Final Report
ME 450
Team 19
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US-2 Drone Drop Tether Project

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EXECUTIVE SUMMARY

Foreword. Vayu Aerospace has commissioned our design team to develop a drop tether system for their US-2 drone prototype. The US-2 prototype is an autonomous aerial surveillance drone.

Design Problem. Law enforcement agencies and surveillance services utilize camera-equipped drones for both surveillance and pursuit. Current solutions to improve the relatively short drone flight time, such as tethers, result in the inability to transition from surveillance to pursuit in a timely manner. Our goal is to engineer a solution to quickly and safely transition tethered drone surveillance into target pursuit.

Requirements and Engineering Specifications. Through our own research and benchmarking, along with conducting an interview with Vayu and considering the contextual factors, we have drafted a list of requirements for the design as well as engineering specifications. Notable members of this list include the requirements of safety within the tether drop, adhering to maximum takeoff weight regulations, and enabling as much altitude as possible.

Concept Selection and Alpha Design. In the concept selection phase, a clear process narrowed down 61 initial design ideas to the top three viable concepts for each function, determined via our functional decomposition, through analysis using Pugh charts and an Analytical Hierarchy Process. The top concepts were chosen for our alpha design, and further iterated on for our final design.

Design Testing and Analysis. First-principles calculations and empirical tests were done to assess our alpha design's proficiency to meet the design problem requirements. Several iterations of the design were completed based on the results of the analysis.

Build Prototype. Information from our engineering analysis was used to create a build prototype for the tether connection. Verification and validation tests were performed on this prototype and it was presented at the design expo.

Verification and Validation. Several verification plans have been tested to verify our requirements and specifications, while additional tests still need to be completed. We created plans for Vayu to execute in their own time. Validation plans have been created to ensure our design is solving the correct problem, this includes communicating with our sponsor and incorporating their feedback into the next design.

Recommendations. Recommendations to improve the design include more iterations on the drop box, exploring higher-end components, a mechanism to physically detach the tether connection, more system testing, and working on the reel design.

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PROJECT ABSTRACT

Highly capable, camera-equipped drones are currently used by many law enforcement agencies and surveillance services for both general surveillance and target pursuit. One current option is the US-1 Quadcopter shown below in Figure 1, a leading drone solution in the surveillance market. The creator of the US-1, Vayu Aerospace, is currently developing the US-2 as a successor to the US-1 model. One underserved capability they have identified in the market is the use of a detachable tether system to prolong flight while tethered and still allow quick pursuit due to a detachable mechanism. This project aims to design this detachable tether system and create a proof-of-concept prototype.

Figure 1. The US-1 Quadcopter Drone[1]

PROJECT INTRODUCTION, BACKGROUND, AND INFORMATION SOURCES

Project Introduction

The US-2 Drone Drop Tether project is aimed at developing a unique solution within the surveillance drone industry—a disconnectable tethered drone. The sponsor, Vayu Aerospace, has commissioned our team of engineers to address this challenge, motivated by the potential to offer a groundbreaking capability that fills a gap in the market. The development of a drone capable of disconnecting from its tether in flight is attractive because it aligns with Vayu's customers' demands, improves Vayu's sales prospects, and enhances the drone's versatility in surveillance and rapid pursuit scenarios.

The major objectives and goals of the project, as designated by Vayu in an interview[2], include creating a system that enables a drone to hover indefinitely at a target height of 100 feet and disconnect from the tether on command. The tether itself should deliver approximately 2500 watts of power to ensure a net zero decrease in the battery state of charge (SOC) during use. Additionally, the system should be reusable, durable in adverse weather conditions, and easily integrated into Vayu's new US-2 drone prototype. A successful project outcome will involve delivering a first proof-of-concept prototype to Vayu who will ultimately own the intellectual property that we develop during the course.

Problem Statement

After meeting with Vayu to discuss their requirements for this project as well as conducting independent benchmarking, we have written a problem statement to guide the remainder of the design process. The statement is as follows:

Law enforcement agencies and surveillance services utilize camera-equipped drones for both surveillance and pursuit. Current solutions to improve the relatively short drone flight time, such as tethers, result in the inability to transition from surveillance to pursuit in a timely manner. Our goal is to engineer a solution to quickly and safely transition tethered drone surveillance into target pursuit.

Background and Benchmarking

Previous work on this project completed by Vayu has involved recognizing the potential profit of adding this feature to their US-2 drone prototype. Moving to current solutions and possible competitors, some other companies have released tethered drones, however, none offer a detachable tether system that allows the drone to transition seamlessly from surveillance to pursuit. One example of a tethered drone competitor is the Orion 2.2 TE Tactical Tethered Drone created by Elistair shown in Figure 2 below.

Figure 2. Orion 2.2 TE Tactical Tethered Drone created by Elistair[3]

The Orion drone can hold a payload of up to 11 pounds, can reach an altitude of ~328 ft (100 m), and boasts a 50-hour flight time while tethered. The key issue with previous solutions, such as the Orion drone, is the lack of a mechanism for detaching the tether while in flight. Through talks with customers at security expos, Vayu has heard that customers of tethered drones have a strong desire for such a detachable system, as it would enable drones to pursue identified targets immediately when spotted without the need to land the drone, disconnect the tether, then take off again[2]. Having a detachable tether system allows for the fastest identification to pursuit time, even faster than using a second drone for pursuit, for instance. This capability would be a huge competitive advantage for the US-2 drone product.

Looking at a different type of solution, there are aftermarket tether kits available at the consumer level that are designed to replace the standard drone battery with the ground power supply and tether system. This solution does not supplement the battery's power; rather it plugs directly into the drone operating system, limiting the ability to land, disconnect the tether, and then take off again for target pursuit. The kits available at the consumer level, like the FoxTech T3500[4], advertise a 3500 W continuous power source on a ~328 ft (100 m) tether to a power supply that replaces the drone battery, and the FUSE Tether System[5] supplies 2200 W continuous power over 400 ft. Both feature a winch-like system to provide tension to the power cord to mitigate slack, as well as acting as the storage system when not in use. This informs that our current goal of ~2500 W power supplied to the drone over a 100 ft power cord is realistic compared to other available tethers on the market, since both wattage and length of cord are within or below the maximum range of both respective values. In fact, the three systems above - the Orion drone and the FoxTech and FUSE tether kits - provide a tether range of more than three times our current goal, indicating the 100 ft goal may be too low to be a competitive product. These kits also show common trends and features like the cord tensioner which are somewhat standard commodities within the market, and as such we should consider targeting the needs they meet in our design.

Looking into the connection mechanism for our design, there are lots of possible connectors on the market today. Figure 3 displays five different disconnectable electrical connectors.

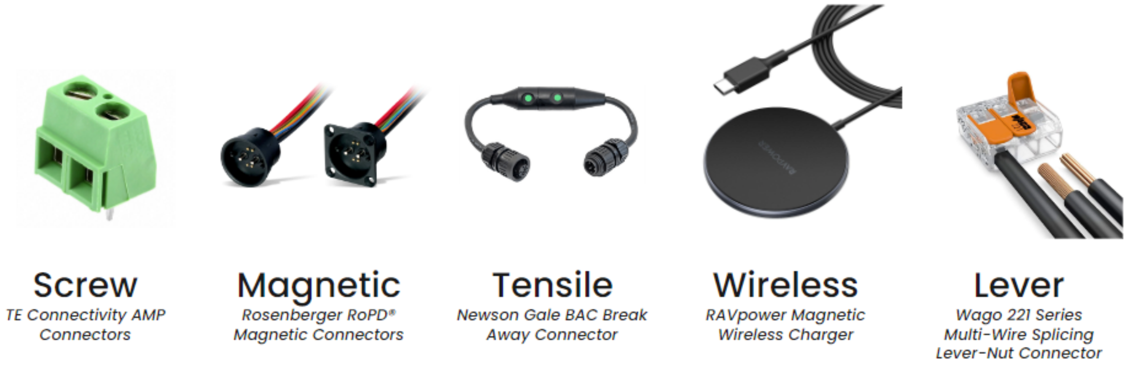


Figure 3. Disconnectable electrical connector types[6-10]

Using the connectors as a benchmark, we analyzed these connection types against our engineering requirements and specifications. For this ranking, we looked at six of our requirements that applied to the connection mechanism. These requirements and specifications are compared to each of the connection types shown above. We compared the designs using a Pugh chart with the screw connector type as the baseline. The results are shown below in Table 1; the full list of requirements and specifications can be found in Table 2 on page 16.

Table 1. Pugh chart of the five disconnectable electrical connector types

Requirement	**Specification**	**Screw**	**Magnetic**	**Tensile**	**Wireless**	**Lever**
Drops tether only upon command	0 unintended tether drops during normal use	-	-1	-1	-1	1
Fast disconnect time when ready to detach	Detaches in < 3 seconds from time of command sent to mechanism to release from drone	-	1	1	1	1
Durable	Can survive ≥ 50 drop uses	-	-1	-1	-1	1
Reusable	≥ 100 actuations before failure ("open" or "close") 0 single use parts	-	0	1	1	1
Weather resistant	Rating of IP67[11]	-	-1	-1	-1	0
Easy to attach and detach	0 tools required to operate ≤ 3 steps to attach or detach	-	1	1	1	1
	Total Score:	0	-1	0	0	5

Based on the Pugh chart in Table 1, the best connector type was a lever connector with a score of 5, outperforming the baseline of the screw connector in five of the six requirements. The worst design was the magnetic connector with a score of -1. We recognize that the Pugh chart above shows us a potential preliminary design concept, but is not completely accurate without more data-driven research. Using this information as a baseline, moving forward into the concept generation and concept selection phase, we will tentatively look into designs using a lever connection point.

