made the project more reasonable. It was also important that the teammates trusted each other and were able to take critical feedback. All components were reviewed, and it was important that a team member speaks up if there is something that was not clear or there was an error. In these situations, it was important for everyone to trust the other team member had the right intentions, of making the project the best it can be. Without this level of trust, this project would become more stressful, and it would have made it harder for the team to work together. With all of this said, teamwork made a challenging project less difficult and more manageable.

8. Lessons Learned

Many things were learned from this project. One of the most important things learned is the significance of the order of the way of things are done. Doing things in a strategic way can make things easier and lead to a better a project. Another lesson that was learned was the importance of good research. Finding the right information is so significant to a good project. Without a good background of research, this project would have ended in disaster.

9. Global, Social, Economic Impact

This project has a lot of potential for global, social, and economic impact. If this project was to be implemented into space for cleaning debris this would create a safer LEO. This would have the global impact of limiting the amount of space debris. This makes space safer for manned space flights and reduces the risk of Collison. This has the economic impact of reducing the number of potential repairs due to impacts. The projects design is cheap at a price of 108.18 dollars as seen in the Bill of Material in Appendix K. Overall society benefits by the potential impact the project could have if implemented.

10. Future Work

10.1 Better Release Mechanism

The current release mechanism relies on pins to be pulled out by spin ejection. This is dependent on the rotational speed, mass of the pins, and friction. It was found through testing, getting 6 pins to release all at one time is a challenge and friction is indeed hard to manage.

However, it was much more manageable to get 2 pins released. A design that attaches the 2 pins together and uses a force that connects them to resist centrifugal force may be a better than relying on friction. A different idea could be using springs to resist the centrifugal force instead of friction. This could work like an inverted centrifugal clutch. Another option would be having some device at the bottom pulling the hub into the springs. At the very worst, a device that uses electrical components could be used as a release mechanism.

10.2 More Compact Design

The current design is larger and bulkier than it needs to be. This can be solved by a complete design rework or by simply making the current parts smaller. Currently the hanging masses could be made smaller if a denser material is used. This wasn't done as this was simply a prototype to prove the concept. Other things include the outer cylinder as a new concept could be created to be smaller and achieve the same goal. This could also cause a need for a new release mechanism also. Other options include a better analysis on the volume needed by the net. This would cause a further reduction in overall size if the net was smaller, had less meshing, or was wrapped tightly every time.

10.3 Auto Debris Detection and Launch System

For this system to be launched into space it would require a system to auto detect debris at a short range and be able to launch the space net at the appropriate time. This would require a computer program that understands the relative motions of the satellite and the piece of debris being tracked. The debris would then need to be tracked by some sort of sensor, camera, or sonar. Research would need to be conducted on which method would be appropriate. All of this would take considerable amounts of time to program correctly.

10.4 Full End to End Design

This design was only for a proof of concept and so it is not fit for actual use. A full end to end design would be needed to complete the design and make it viable for a space environment. This would include some redesign as mentioned above, change in materials, and end to end dynamic analysis on a satellite that would have this attached. This would require a lot of work and dedication to achieve the correct dynamics.

11. Conclusion

Overall, this project was a success. The objective of this project is to design a mechanism that spins and launches a net to capture space debris was completed. A Solidworks model was made, and a prototype was built. The prototype was tested and confirmed the ability to get a net to deploy using spin ejection. While there were some flaws in the design, this design project produced a good background in research, and a great foundation for future teams eventually capture space debris using rotating nets.

References

[1] Yang, Leping, et al. *Dynamics and Design of Space Nets for Orbital Capture*. Tsinghua University Press and Springer, 2019.

[2] Boting Xu, Yueneng Yang, Ye Yan, Bin Zhang, Bionics design and dynamics analysis of space webs based on spider predation, Acta Astronautica, Volume 159, 2019, Pages 294-307, ISSN 0094-5765, https://doi.org/10.1016/j.actaastro.2019.03.045.

[3] Minghe Shan, Jian Guo, Eberhard Gill, An analysis of the flexibility modeling of a net for space debris removal, Advances in Space Research, Volume 65, Issue 3, 2020, Pages 1083-1094, ISSN 0273-1177, https://doi.org/10.1016/j.asr.2019.10.041.

[4] Justus Askren, Zach Breault, Wes Cooper, Emma Wargel, Design and Construction of an Orbital Debris Capture System Prototype Attachable to a Small Satellite: Concept Proposal, University of Southern Indiana, Fall 2020

[5] Wormnes, K, et al. *ESA TECHNOLOGIES FOR SPACE DEBRIS REMEDIATION*, www.esa.int/gsp/ACT/doc/MAD/pub/ACT-RPR-MAD-2013-04-KW-CleanSpace-ADR.pdf.

[6] Missel, Jonathan William. "Active Space Debris Removal Using Capture and Ejection." *ACTIVE SPACE DEBRIS REMOVAL USING CAPTURE AND EJECTION, Texas A&M University*, 22 Apr. 2013, oaktrust.library.tamu.edu/bitstream/handle/1969.1/149391/MISSEL-DISSERTATION-2013.pdf?sequence=1.

[7] Gärdsback, Mattias et al. "Design Considerations and Deployment Simulations of Spinning Space Webs." (2007).

[8] Botta, E. M., Sharf, I., & Misra, A. K. (2017). Energy and momentum analysis of the deployment dynamics of nets in Space. *Acta Astronautica*, *140*, 554–564.

[9] *Elsa-D - satellite missions - eoportal directory*. d. (n.d.). Retrieved January 25, 2022, from https://directory.eoportal.org/web/eoportal/satellite-missions/content/-/article/elsa-d

[10] Carlson , Erika, et al. *Final Design of a Space Debris Removal System*, The University of Texas at Austin , 1990, pp. 1–126. *NASA Technical Report Server.*

[11] Tinert, Gunnar, Gardsback Mattias. S*pace Webs Final Report*, Royal Institute of Technology. 2006 https://www.esa.int/gsp/ACT/doc/ARI/ARI%20Study%20Report/ACT-RPT-MAD-ARI-05-4109a-SpaceWebs-KTH.pdf

[12] Sinn, Thomas, et al. "Results of Rexus12's Suaineadh Experiment : Deployment of a Spinning Space Web in Micro Gravity Conditions." *Strathprints*, 1 Oct. 2012, https://strathprints.strath.ac.uk/41570/.

[13] Mao, Huina & Sinn, Thomas & Vasile, Massimiliano & Tibert, Gunnar. (2016). Simulation and Control of a Space Web Deployed by Centrifugal Forces in a Sounding Rocket Experiment. 10.2514/6.2016-4421. .

[14] *Removedebris's net captures space debris - youtube*. Youtube. (2018). Retrieved February 8, 2022, from https://www.youtube.com/watch?v=PIfRPTIgXuw

[15] Slocum, Alexander. "Topic 4 Linkages." *Fundamentals of Design*, 2008.

[16] Gao, Qingyu et al. "Study on launch scheme of space-net capturing system." *PloS one* vol. 12,9 e0183770. 6 Sep. 2017, doi:10.1371/journal.pone.0183770

[17] "Ares." *NASA*, NASA, https://orbitaldebris.jsc.nasa.gov/.

[18] "Wave Springs." *Smalley*, 9 Dec. 2021, https://www.smalley.com/wave-springs.

[19] Paikowsky, Deganit. "Why Russia Tested Its Anti-Satellite Weapon." *Foreign Policy*, 26 Dec. 2021, https://foreignpolicy.com/2021/12/26/putin-russia-tested-space-asat-satellite-weapon/#:~:text=3%3A00%20AM-,On%20Nov.,Earth%20for%20a%20long%20time.

[20] "Want to Snag a Satellite? Try a Net." *ESA*, https://www.esa.int/Safety_Security/Clean_Space/Want_to_snag_a_satellite_Try_a_net.

[21] "Help Solve Space Waste." *Clear Constellation*, 17 Aug. 2021, https://www.clearconstellation.com/.

Appendix

Appendix A System Hierarchy

This shows a breakdown of the systems used in this project. Figure 60 shows the electrical components in the system. Figure 61 shows the mechanical system and where the components are in before launch.