Summary of Information Sources and Standards

To support this project, a variety of information sources - both primary and secondary - have been and will be consulted, including stakeholder interviews (Vayu Interview[2]), Federal Aviation Administration (FAA) Guidelines (FAA 14 CFR Part 107[12]), literature reviews (Learning Blocks[13]), competitor drone analysis (Orion 2.2 TE[3]), after-market tether kit analysis (FoxTech T3500[4], FUSE Tether System[5]), test data (Vayu Test Data[14]), and relevant engineering standards such as ISO 24356:2022 (General requirements for tethered unmanned aircraft systems[15]) and the Occupational Safety and Health Administration (OSHA) 1910.28(c)(1-3) (Duty to have fall protection and falling object protection[16]).

Stakeholder interviews offer valuable insights into our project, enriching our understanding of the task at hand and guiding our requirements and specifications. The guidelines established by the FAA describe the regulatory framework governing small unmanned aircraft systems. Adhering to these guidelines is crucial to ensuring that our design complies with the requirements and restrictions. Furthermore, our project benefits from the wisdom gleaned from literature reviews, which explain design processes and concept generation strategies. This knowledge relates to our project plan and facilitates the analysis of various concepts. A comprehensive analysis of competitor drones and an examination of aftermarket tether kits serve to benchmark our design against existing industry standards. The utilization of test data obtained from Vayu is instrumental in our analysis and testing of specific components and design ideas, particularly when interfacing with their flight data. Also, it is imperative that our design adheres to the requirements stated by the ISO for tethered unmanned aircraft systems[15]. Compliance with these standards is essential for the usability of our design. Additionally, the OSHA guidelines provide specific regulations pertaining to falling objects, which is crucial in ensuring tether safety[16]. These sources collectively provide a comprehensive foundation for the project, ensuring a well-informed and thorough approach to solving the disconnectable tethered drone problem.

DESIGN PROCESS

In this section, we will discuss the design framework we will be using throughout the project and the respective design phases. We will dive into problem definition, concept exploration, and solution development and verification, along with further guidelines we will follow throughout.

The ME 450 Design Framework

During the initial stage of our design project, we carefully considered what engineering design process we would adhere to, ensuring that it would effectively help us achieve our goals. After consideration, the ME 450 design framework was chosen to serve as our primary source. This process consists of three distinct stages that are relevant for our project: Problem Definition, Concept Exploration, and Solution Development and Verification (Need Identification has already been completed by our sponsor and Realization is out of scope for our project[13]). However, it is crucial to note that these stages are not linear but rather iterative, allowing us to revisit and refine our work as needed. This framework is shown in Figure 4 below.

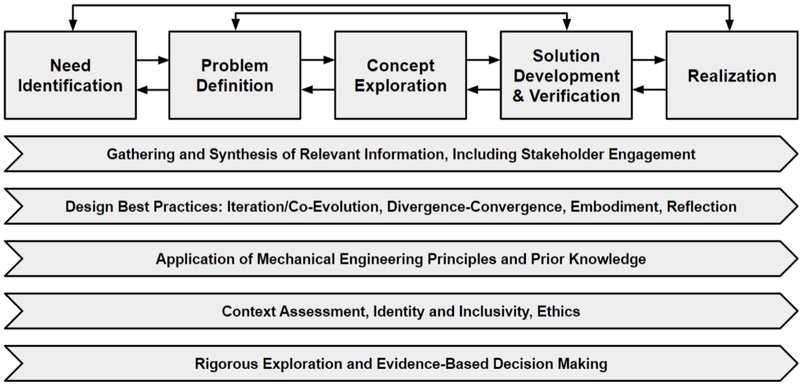


Figure 4. ME 450 Design Framework[13]

Problem Definition

In the problem definition phase, the focus is on understanding and framing the problem, eliciting stakeholder needs, and developing clear engineering requirements and specifications. Activities in this phase include conducting interviews, literature reviews, benchmarking, and more. The goal is to establish a well-defined problem based on genuine needs, articulate individual stakeholder requirements, and create unambiguous, measurable engineering specifications. Our work for the problem definition phase has been summarized throughout this report and is the beginning of our overall design project. The framing and background of our design problem are discussed in the Project Introduction, Background, and Information Sources section of the report starting on page 5. Our analysis of stakeholders and engagement, including a stakeholder map, is shown in the Design Context section of this report starting on page 12. Lastly, our defined engineering requirements and specifications are laid out in the User Requirements and Engineering Specifications section starting on page 15.

Concept Exploration

The concept exploration phase involves generating, developing, and evaluating solution concepts through structured creativity sessions, brainstorming, and using various tools to encourage divergent thinking. The aim is to explore a wide variety of solution concepts that represent divergent thinking and systematically progress from many ideas to the best solution concepts, all backed by evidence-based justification. The majority of this thinking will be documented in Design Review 2 on October 10th, 2023.

Solution Development & Verification

The solution development and verification phase is the final phase, where the focus shifts to developing a detailed design solution that meets our requirements and specifications. This phase incorporates rigorous mechanical engineering analysis, consideration of design best practices, CAD, materials selection, and verification. The outcomes include a detailed design solution, engineering analysis, and evidence-based justification of the solution and its verification. This stage of the process will be documented in Design Review 3 on November 14th, 2023.

Further Guidelines

Throughout the entire design process, several general considerations such as gathering and synthesizing relevant information, rigorous exploration and evidence-based decision-making, design best practices (such as iteration, divergence-convergence, embodiment, and reflection), and the application of mechanical engineering principles and prior knowledge are included. Moreover, the framework underscores the importance of considering context, identity, inclusivity, and ethics during every phase of the design process.

Other Design Frameworks

While the ME 450 design process forms the core of our approach, we have also explored other design process models. Notably, we have considered the National Aeronautics and Space Administration (NASA) Beginning Engineering Science Technology (BEST) Engineering Design Process model[17], which offers a structured approach for students working on design projects. This model involves several stages, including Ask, Imagine, Plan, Create, Test, and Improve. NASA's model is renowned for its clarity and suitability for educational purposes. This model is shown below in Figure 5.

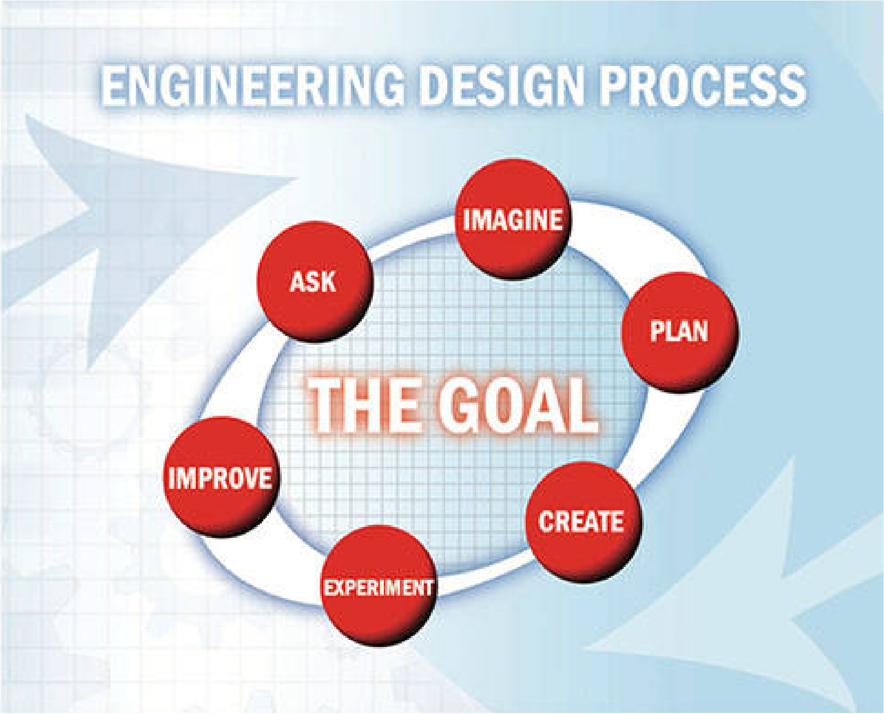


Figure 5. NASA's BEST Engineering Design Process model[17]

Considering the most useful design process models for our project, the ME 450 framework is likely to be our guiding model due to our familiarity with it. However, simpler models like NASA's student model serve as valuable reminders when we need to simplify complex concepts and focus on high-level tasks.

Rapid Prototyping Capabilities

One significant difference in our design process is the availability of cost-effective and rapid prototyping capabilities, primarily through 3D printing at Vayu and in U-M machine shops. This allows us to quickly hash out and evaluate earlier-stage concepts against our specifications. Unlike the standard design process introduced during our course introduction, where prototyping might be more resource-intensive, our approach takes advantage of readily available 3D printing technology to expedite testing, iterate rapidly, communicate design ideas effectively, and identify and address potential flaws early in the design process.

DESIGN CONTEXT

In this section, we examine the broader context that influences our design project, considering various factors like public health, safety, and welfare, as well as global, cultural, social, environmental, and ethical contexts. Our analysis builds on the insights gained from prior learning blocks[13]. It involves careful consideration of the stakeholders involved, the social impact of the project, intellectual property, sustainability, ethical dilemmas, and power dynamics.

Stakeholder Analysis and Engagement

Our project involves numerous stakeholders, each with distinct interests and impacts on the project. Through discussion with our sponsor and our own deliberation, we have come up with a stakeholder map shown below in Figure 6.