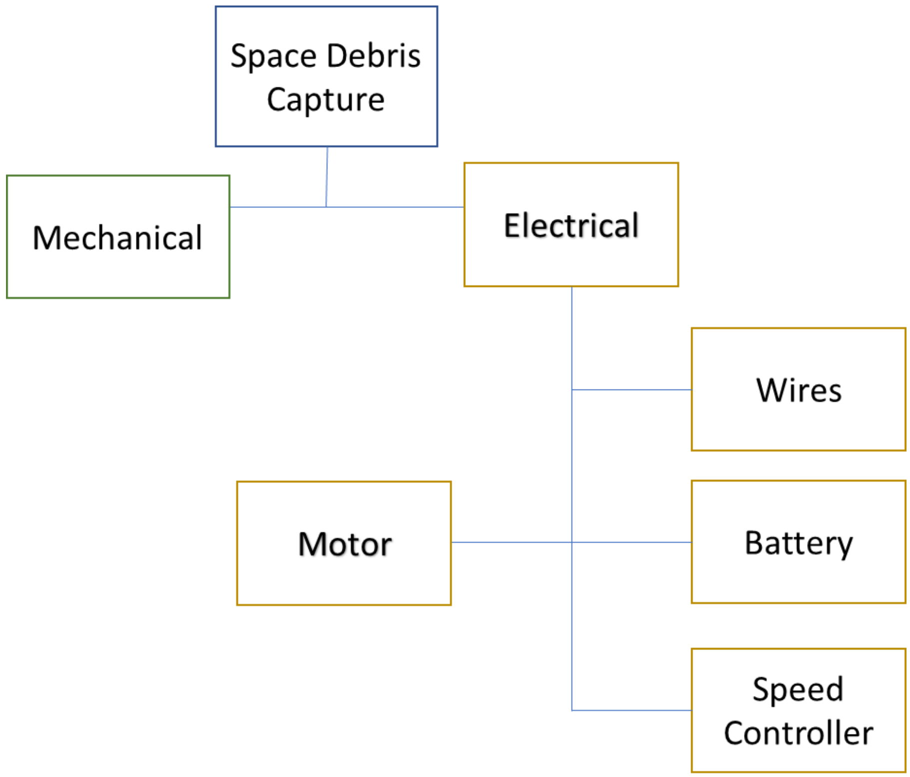

Figure 60 Electrical System Hierarchy

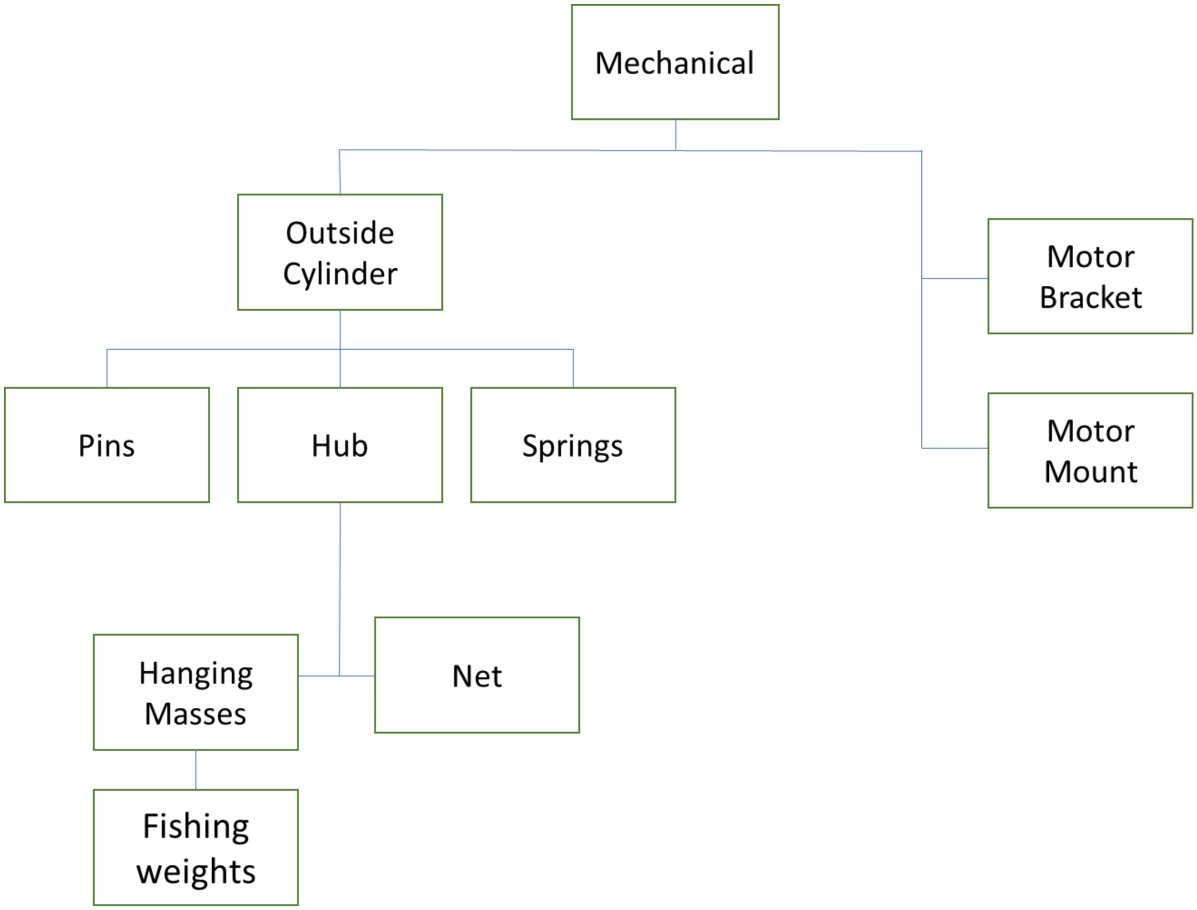

Figure 61 Mechanical System Hierarchy

Appendix B Schedule

In this section, the schedule shows the order and dates of which things were done.

Schedule -

Week	Logistics	Design
Jan 17 - Jan 23	-figure out time needed in AEC/ what is needed to get access there (week 5) -create an updated budget (week 1) -request access to needed rooms to work (such as CAD LABS) (week 3) -make an updated list of parts (week 2) -find out how to acquire parts (in progress) -figure out where the prototype will be tested and how to get access to needed places (week 5)	-Choose Critical Design (week 3)
Jan 24 - Jan 30		-design Net Hub (week 5) -Design hanging masses (week 5) -Choose Net and folding technique (week 5) -dynamics of net
Jan 31 - Feb 6	-determine desired motor and other electrical devices needed (week 5)	-Finish Design of release Mechanism (week 6) -Finish Launch Mechanism Design (week 5) -Determine if a motor is needed or if a torsional spring would be better (week 4)
Feb 7 - Feb 13	-updated parts list/ budget	-finish design of bearings/case/mountings -check previous calculations and designs (Repeat)
Feb 14 - Feb 20	-Start Ordering parts -updated parts list/ budget -start building report/final presentation	-Have Solid Works Model Finished -create good blueprints from the solid works model -Design Review -Experiment with net deployment
Feb 21 - Feb 27	-Start building	-Review dynamic analysis -Review Net Canister -Critical Design Review

	-continue building report and presentation (have a decent portion of it built out)	
Feb 28 - Mar 6	-order motor and speed controller -start building net	-Review Net Launching Design -Review Releases Mechanism Design
Mar 7 - Mar 13	-finish building net	-finish design of pins
Mar 14 - Mar 20	-finish building -put components together -Prepare for presentation -work on report	
Mar 21 - Mar 27	- Test Build -Prepare for presentation -work on report	
Mar 28 - April 3	-Design Presentation Review 4/3 -Test Build	
April 4 - April 10	-Draft Report to Advisor 4/8 -Test Build	
April 11 - April 17	-Poster is due 4/14 -Test Build	
April 18 - April 24	-Final Presentation Due 4/22 -*Second Draft Due 4/18 (may change)*	
April 25 - May 1	-Advisor Has Final Report 4/28 -Poster Session 4/28 -Final Presentation	
May 2 - May 8	-Final Report Due 5/5/22	

Appendix C Budget

The budget shows how much each piece coast. Parts that were given for free or not purchased with school funds will be marked with an asterisk.

Table 5 Budget

Item	Amount
Speed Controller	$5.59
Motor	$6.89
PLA (estimate)	$44.84
Nylon Twine	$9.99
Springs	$0.00
Gorilla Glue	$6.97
Screws	$0.00
14 Gauge Electrical Wire	$33.02
3/4 Oz Fishing Weight	$1.88
Total	$109.18

Appendix D Mass Table
This table shows the mass of the components.

Table 6 Mass

Components	Mass (kg)
Net	0.070
Hub	0.300
4 Hanging Masses	0.320
Fishing Weights (8)	0.170
Motor	0.010
Speed Controller	0.014
Spring (8)	0.003
Outside Cylinder	0.130
Pins (6)	2.400
Total	3.417

Appendix E Functional Block Diagram

This figure shows how the component function together.

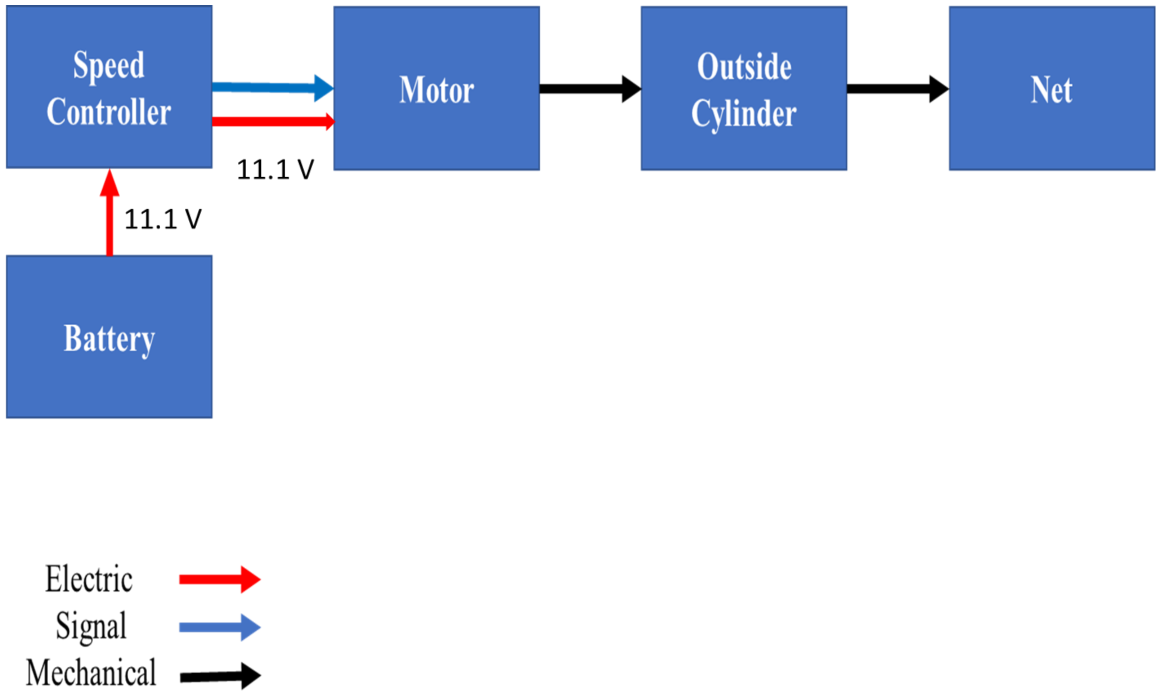

Figure 62 Functional Block Diagram

Appendix F Solid Works Models

These figures show detailed sketches of each part the was designed as well as the parts that were broken up to be 3d printed. All of the dimensions are in centimeters.