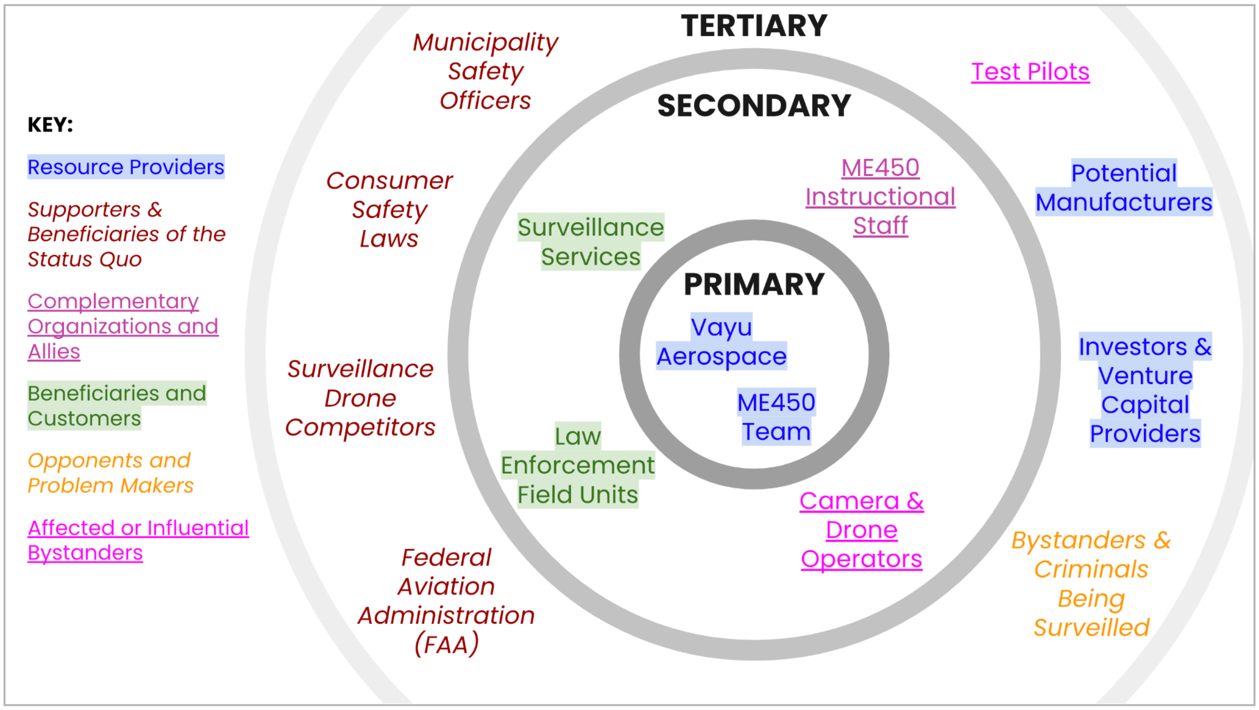


Figure 6. Stakeholder map for the Drone Drop Tether Project

The stakeholders shown in the figure above were organized into primary, secondary, and tertiary groups based on their involvement with our project. The primary stakeholders will have a direct impact on the design, the secondary stakeholders will have a medium impact on the design, and the tertiary stakeholders will have a low impact on the design. For stakeholder engagement, we have only been in contact with Vayu Aerospace so far. They have helped us identify the design problem and offered their help in finding a solution. In the future, we plan to engage with more stakeholders to gain their valuable feedback.

Several stakeholders will be positively affected by our project, including Vayu Aerospace, surveillance services, law enforcement field units, camera and drone operators, test pilots, and investors. These stakeholders will benefit from the enhanced surveillance capabilities and unique detachable tether advantage our project offers. Conversely, the project may negatively affect some stakeholders, such as surveillance drone competitors and individuals being surveilled. For competitors, this unique design will put Vayu Aerospace at an advantage, possibly hurting competitor sales. The surveillance process, while intended for safety, could raise privacy concerns for individuals who may feel their privacy is being invaded. Therefore, it is crucial to carefully address these ethical and privacy considerations.

Social, Global, Cultural, Environmental, and Economic Impact

Our project sponsor, Vayu Aerospace, places a high priority on the social impact as it directly aligns with the core objective of enhancing safety. This product can increase feelings of safety for those individuals under surveillance. On the other hand, as mentioned above, this design product could raise privacy concerns which is an important consideration for our design process. Ensuring we are cognizant of privacy within our testing of the product and making sure the customers of our product will adhere to privacy regulations is crucial.

For the global impact, this design will be a breakthrough in surveillance technology. Having an indefinite hovering drone that can quickly switch to pursuit is something that many companies and customers will want, across many different geographies and countries.

For the cultural impact, our product can both help and hurt. First, it may help to reduce acts of crime and help law enforcement catch criminals. Conversely, our product could be used to harm others by inappropriately conducting surveillance and by targeting certain groups.

More research needs to be done on our part to adequately assess the environmental impact of this project, including but not limited to pollutants and emissions. The drone itself is electric so it does not emit any pollutants while in use, but the power supply for the tether system might contribute to pollution (this is outside the scope of our project). Because the drone will be flying at 100 ft, we suspect it will emit minimal noise pollution for those nearby. Furthermore, our project aims for sustainability through the use of parts that have a long lifetime, particularly the tether and its disconnection mechanism.

As our product is being marketed towards mainly government agencies such as law enforcement, it is in our interest to make it cost effective. This reduces the burden on these organizations which are funded by taxpayer dollars and allows for reinvestment in more diverse applications in the communities it is deployed.

Intellectual Property and Sustainability

The intellectual property generated by our project is vital, as the design represents a unique solution in a niche field. All intellectual property rights are transferred to Vayu Aerospace, our project sponsor, as per our agreement.[18]

Ethical Dilemmas

The ethical dilemmas we anticipate are privacy infringement and the safety of the tether detachment. For privacy infringement, as stated above, surveillance raises privacy concerns, potentially infringing on the public's privacy. We will manage this by implementing privacy guidelines and adhering to applicable laws and regulations. The safety of bystanders and users during the tether detachment process is a major concern during tether detachment. We will address this by designing fail-safes and conducting thorough testing to minimize the risk of injury. Our personal ethics align with the professional ethics expected by the University of Michigan and future employers, ensuring we maintain high ethical standards throughout the project.

Inclusivity and Power Dynamics

As a team, we have discussed our individual responses to inclusivity issues and strategies to address them. To address potential inclusivity problems not yet identified, we will maintain open and regular communication within the team, encouraging everyone to voice concerns and ideas. Additionally, we will remain receptive to feedback from diverse perspectives, ensuring inclusivity is a fundamental aspect of our project. For the power dynamics of our team, we all work very well together. We each have our own strengths that will help us complete certain tasks. We also keep a high level of communication and ensure everyone is doing their part.

USER REQUIREMENTS AND ENGINEERING SPECIFICATIONS

In this section, we will delve into the requirements for the design project and how we have translated them into precise engineering specifications. To facilitate comprehension, we have included a table that lists our requirements and their associated engineering specifications along with justifications below in Table 2.

Process of Determining Requirements and Specifications

The first step in establishing our engineering targets was to hold an initial meeting with our project sponsor. This meeting allowed us to gain an understanding of what the sponsor saw as the requirements and objectives of the design project. From this meeting, we learned about the emphasis on having a net-zero decrease in the battery of the drone when tethered and the goal of enabling as much altitude as possible given weight and power constraints. Additionally, we conducted an analysis of related and competitive products and solutions in the surveillance drone industry to ensure that our engineering targets aligned with industry standards and customer expectations. The respective specifications for the requirements outlined to us by Vayu were set based on the values they suggested as desirable in our interview.

Prioritization of Requirements and Specifications

Our project requirements have been systematically prioritized in Table 2 below, with the most critical requirements positioned at the top. We determined this prioritization based first on which must be fulfilled for the product to adhere to all laws, such as workplace safety as outlined by OSHA[16] requiring a barricaded area and meeting the FAA weight limit for drones of 55 pounds[12] to be classified as such. Then we looked at which requirements made the project a worthwhile addition to the US-2 drone product, such as enabling as much altitude as possible, because if the drone could not fly high with the tether attached, there would be no reason for the tether system. Then we looked at which requirements must be met for the product to function. These are the requirements of ensuring a net zero battery decrease allowing indefinite flight, having zero unintended tether drops during normal operation, and having a fast tether disconnect of less than three seconds. Lastly, we considered “nice-to-have” features that will enhance the usability, durability, and longevity of the design but are not imperative for the design to function properly.

Table 2. Design requirements and associated engineering specifications and justifications

Rank	Requirements	Specifications	Justification
1	Safety of tether drop	Entire system, including drop, operates within a barricaded 20 ft diameter circle	The falling cord and tether connection system pose a great safety risk, so by wearing head protection and barricading the area into which objects fall, OSHA guidelines can be met[16]
2	Adhere to maximum takeoff weight regulations	< 55 pounds	Drones are labeled as “small unmanned aircraft” by FAA if the drone and payload does not exceed 55 lbs[12]
3	Enable as much altitude as possible	Tether length ≥ 100 ft	100 ft is provided by our sponsor as an initial goal but is below benchmarked tethered drones. After a proof of concept we can aim to increase length
4	Drone should stay fully charged while in use with tether	Net zero decrease in battery State Of Charge (SOC) during use	Net zero battery decrease allows for indefinite flight while tethered, a key use case for the tether system
5	Drops tether only upon command	0 unintended tether drops during normal use	Limiting unintended drops of the tether ensures the design is highly reliable
6	Fast disconnect time when ready to detach	Detaches in < 3 seconds from command sent to mechanism to release from drone	Tether detach needs to be faster than a takeoff, landing, and take off again. Detach also must be fast enough to maintain sight of the target
7	Durable	Can survive ≥ 50 drop uses	Estimated target to demonstrate sufficient durability and maintain usability
		Maintains flat surface finish between steel plate and magnets. (Class B or better [19] and 3.2 µm Ra[20])	
8	Reusable	≥ 100 actuations before failure (“open” or “close”)	Estimated target to demonstrate reliable and sustainable connection/disconnection from drone
		0 single use parts	
9	Unobtrusive to drone operation, including sensors, motion, and camera	< 1% affect on drone magnetometer sensor	Tether system should act as a supplementary system to the nominal operation of the drone; should not interfere besides acting as payload
		360° drone motion in yaw axis and ≥ 20° of pitch and roll	
		≥ 180° horizontal motion of camera with unobstructed view and ≥ 90° vertical motion of camera with unobstructed view	
		Failure mode of the system is disconnection of the tether	
		< 5 lb. onboard components	

Rank	Requirements	Specifications	Justification
10	Weather resistant	Rating of IP67[13]	The tether connection should function in rainy or dirty conditions
11	Cord cannot exceed a target temperature	When in use, the temperature must be ≤ 15°C more than the temperature of the drone	The tether system should not add thermodynamic strain to the drone and cause other potential failure modes
12	Fast cord storage time	< 60 seconds	Ease-of-use estimate for users to safely and quickly store the cord
13	Easy to attach and detach	0 tools required to operate	The connection should be simple to use so it can be attached quickly to increase surveillance time
		≤ 3 steps to attach or detach	

CONCEPT GENERATION

Our concept generation phase began with an initial brainstorming session to generate as many ideas as possible. A few strategies were utilized to assist in our brainstorming, such as a morphological chart and design heuristics.