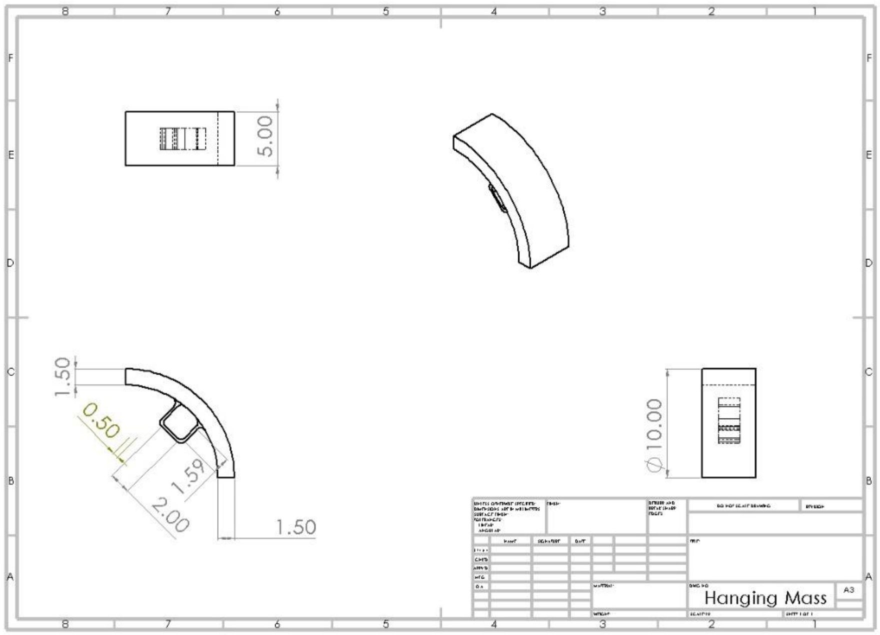

Figure 63 Hanging Masses Solidworks Drawing

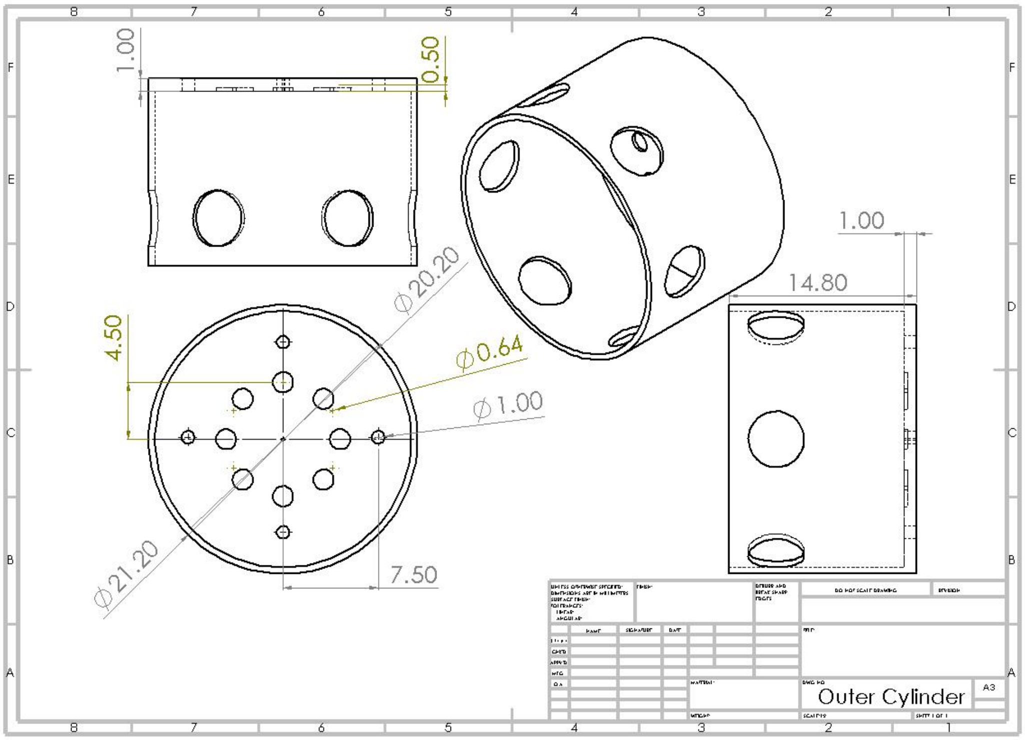

Figure 64 Outer Cylinder Solidworks Drawing

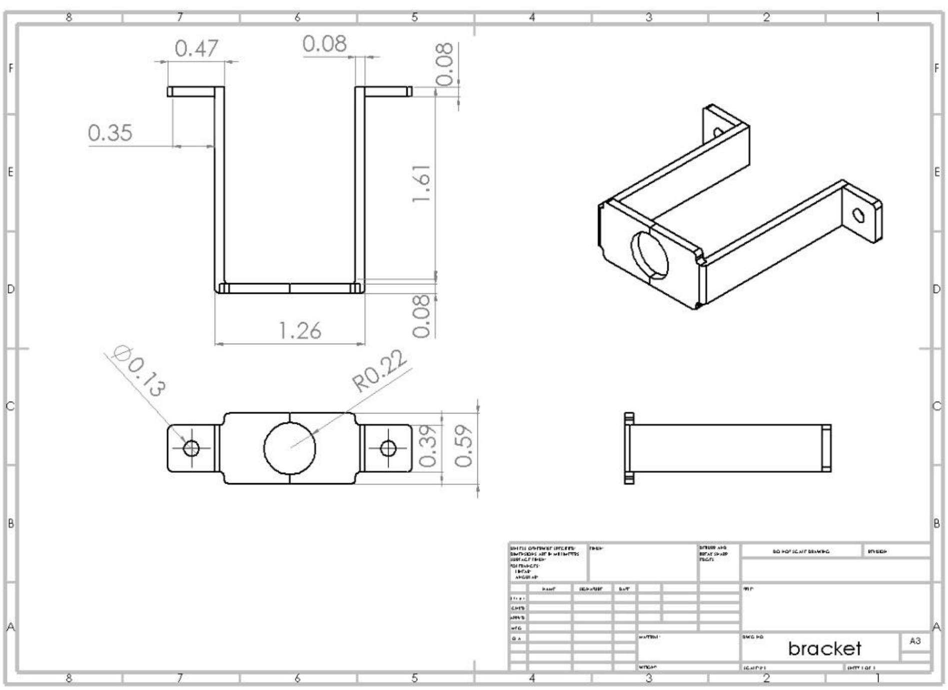

Figure 65 Bracket Solidworks Drawing

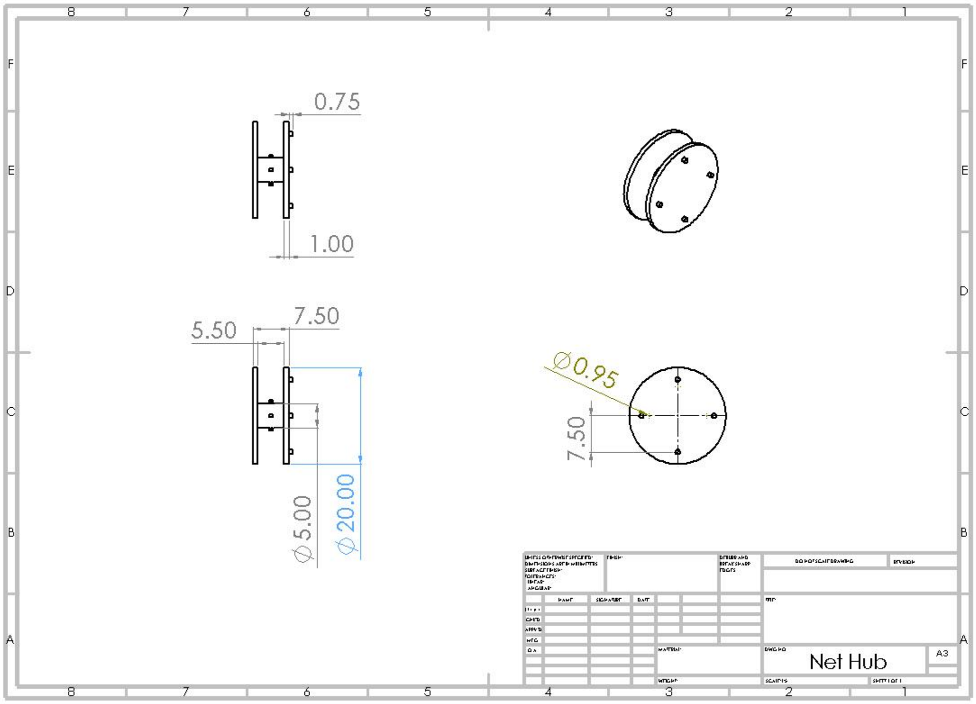

Figure 66 Net Hub Solidworks Drawings

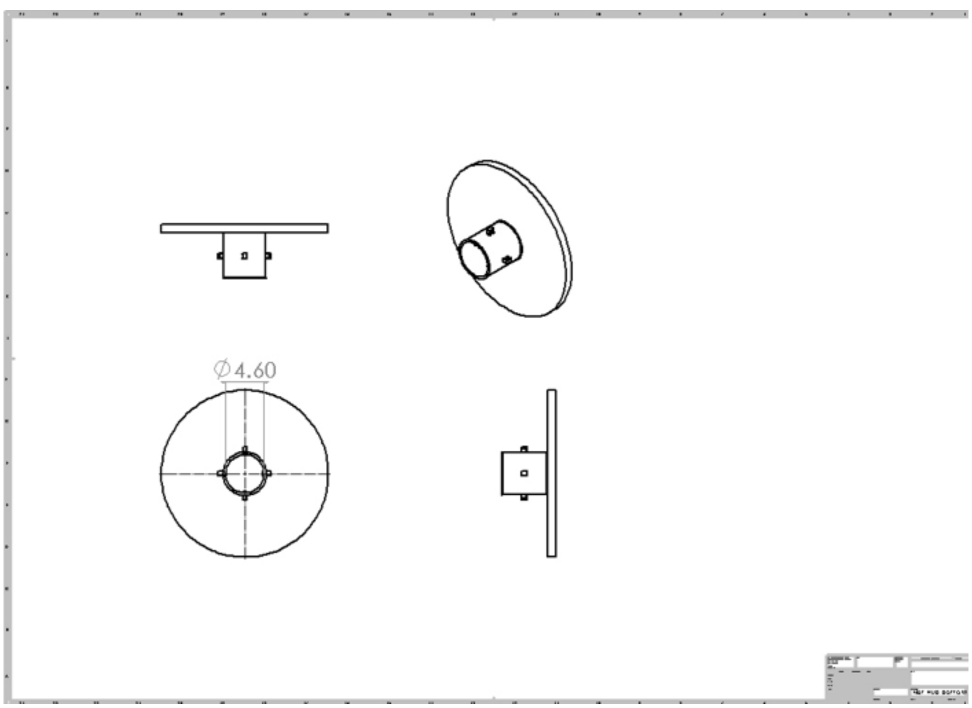

Figure 67 3D Printed Top of Hub

It is important to note on the top of the hub that not much has changed but that inside diameter is important to how the 2 hub pieces connect.

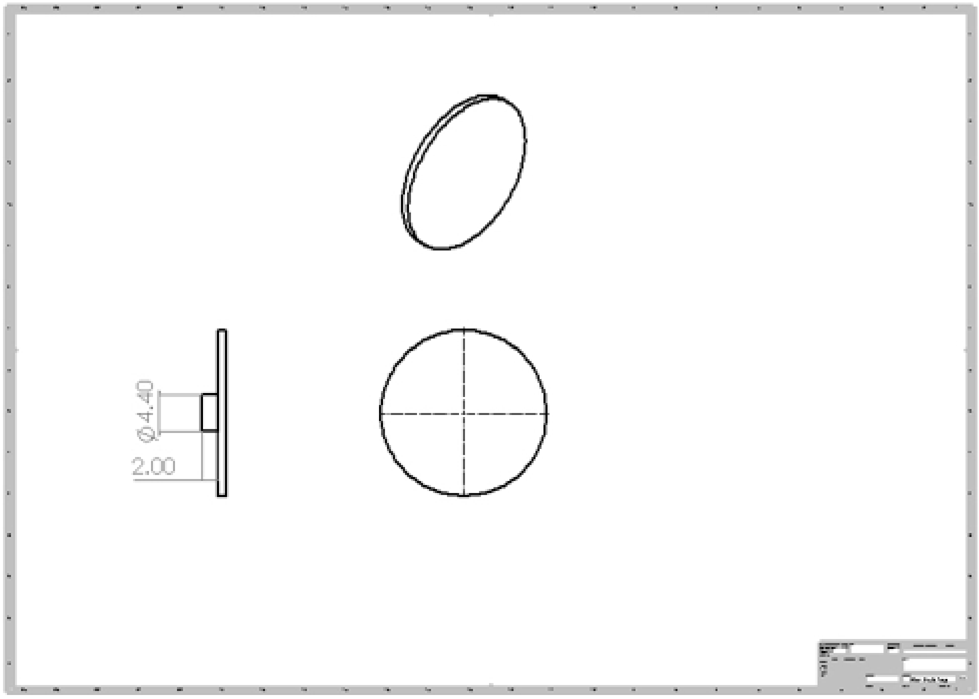

Figure 68 3D Printed Bottom Part of the Hub

If this part was to be 3d printed again, there would be hollow holes shown in the right part of the sketch to make attaching the pegs easier.