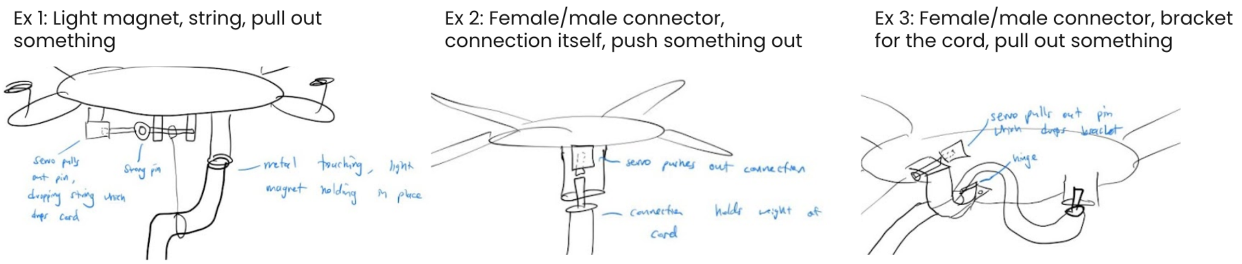
Morphological Chart

First, we employed a morphological chart to assist in generating our concepts. A morphological chart breaks down the overall design into multiple subsystems. Then, multiple solutions are brainstormed for each subsystem. Lastly, these solutions are mixed and matched together to generate a high volume of different designs. One morphological chart we employed broke the design into three sub systems; 1) the cord connection point; 2) the system that would hold the weight of the cord; and 3) the system that would disconnect the cord. This morphological chart is displayed in Table 3 below.

Table 3. Morphological chart for developing initial designs

Sub system:	**Solutions:**		
Cord connection point	Female/male connector	Light magnet	Wireless
Hold weight of the cord	String	Connection itself	Bracket for the cord
Disconnect the cord	Pull out something	Cut something	Push something

This resulted in designs such as the three examples shown below in Figure 7 with three different combinations of solutions to the three subsystems.



Ex 1: Light magnet, string, pull out something

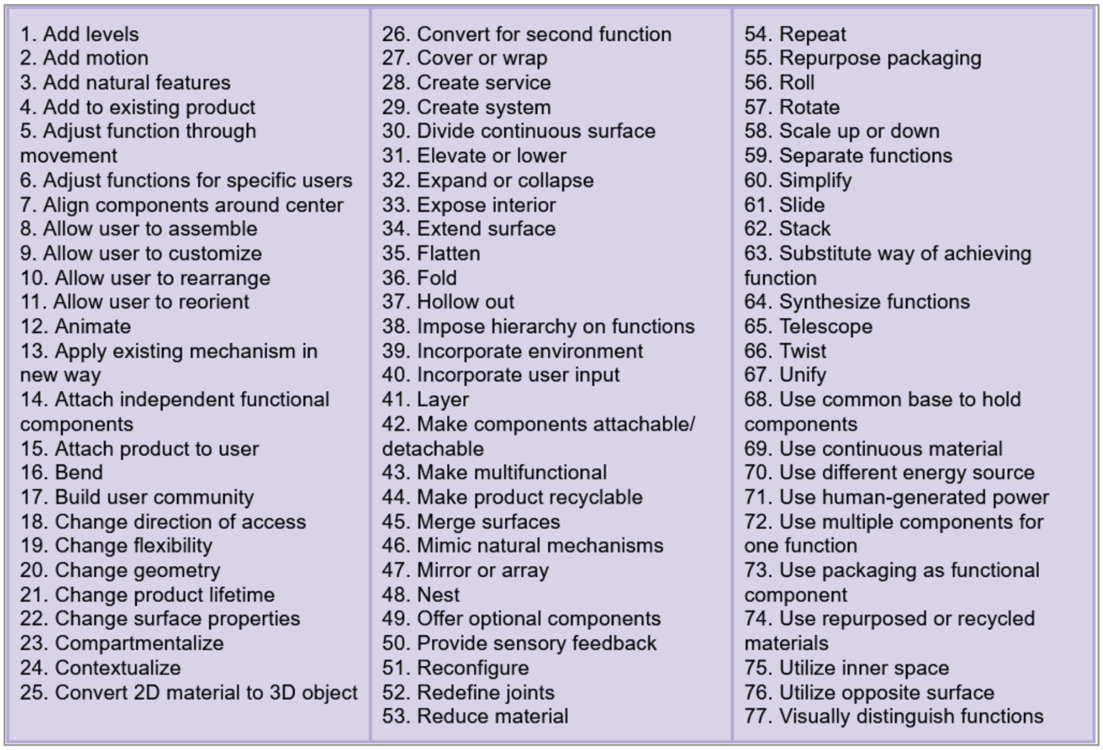
Ex 2: Female/male connector, connection itself, push something out

Ex 3: Female/male connector, bracket for the cord, pull out something

Figure 7. Ideas generated from Morphological chart

Design Heuristics

The second method we employed was utilizing design heuristics. Design heuristics are a list of different modifiers, twists, or instructions for how to change existing designs or create new designs. For example, one design heuristic is “Separate functions”. This is a modifier that can be applied to an existing design to generate a new design idea. We used these design heuristics to build upon our design ideas and to generate new and unique ideas. Figure 8 below shows a full list of design heuristics that we relied upon for helping to generate new ideas.



1. Add levels
2. Add motion
3. Add natural features
4. Add to existing product
5. Adjust function through movement
6. Adjust functions for specific users
7. Align components around center
8. Allow user to assemble
9. Allow user to customize
10. Allow user to rearrange
11. Allow user to reorient
12. Animate
13. Apply existing mechanism in new way
14. Attach independent functional components
15. Attach product to user
16. Bend
17. Build user community
18. Change direction of access
19. Change flexibility
20. Change geometry
21. Change product lifetime
22. Change surface properties
23. Compartmentalize
24. Contextualize
25. Convert 2D material to 3D object
26. Convert for second function
27. Cover or wrap
28. Create service
29. Create system
30. Divide continuous surface
31. Elevate or lower
32. Expand or collapse
33. Expose interior
34. Extend surface
35. Flatten
36. Fold
37. Hollow out
38. Impose hierarchy on functions
39. Incorporate environment
40. Incorporate user input
41. Layer
42. Make components attachable/ detachable
43. Make multifunctional
44. Make product recyclable
45. Merge surfaces
46. Mimic natural mechanisms
47. Mirror or array
48. Nest
49. Offer optional components
50. Provide sensory feedback
51. Reconfigure
52. Redefine joints
53. Reduce material
54. Repeat
55. Repurpose packaging
56. Roll
57. Rotate
58. Scale up or down
59. Separate functions
60. Simplify
61. Slide
62. Stack
63. Substitute way of achieving function
64. Synthesize functions
65. Telescope
66. Twist
67. Unify
68. Use common base to hold components
69. Use continuous material
70. Use different energy source
71. Use human-generated power
72. Use multiple components for one function
73. Use packaging as functional component
74. Use repurposed or recycled materials
75. Utilize inner space
76. Utilize opposite surface
77. Visually distinguish functions

Figure 8. List of design heuristic modification strategies[14]

Concept Generation Results

These two strategies, morphological charts and design heuristics, along with simple brainstorming sessions led us to generate 61 initial design ideas. These greatly ranged in feasibility and overall are a comprehensive list of possible design solutions to our problem. Figure 9 on the next page depicts five concepts from our concept generation phase. These five concepts are widely different and depict many different solutions. These five, in order of the figure below, include a servo which actuates to hold the cord inside the connection point, a wind turbine on the drone, a tall landing pole in which the drone sits on, a small tension band holding the connection point together, and lastly a claw that pulls the connection apart. A larger list of the concepts that were generated can be found in Appendix A.