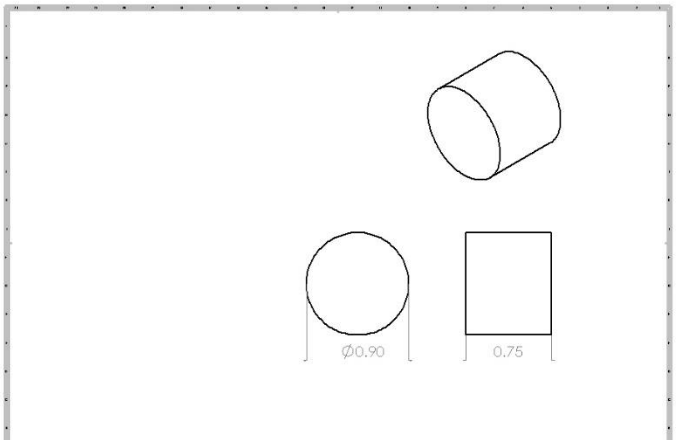

Figure 469 3D Printed Hub Pegs

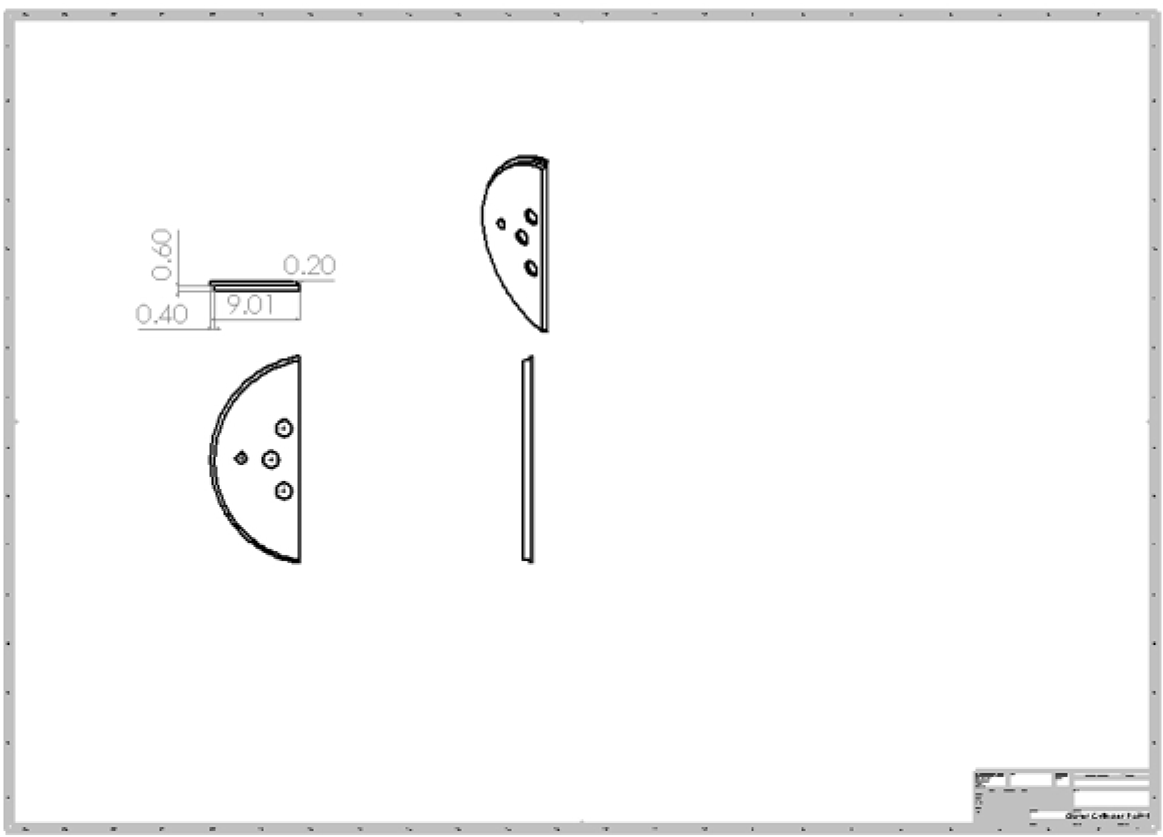

Figure 70 3D Printed Outside Cylinder Part 1

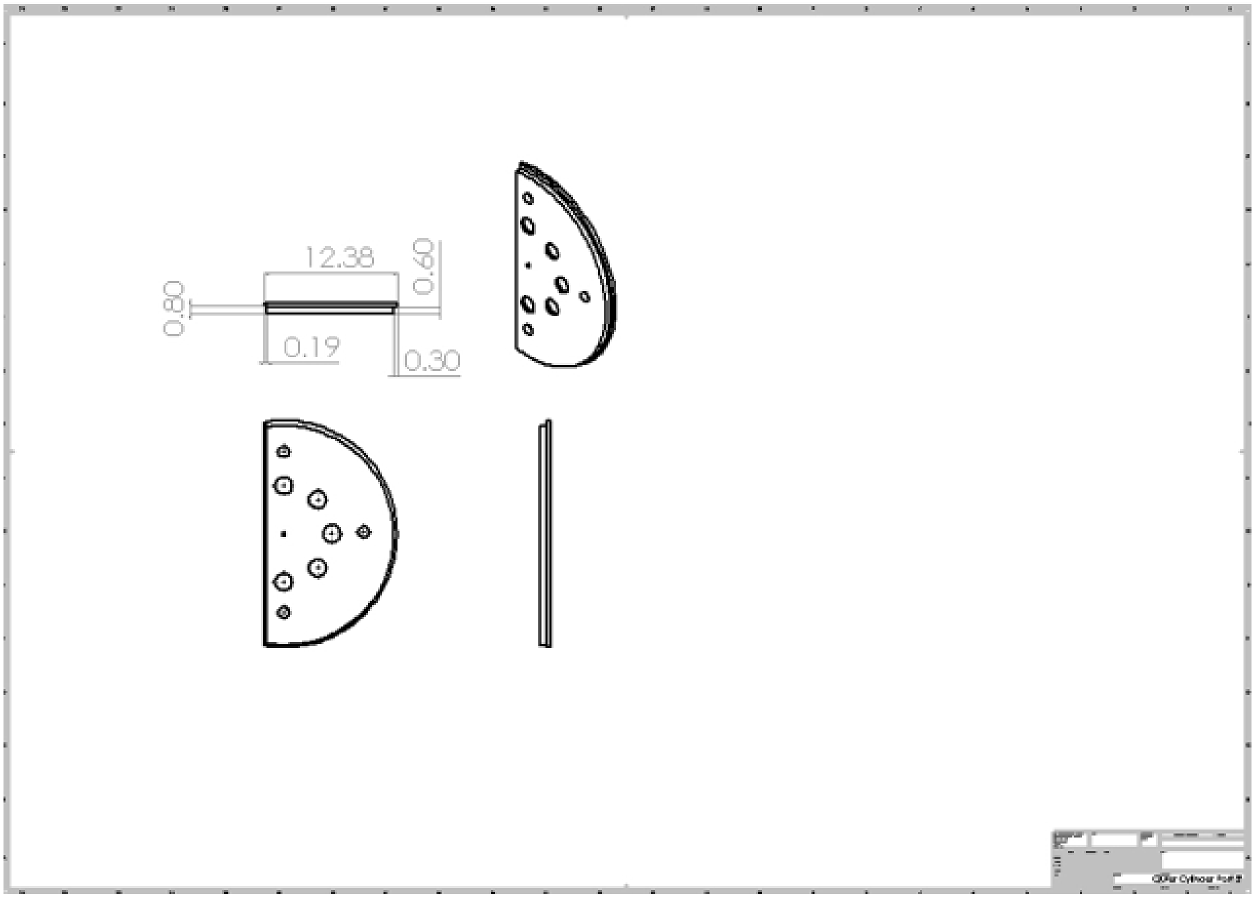

Figure 71 3D Printed Outside Cylinder Part 2

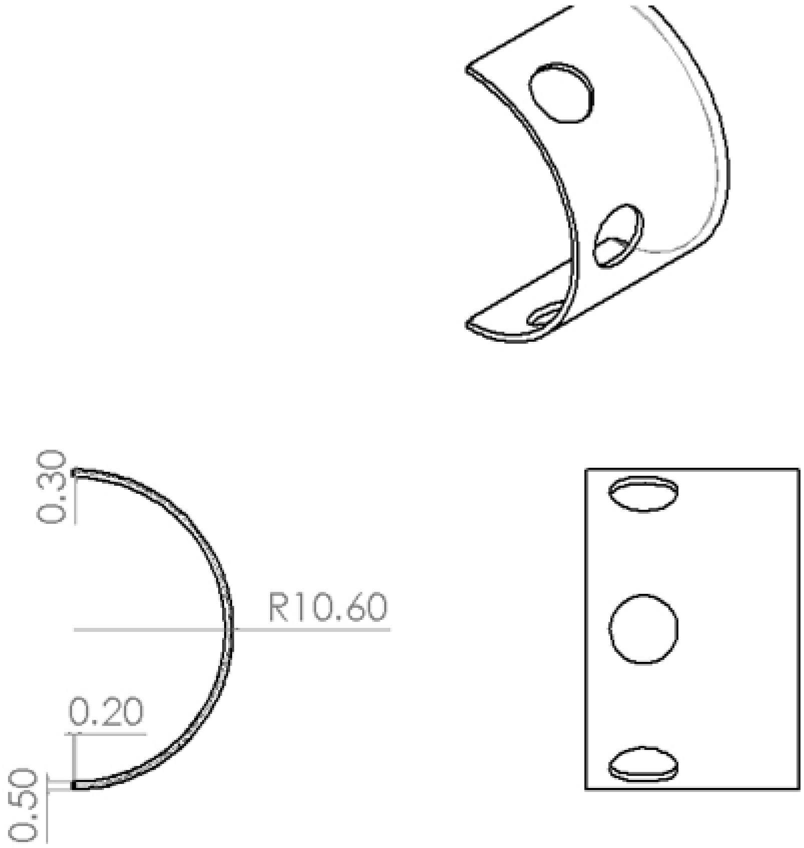

Figure 72 3D Printed Outside Cylinder Part 3

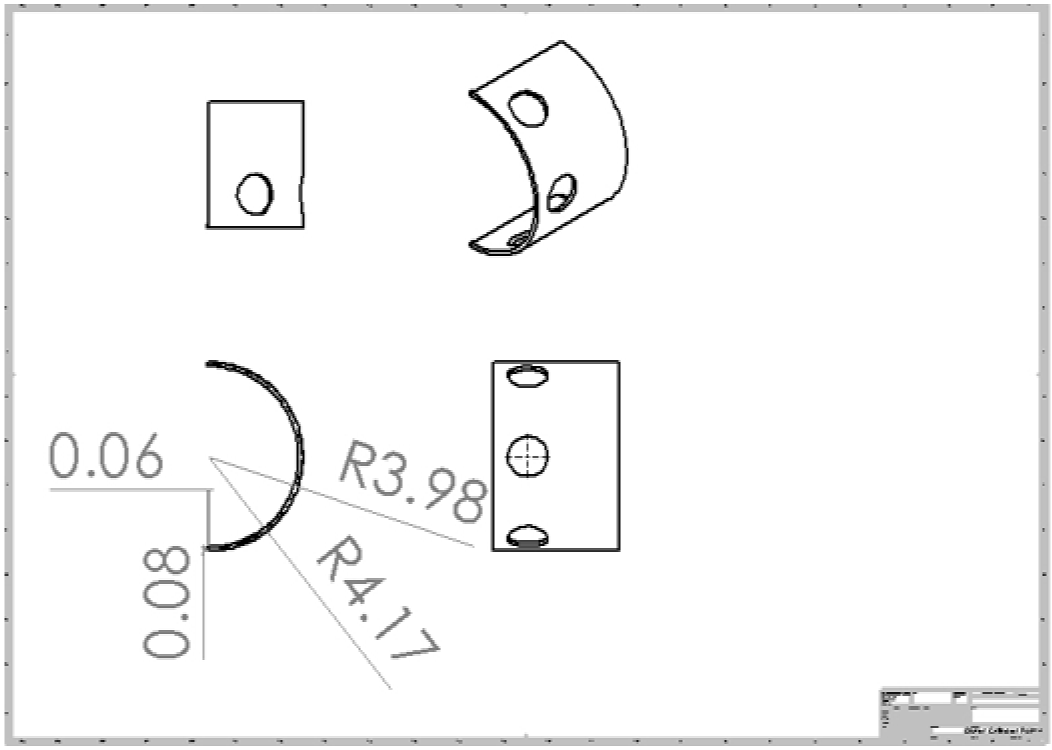

Figure 73 3D Printed Outside Cylinder Part 4

Appendix G Specs of Purchased Parts

This section shows detailed information about parts that were bought.

Part Number	CM15-H1
Spring Type	Crest-to-Crest
D_b: Operates in Bore (mm)	15.00
D_s: Clears Shaft Diameter (mm)	10.00
Load (N)	80.0
Work Height (mm)	3.20
H_f : Free Height REF. (mm)	5.18
Number of Waves/Turn	3.5
Number of Turns	3
Number of Shims	0
t: Wire Thickness (mm)	0.25
b: Wire Radial Wall (mm)	1.47
Spring Rate REF. (N/mm)	40.4

Figure 74 Spring Specs from Smalley [18]

Appendix H Web Shapes

This figure shows the different shapes the net could have been. Here n represents the number of points and μ represents the points on the meshing design.

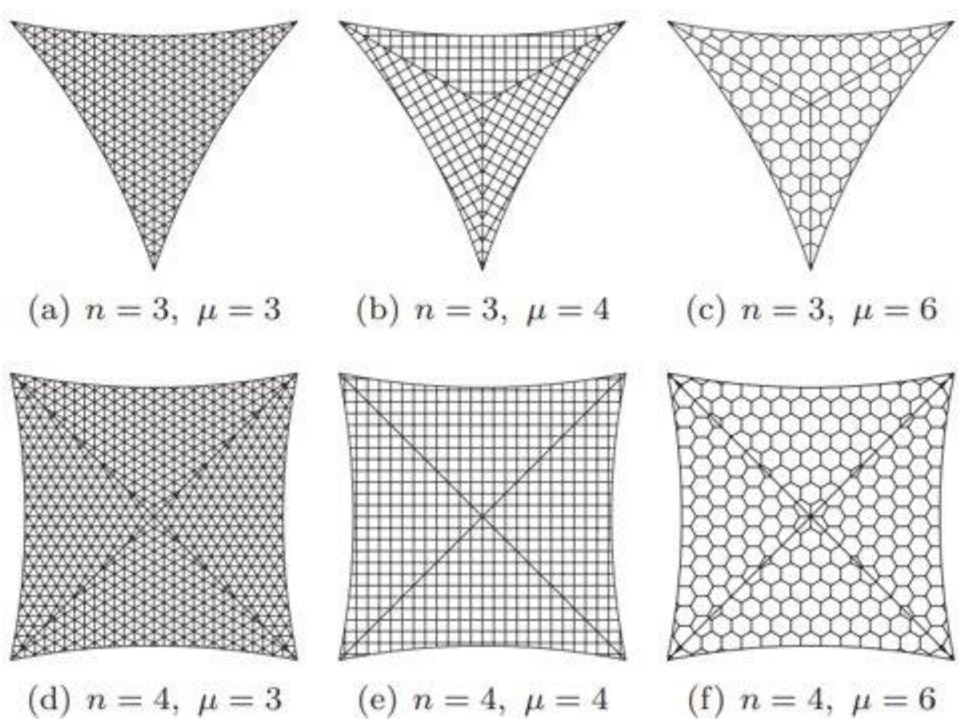

Figure 75 Web Shapes and Meshes [11]

Here n represents the number of points and μ represents the points on the meshing design.

Appendix I Mechanical Block Diagram

The mechanical block diagram is a simplification of the Launching Mechanism. It was used to get an idea of how the launching mechanism was going to work. In this, there is a depiction of where each component sits. However, the number of springs and pins are not accurate in the block diagram, because it was not practical to show 6 pins and 8 springs in a block diagram. Also, it is important to recognize that this is a half geometry cut such that if the device was cut down the center this is what would be seen.

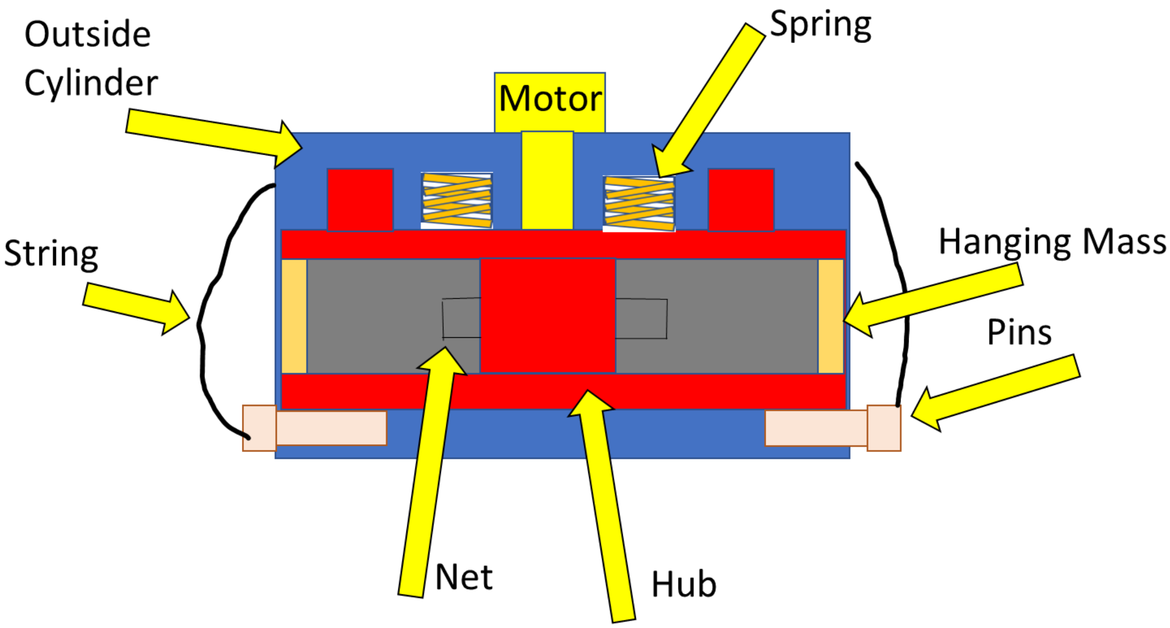

Figure 76 Mechanical Block Diagram

Appendix J Folding the Net

The next figures depict how the net was folded up. In the first four steps the net is inward such that just the diagonals were left in a star shaped pattern. Then the hanging masses were spun counter to the rotation to the motor (in this situation the masses were spun counterclockwise; the motor spun clockwise) around the center of the hub. Finally, the hanging masses can sit on the edge of the hub