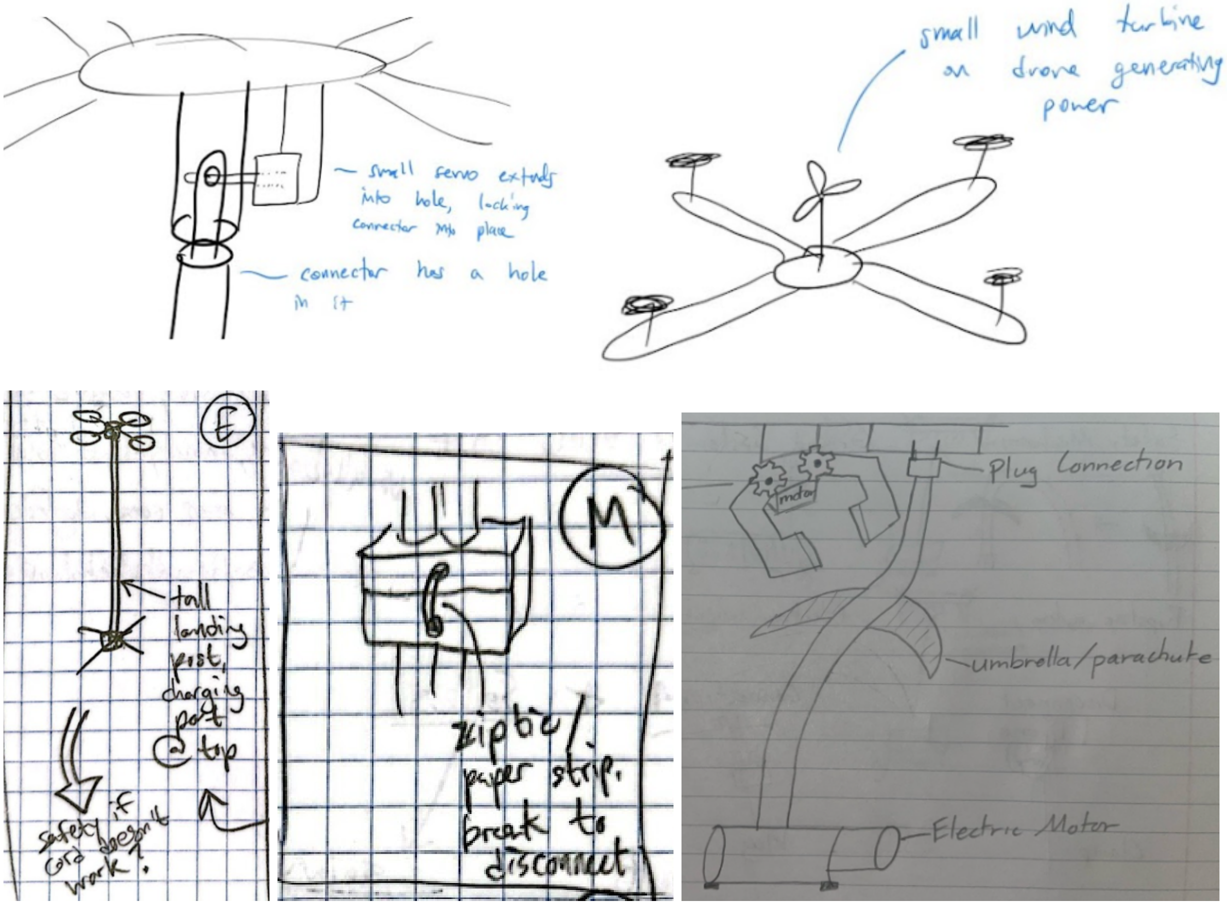


Figure 9. Generated ideas that vary widely in concept

CONCEPT SELECTION PROCESS

Our concept selection phase followed a multi step process as follows. We began by analyzing our large number of initial design ideas for feasibility and removing duplicates. This brought our 61 designs to just 26 designs. After conducting a functional decomposition on our overall design problem, we broke up and categorized the remaining designs by function and took another pass over the designs to determine the top three for each function. Lastly, we conducted a Pugh chart to compare these designs against our requirements utilizing an analytical hierarchy process, resulting in our alpha concept.

First Design Screening

To begin, we took a first pass over our 61 initial design ideas and removed designs that were not feasible either due to technology limitations, such as our design idea of beaming electricity from the ground to the drone, cost, and time. Furthermore, we removed duplicate designs that two or more of us thought of. This first screening also removed any non-cord based designs due to our problem scope being specific to a cord based system. This brought our initial designs down to 26 possible illustrated designs.

Functional Decomposition

Next, we conducted a functional decomposition to break our overall design into four main functions. These four functions are shown below in Figure 10 and consist of the cord selection, actually choosing the cord including length, gauge size, insulator material, etc; the connection point and disconnect method, how the cord connects electrically to the drone and how the cord disconnects upon command; the cord safety mechanism, how do we ensure the dropping of the cord is safe; and lastly, the cord storage system, how do we store and hold the cord.

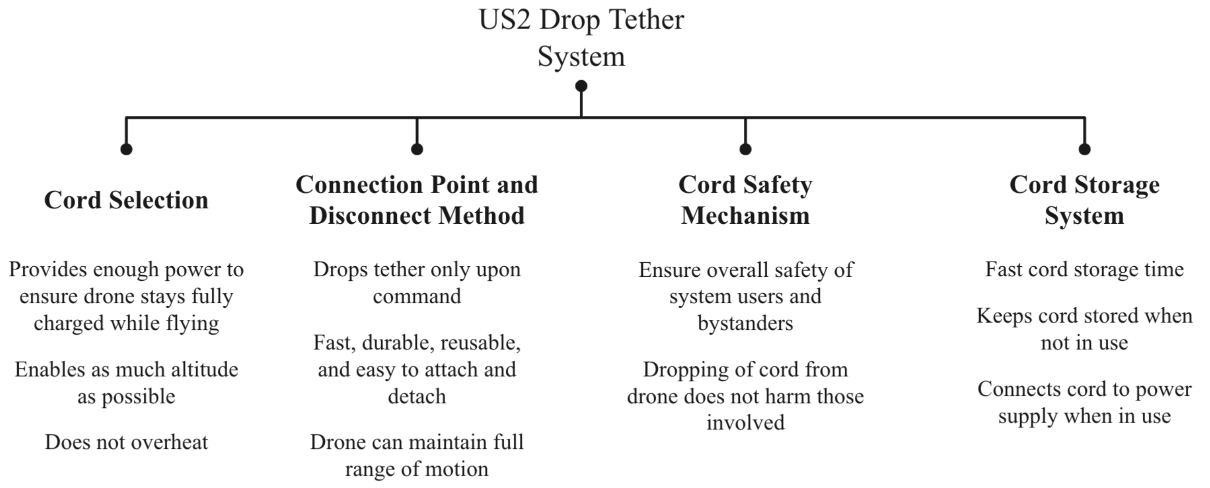


Figure 10. Functional decomposition of the overall design problem

Second Design Screening

Utilizing this functional decomposition, we broke up each design into the different specific functions it was solving and then grouped these individual aspects by function. We only did this for the three categories of connection point and disconnect method, cord safety mechanism, and cord storage system, as cord selection is a more analytical process and does not require different design drawings or ideas. During this step, we realized our initial illustrated designs largely encompassed the connection point and disconnect method, but there were very few that also had solutions for the cord safety or cord storage. To remedy this, we conducted further brainstorming for these two functions. This categorization resulted in 20 specific designs for the connection point and disconnect method, 6 designs for the cord safety mechanism, and 8 designs for the cord storage system. Next, we set out to determine the top three designs in each functional category. To do this, we analyzed the designs across the requirements that applied to each of the functions.

Connection Point and Disconnect Method. Starting with the connection point and disconnect method, we analyzed the designs against the requirements that applied to this specific function. We compared these designs qualitatively to determine which three we found to best fit the requirements, keeping in mind the requirement rankings. During this stage, we also redrew these top three designs, iterating slightly on the initial illustrations, and fleshing out any assumptions or oversights. This resulted in the three designs shown below in Figure 11 depicting the tensile design, Figure 12 depicting the electromagnet design, and Figure 13 depicting the pin design.

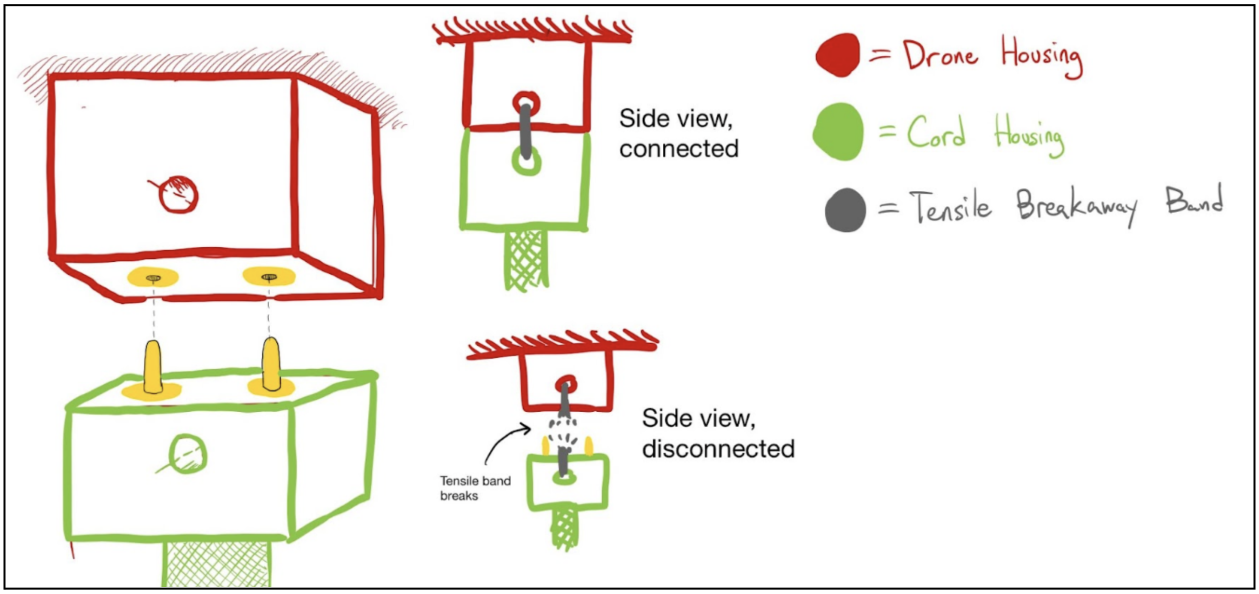


Figure 11. Tensile design in which a small tensile band which is rated for a certain force is holding the electrical connection together. When the drone applies a force higher than the rating, such as when the cord is locked and the drone attempts to fly higher, the band breaks, disconnecting the cord