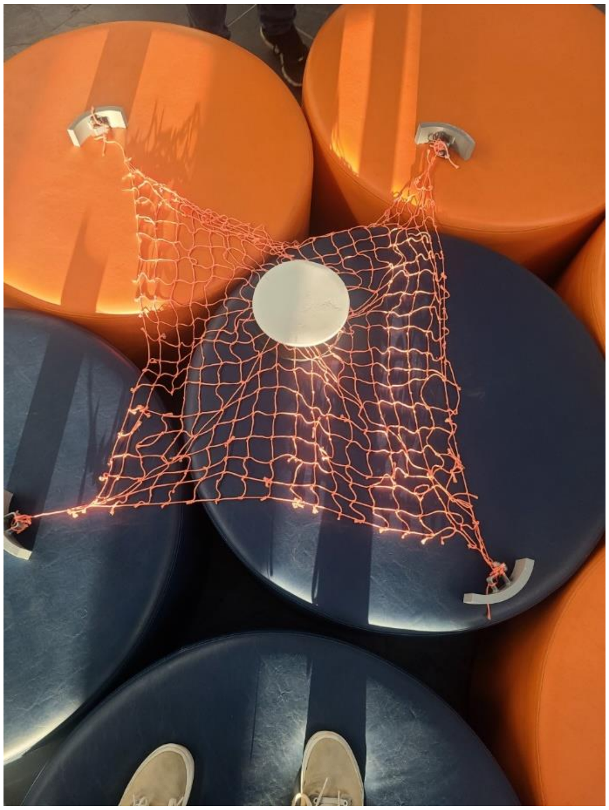

Figure 77 Step 1 Folding the Net

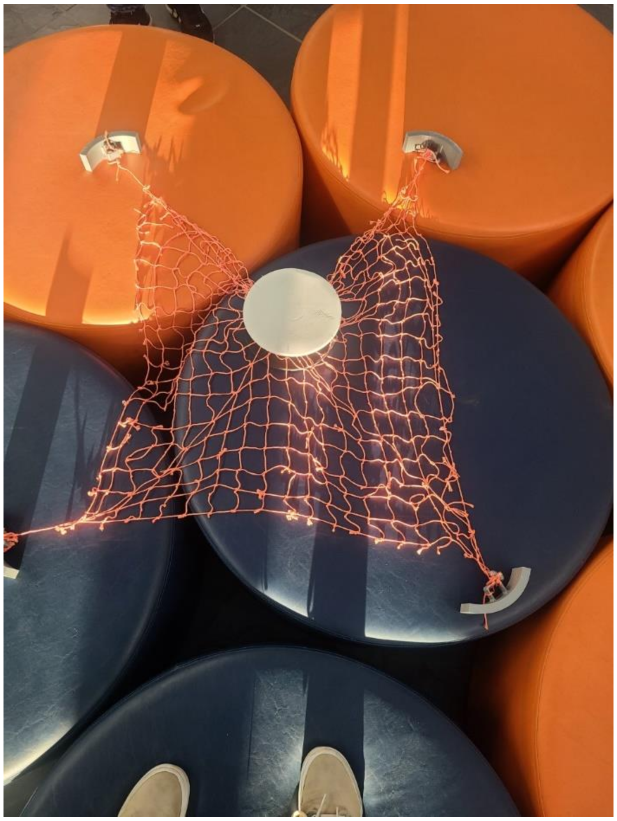
Figure 78 Step 2 Folding the Net

Figure 79 Step 3 Folding the Net

Figure 80 Step 4 Folding the Net

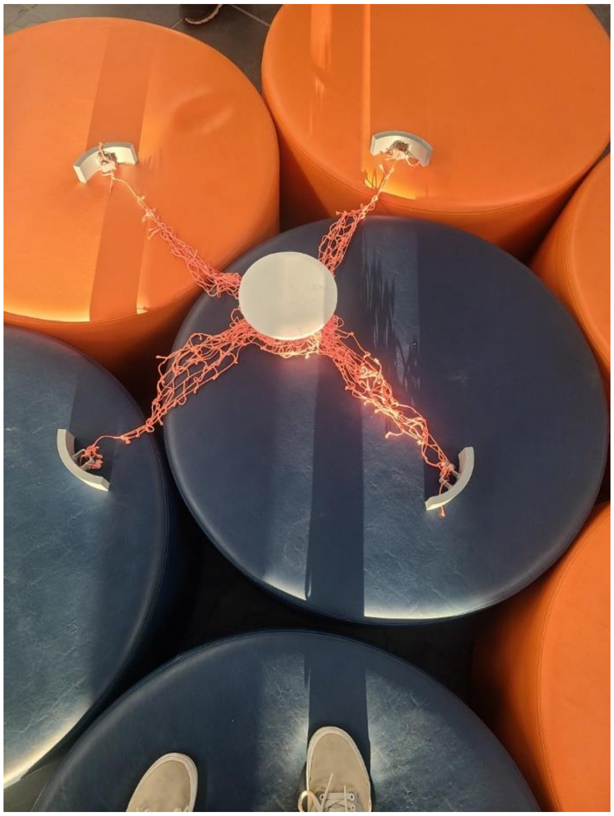

Figure 81 Step 5 Folding the Net

Figure 82 Step 6 Folding the Net

Figure 83 Step 7 Folding the Net

Appendix K Bill of Materials

	Item	Source	SKU/ASINS	Unit Cost	Units	Total Costs
1	Speed controller	Amazon	B07P2BLG2L	$5.59	1	$5.59
2	AUTOTOOLHOME Mini DC High Torque Motor	Amazon	B01M58POHF	$6.89	1	$6.89
3	PLA Filament (1.75 m, 1 kg)	Amazon	B07T2R1BQJ	$22.42	2	$44.84
4	Nylon Twine	Amazon	B08ZJ2XNG2	$9.99	1	$9.99
5	Springs	Smalley	CM15-H1	$0.00	12	$0.00
6	Gorilla Glue Gel	Amazon	B00OAAUAX8	$6.97	1	$6.97
7	Screws (Miscellaneous)	NA	NA	$0.00	4	$0.00
8	14 Gauge Electrical Wire	Grainger	26121517	$33.02	1	$33.02
9	¾ Oz Fishing Weight	Walmart	EG6-24	$0.94	2	$1.88

Appendix L FEA

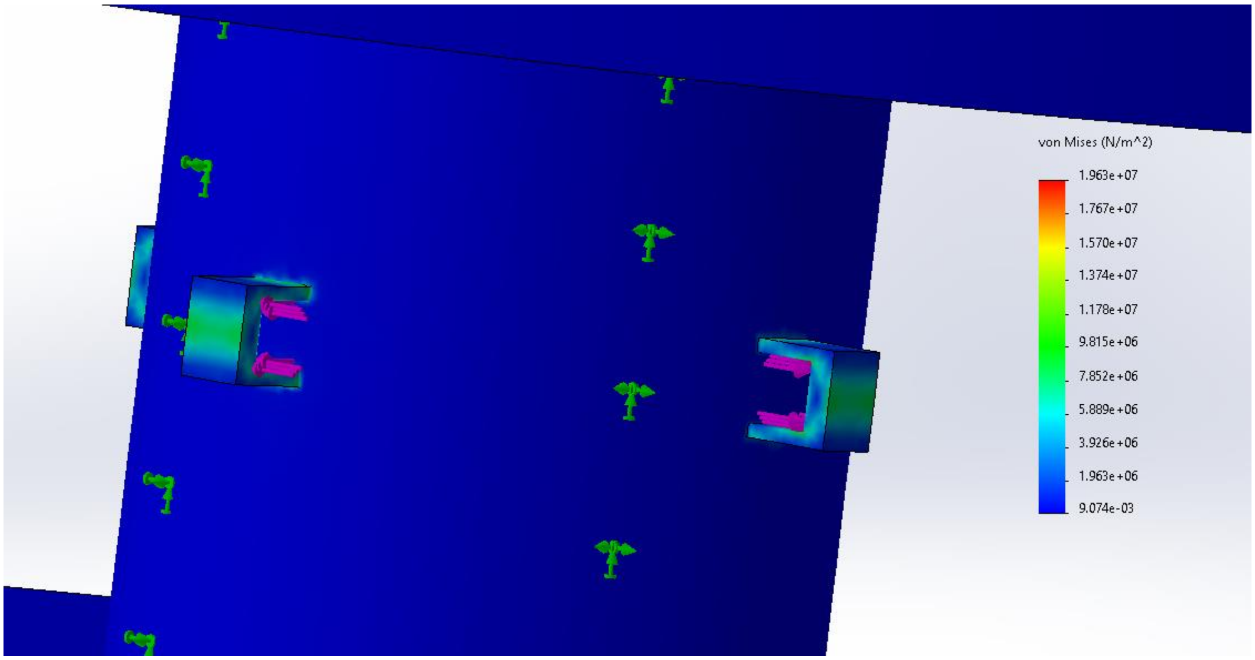

Figure 84 FEA Zoomed in Photo on Inner Hook

Figure 84 shows the hooks on the hub with a force of 40 Newtons applying outward and 1.6 Newtons perpendicular to it. These values represent the normal and tangential forces acting on the hooks. The equations for the normal and tangential forces are given in equations 14 and 15. This results in a maximum stress of 19.6 MPa which results in a factor of safety of 1.6. This is a good factor of safety for this part as the forces through the net are difficult to simulate and thus a high factor of safety ensures the hooks will not break during deployment.

$$F_n = m\omega^2 r_G \tag{14}$$

$$F_t = m\alpha r_G \tag{15}$$

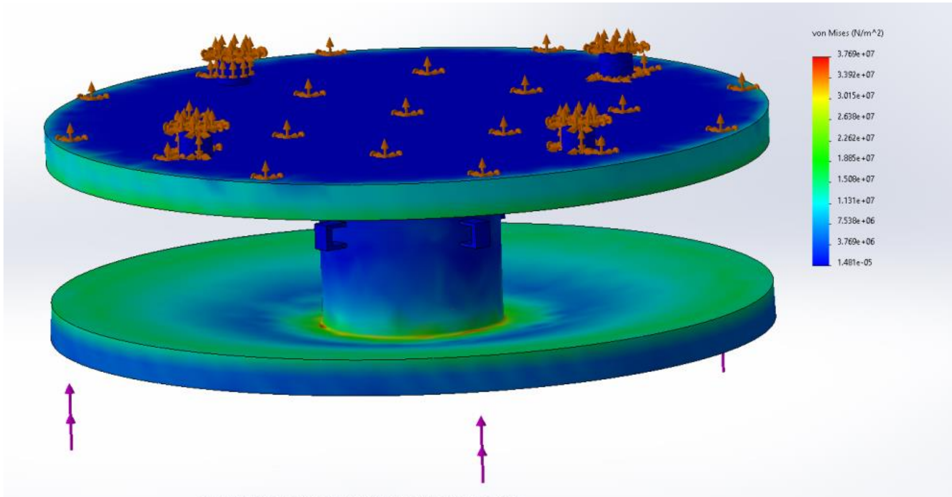

Figure 85 FEA On Net Hub for Spring Forces

This FEA was conducted to verify the hub would be able to withstand the forces of the springs. The loading from the springs was calculated at 326.4 N. This force was then spread around edges on the top surface of the hub as 400 N. This was done to simulate the reaction force from the pins acting on this top surface and to give a larger factor of safety. This was done because the bottom plate was to be printed with a larger infill on the 3D printer. This would cause the bottom plate to thicker and henceforth stronger and thus not going to break unlike the top plate which had a lower in fill. Finally, the lowest factor of safety according to the FEA analysis was approximately 1.47. This factor of safety was acceptable for the project as it was only a prototype that would be tested a few times.