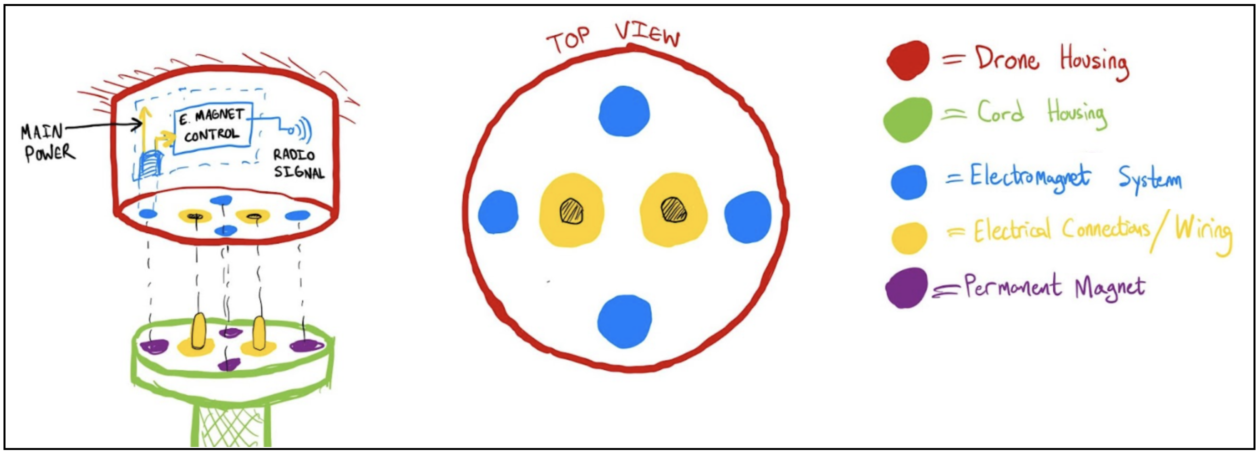


Figure 12. Electromagnet design in which the electrical connection is held together by four electromagnets that can be remotely powered off to allow the cord to disconnect and fall

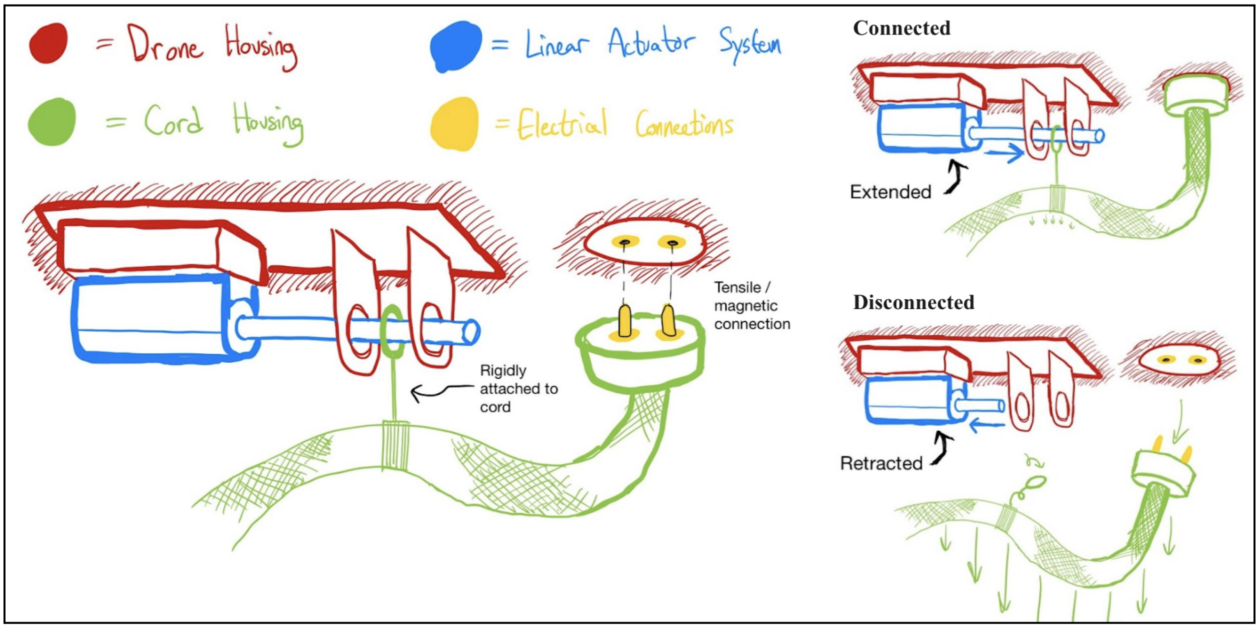


Figure 13. Pin design in which an actuating pin or bar is extended holding a small ring which is then attached to the cord via a strong string. When the actuating pin/bar retracts, the ring slides off allowing the cord to fall which also disconnects the light electrical connection.

These three designs were chosen as the top three due to their simplicity, reliability, durability, and reusability. Furthermore, another consideration that was brought up was the aspect of failure modes. For instance, if the drone is to go haywire, it would be better for the connection to disconnect before the drone crashes due to pulling on the cord. This consideration is present in all three of these above designs, as the tensile band can snap, the electromagnet can disconnect with enough force, and the string can break.

Cord Safety Mechanism. Moving on to the cord safety mechanism, we performed a similar analysis as above, comparing the designs for this specific function against the requirements to qualitatively determine the top three designs. This resulted in the three designs shown below in Figure 14 depicting the parachute design, Figure 15 depicting the airbag design, and the last design being enacting a large radius in which individuals are instructed not to enter with the drone and cord system in the center.

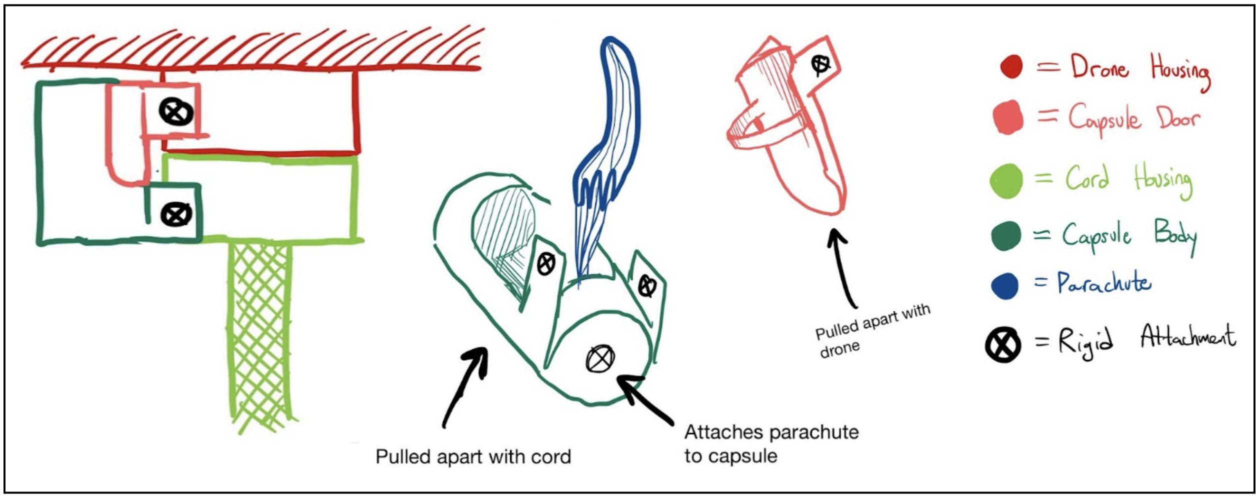


Figure 14. Parachute design in which a capsule housing is broken into two parts, the body rigidly attached to the cord and the door rigidly attached to the drone. When the cord disconnects, the capsule splits apart and the loop on the capsule door pulls the parachute out of the capsule body, deploying the parachute.

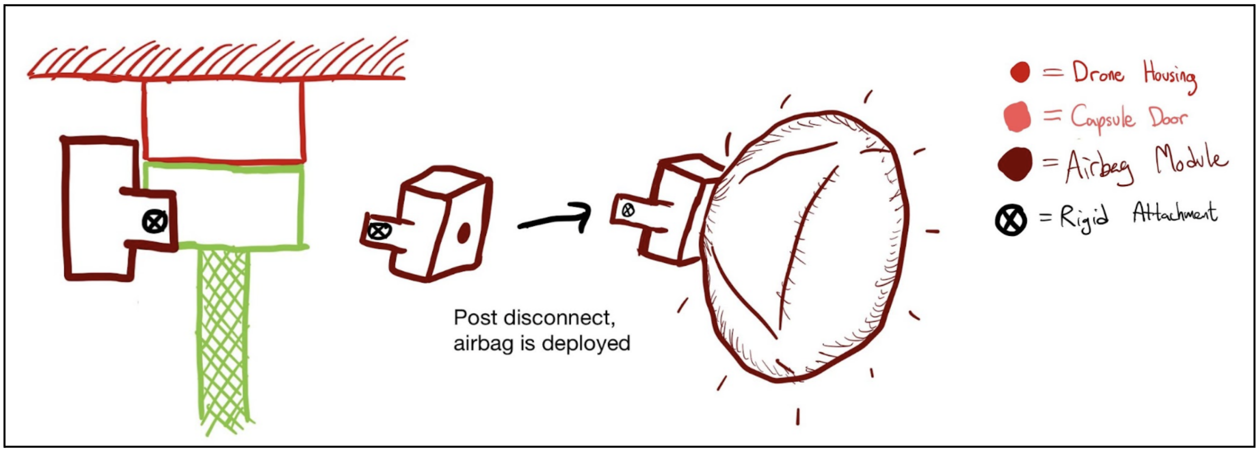


Figure 15. Airbag design in which an airbag system is rigidly attached to the cord. When the cord disconnects and experiences high acceleration, the airbag deploys, lessening the impact on the ground.