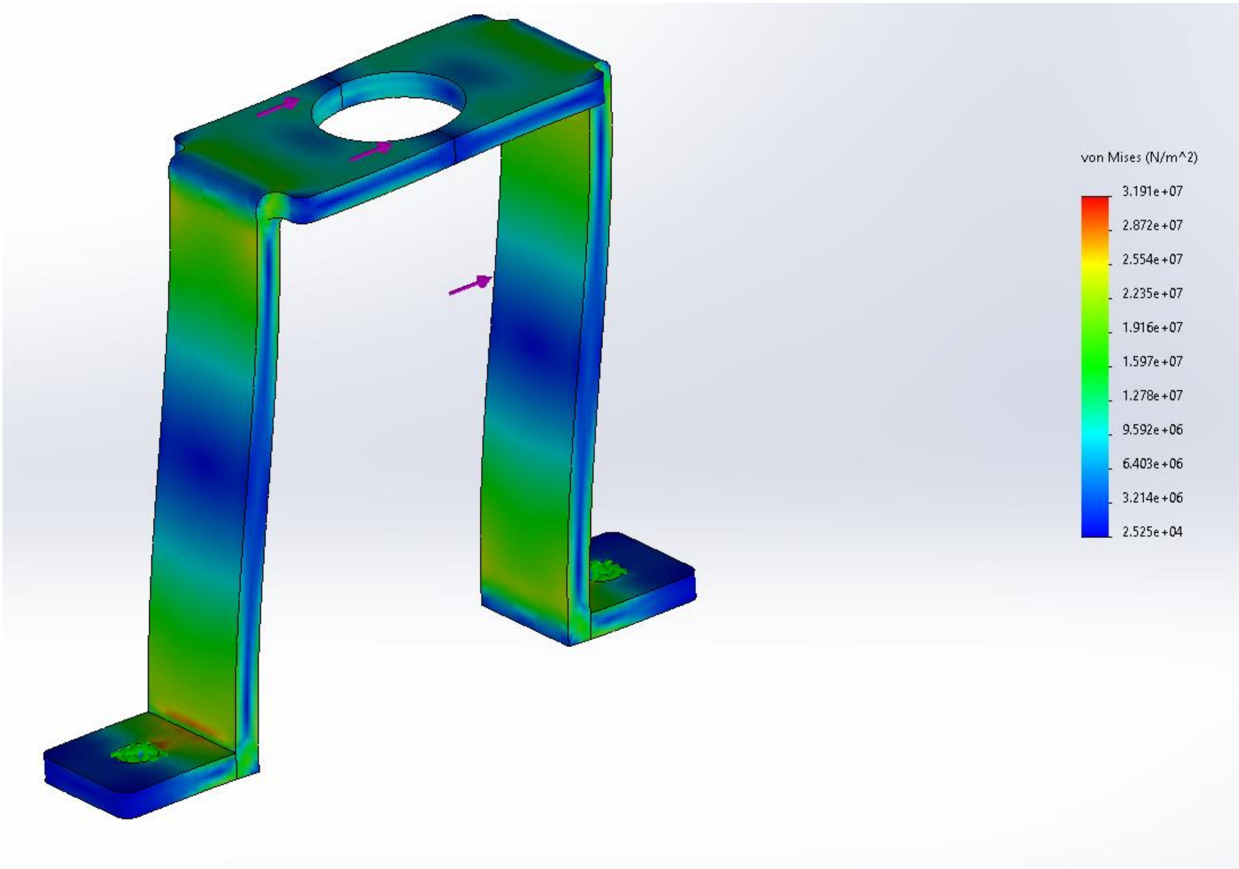

Figure 86 FEA on Motor Mount in Weak Direction

The Figure 86 shows the motor mount with a 17.5 newton force in what was determined to be the weak direction. The strong side was determined by observing the bending stress equation and recognizing that that the distance y is larger than the inertia for the so-called strong direction. Thus, the above was considered the weak direction with the point of interest being the bend in the base where it connects to the leg. For reference the bending stress is seen in equation XX. The maximum stress for this load was 31.97 Mpa which gave a safety factor of 1.03. This was considered ok as the top section of the project (outer cylinder, hub, net, hanging masses, pins (two), and springs) were significantly less than the presumed 3 kg used to calculate the 17.5 newtons.

$$\sigma_{bending} = \frac{my}{I} \tag{16}$$

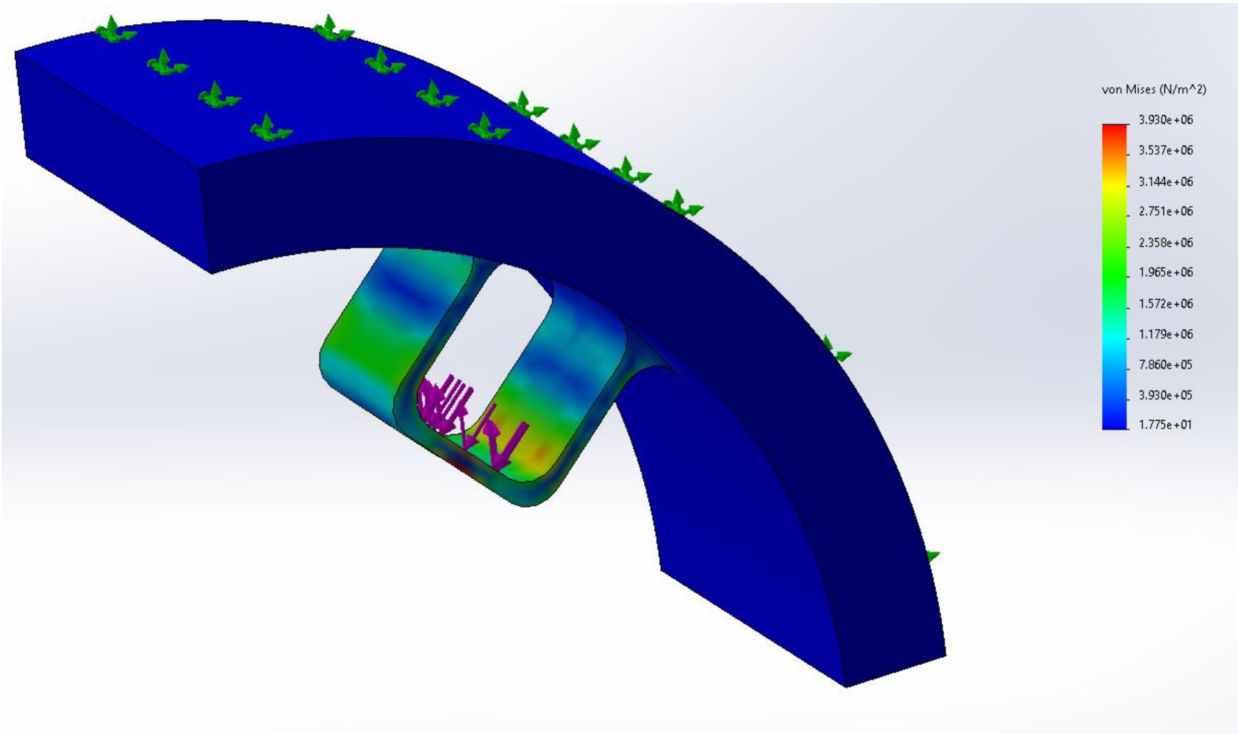

Figure 87 FEA on Hanging Mass Hook

Figure 87 shows the hanging mass with both a tangential and normal force applied. These were the same as earlier on the hooks for the hub. This gave approximately 4 Mpa for the highest possible stress. This resulted in a safety factor of 7 for the hanging masses. This was accepted as these pieces would be detaching from the project in testing and it was important to ensure they would not break off. Thus, the high safety factor was used.

Appendix M Conservation of Angular Momentum Equations

The Institution of Royal Institution Technology was able to derive equations for the initial angular momentum (equation 17) and final angular momentum (equation 18) of the net (m_n), hub (m_h), and the hanging mass (m_{hm}) with units of kg [11]. r_o is the initial radius (.1 m) and L is the length of one side of the net (1 m). The angular velocity has units of $\frac{rad}{s}$. Since angular momentum is conserved in this system, these two equations can be set equal ($L_{initial} = L_{final}$). The ratio of angular velocities such that $\frac{\omega_{fin}}{\omega_{init}}$ was solved for as shown in equation 1. While the units are difficult to understand in equation 1 we can see in equation 17 and equation 18 that a ratio of the units would cancel leaving the ratio unitless.

$$L_{initial} = (\frac{m_h}{2} + m_n + 4m_{hm}){r_o}^2\omega_{init} \tag{17}$$

$$L_{final} = (\frac{m_h}{2}\left(\frac{ro}{L}\right)^2 + \frac{m_n}{6} + 2m_{hm})L^2\omega_{fin} \tag{18}$$

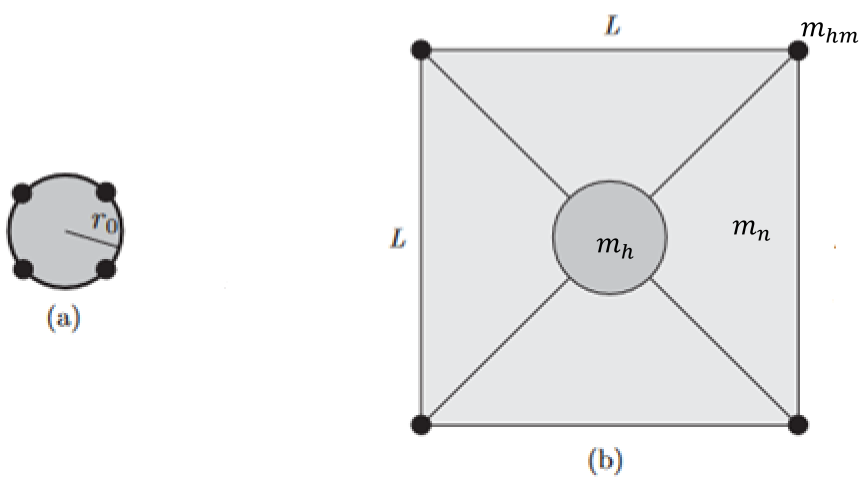

Figure 88 The Diagram Depicting the Various Lengths and Masses [11]

Appendix N FMEA

Table 7 FMEA for Prototype

Item	Failure Modes	Cause of Failure	Possible Effects	Level	Possible Action to Reduce Failure Rate
Net	Does not Deploy Properly	Net gets tangled on the deployment	Complete failure of Deign	Critical	Research correct folding patterns
Launching Mechanism	Does not properly launch the net	Lack of design work	Would cause the net not to deploy correctly	High	Test the launching components before final build
Electrical system	Electronic devices do not work	Improper wiring	The whole system does not function or functions improperly	Medium	Verify that the electrical connections are strong and test for voltages
Release Mechanism	Does not release the system	Improper calculations	The system does not deploy and fails	High	Test the deployment system separate of the whole system and review the calculations multiple times before implementation
Motor	Does not generate the proper angular velocity	Incorrect sizing of the motor	System does not spin fast enough to achieve net deployment or activate the release mechanism	Low	Verify all equations and test the motor when available