Cord Storage Mechanism. Lastly, for the cord storage system, we again performed a similar analysis resulting in the three designs shown on the next page in Figure 16 depicting the hand crank reel design, the motorized reel design, and the spring and ratchet reel design.

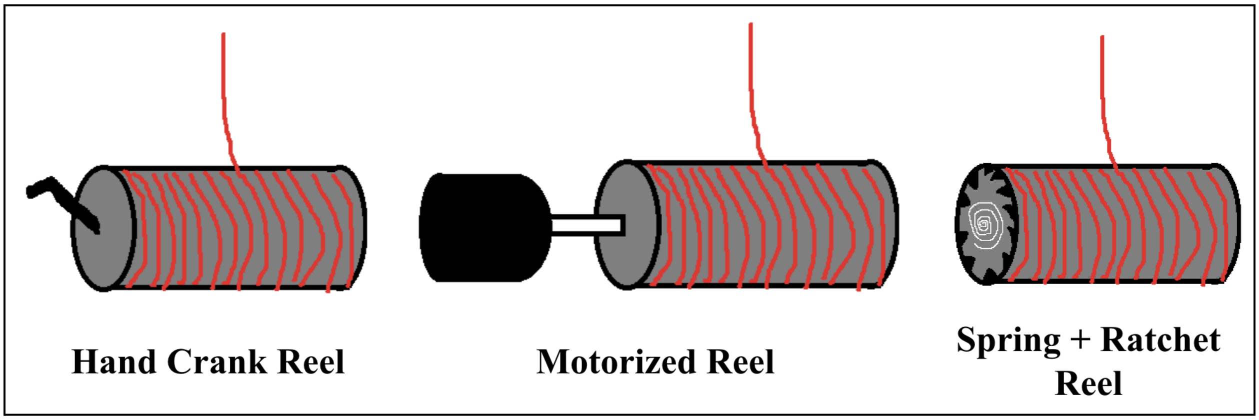
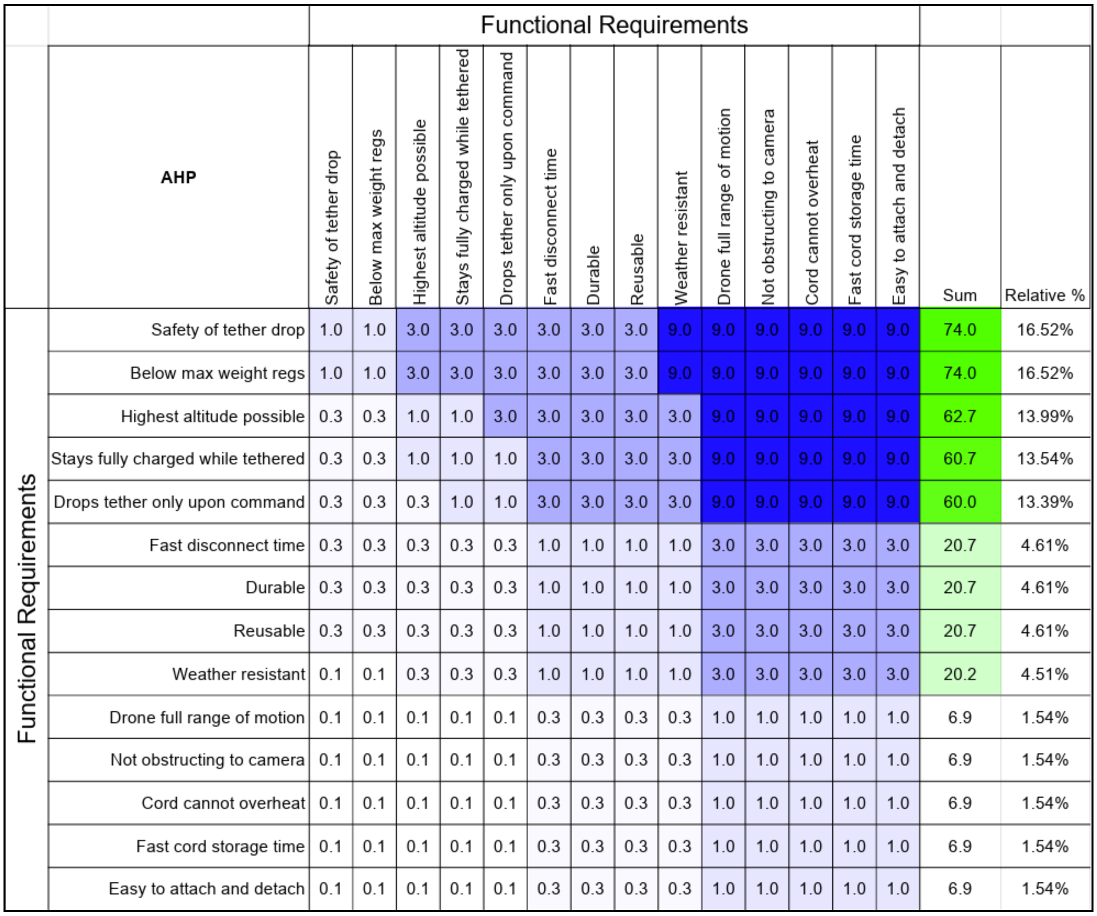


Figure 16. Cord storage system designs

After generating our top three designs for each functional category, except for cord selection, we conducted an analytical comparison to find the best design in each category based on our requirements.

Analytical Hierarchy Process

First, we needed to know the relative weightings and relationships between our requirements. To do this, we conducted an Analytical Hierarchy Process[21] (AHP). An AHP consists of listing our summarized functional requirements and comparing them against one another in terms of relative importance. Each row requirement is assessed compared to a column requirement, and is ranked on a 9-3-1 scale, from high importance to low, respectively. The scoring numbers (9-3-1) correspond to the words (much more - moderately more - about as) when filling in the statement "The requirement in Row X is ___ important (than/as) the requirement in Column Y." In Figure 17 on the next page, the rankings were summed into their corresponding row requirements, giving us a clear indication of the functional requirements that would be most important in considering potential design ideas and design characteristics.



	AHP	Safety of tether drop	Below max weight regs	Highest altitude possible	Stays fully charged while tethered	Drops tether only upon command	Fast disconnect time	Durable	Reusable	Weather resistant	Drone full range of motion	Not obstructing to camera	Cord cannot overheat	Fast cord storage time	Easy to attach and detach	Sum	Relative %
Functional Requirements	Safety of tether drop	1.0	1.0	3.0	3.0	3.0	3.0	3.0	3.0	9.0	9.0	9.0	9.0	9.0	9.0	74.0	16.52%
	Below max weight regs	1.0	1.0	3.0	3.0	3.0	3.0	3.0	3.0	9.0	9.0	9.0	9.0	9.0	9.0	74.0	16.52%
	Highest altitude possible	0.3	0.3	1.0	1.0	3.0	3.0	3.0	3.0	3.0	9.0	9.0	9.0	9.0	9.0	62.7	13.99%
	Stays fully charged while tethered	0.3	0.3	1.0	1.0	1.0	3.0	3.0	3.0	3.0	9.0	9.0	9.0	9.0	9.0	60.7	13.54%
	Drops tether only upon command	0.3	0.3	0.3	1.0	1.0	3.0	3.0	3.0	3.0	9.0	9.0	9.0	9.0	9.0	60.0	13.39%
	Fast disconnect time	0.3	0.3	0.3	0.3	0.3	1.0	1.0	1.0	1.0	3.0	3.0	3.0	3.0	3.0	20.7	4.61%
	Durable	0.3	0.3	0.3	0.3	0.3	1.0	1.0	1.0	1.0	3.0	3.0	3.0	3.0	3.0	20.7	4.61%
	Reusable	0.3	0.3	0.3	0.3	0.3	1.0	1.0	1.0	1.0	3.0	3.0	3.0	3.0	3.0	20.7	4.61%
	Weather resistant	0.1	0.1	0.3	0.3	0.3	1.0	1.0	1.0	1.0	3.0	3.0	3.0	3.0	3.0	20.2	4.51%
	Drone full range of motion	0.1	0.1	0.1	0.1	0.1	0.3	0.3	0.3	0.3	1.0	1.0	1.0	1.0	1.0	6.9	1.54%
	Not obstructing to camera	0.1	0.1	0.1	0.1	0.1	0.3	0.3	0.3	0.3	1.0	1.0	1.0	1.0	1.0	6.9	1.54%
	Cord cannot overheat	0.1	0.1	0.1	0.1	0.1	0.3	0.3	0.3	0.3	1.0	1.0	1.0	1.0	1.0	6.9	1.54%
	Fast cord storage time	0.1	0.1	0.1	0.1	0.1	0.3	0.3	0.3	0.3	1.0	1.0	1.0	1.0	1.0	6.9	1.54%
	Easy to attach and detach	0.1	0.1	0.1	0.1	0.1	0.3	0.3	0.3	0.3	1.0	1.0	1.0	1.0	1.0	6.9	1.54%

Figure 17. Analytical Hierarchy Process resultant table

House of Quality

Next, we conducted a House of Quality[22, 23] analysis (HOQ). An HOQ is a table designed to critically evaluate how potential product characteristics, or specific aspects of the final product, affect each other, and how well they satisfy the functional requirements of a design. We imported our summarized functional requirements and their ranked importance from our AHP into our HOQ table and drafted critical product characteristics of our potential design to compare within the table. Our HOQ table in full is shown in Appendix B.

Interaction Matrix. Our Interaction Matrix at the top of the HOQ was used to compare correlations between our product characteristics if we changed them to intuitively satisfy our functional requirements. If optimally changing one product characteristic also optimally changes another product characteristic, then they have a positive correlation and are marked with a “1”. If optimally changing one product characteristic negatively affects another product characteristic, then they have a negative correlation and are marked with a “0”. If optimally changing a product characteristic has no impact on another product characteristic, then they have a neutral correlation and are marked with a “-”. An enlarged version of the Interaction Matrix is shown on the next page in Figure 18.

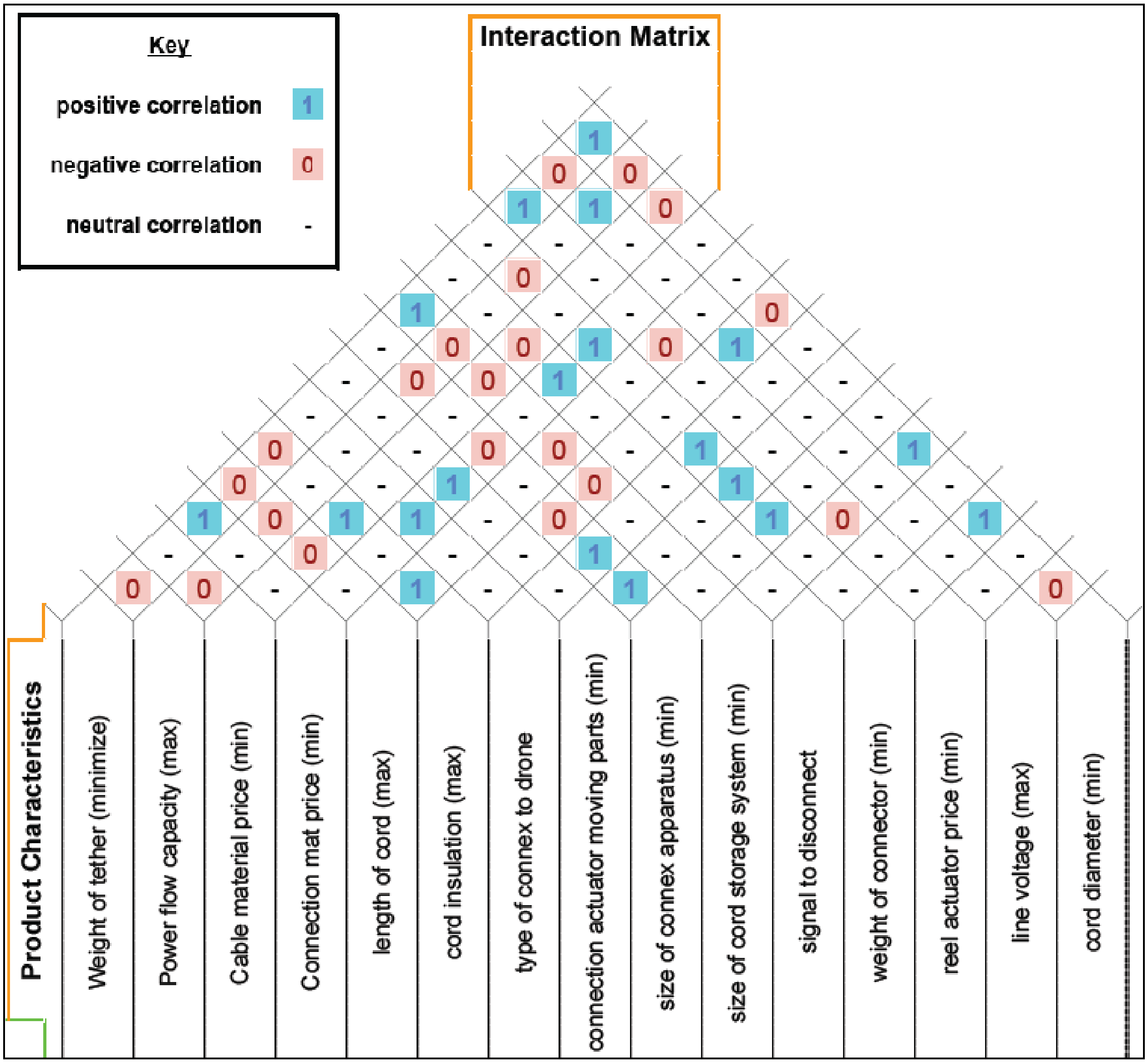
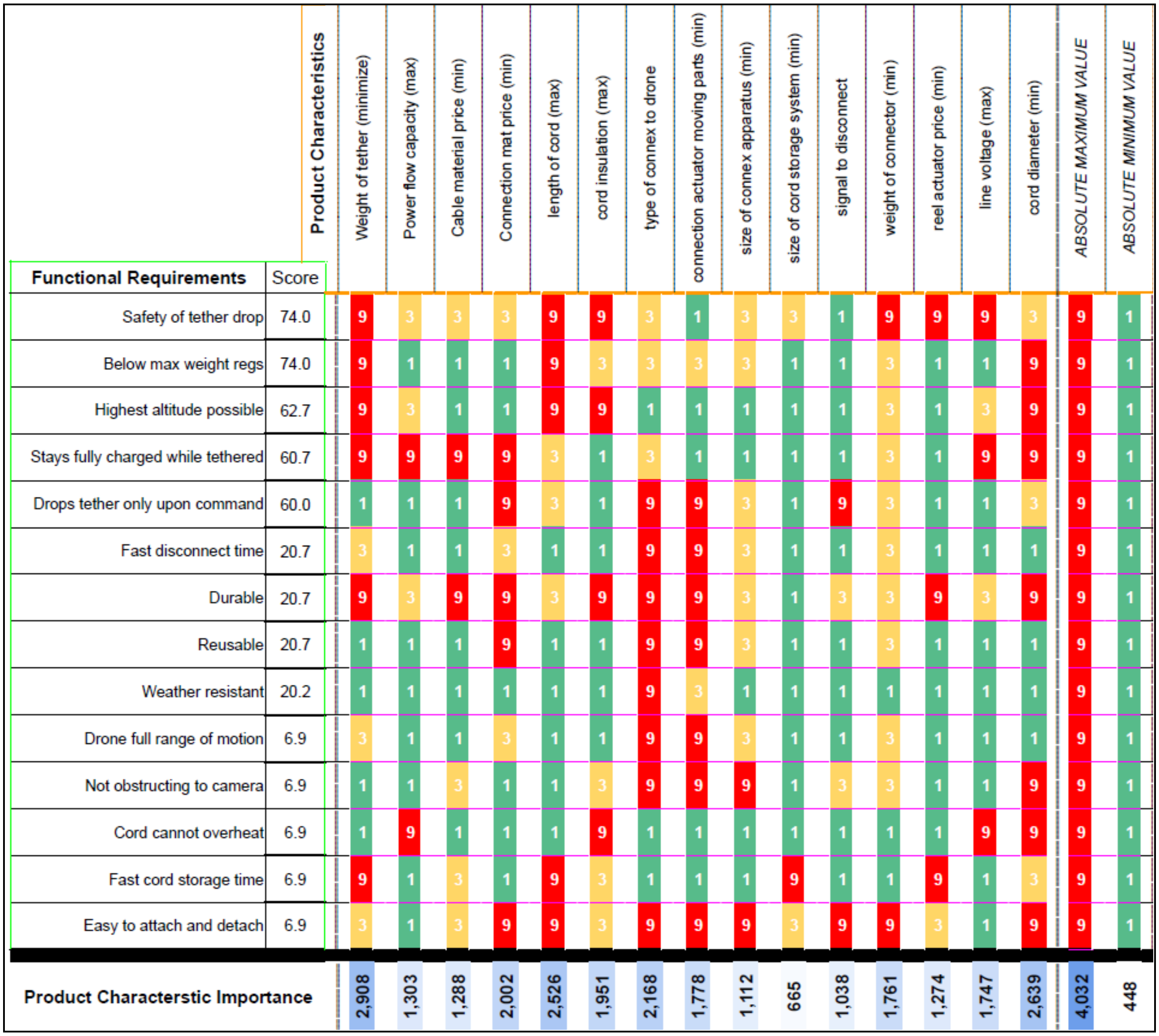


Figure 18. Interaction Matrix of the HOQ shown in Appendix B.

Functional Requirements versus Product Characteristics. Underneath the Interaction Matrix, the functional requirements are ranked against the product characteristics. These rankings also used a 9-3-1 scale from high to low importance, similar to the AHP. The scoring numbers (9-3-1) correspond to the words (highly-moderately-slightly) when filling in the statement "The functional requirement in Row X is ____ influenced by the product characteristic in Column Y." The absolute maximum and minimum importance ratings are also shown in the table as a benchmark for upper and lower bounds of calculated importance rankings. The overall Product Characteristic Importance values are calculated by multiplying a product characteristic's rankings in its column by its corresponding functional requirement's importance score, and these products are all summed to give a corresponding total at the bottom of the table. The enlarged version of this table from the HOQ is shown on the next page in Figure 19.



	Product Characteristics	Weight of tether (minimize)	Power flow capacity (max)	Cable material price (min)	Connection mat price (min)	length of cord (max)	cord insulation (max)	type of connex to drone	connection actuator moving parts (min)	size of connex apparatus (min)	size of cord storage system (min)	signal to disconnect	weight of connector (min)	reel actuator price (min)	line voltage (max)	cord diameter (min)	*ABSOLUTE MAXIMUM VALUE*	*ABSOLUTE MINIMUM VALUE*
Functional Requirements	Score																	
Safety of tether drop	74.0	9	3	3	3	9	9	3	1	3	3	1	9	9	9	3	9	1
Below max weight regs	74.0	9	1	1	1	9	3	3	3	3	1	1	3	1	1	9	9	1
Highest altitude possible	62.7	9	3	1	1	9	9	1	1	1	1	1	3	1	3	9	9	1
Stays fully charged while tethered	60.7	9	9	9	9	3	1	3	1	1	1	1	3	1	9	9	9	1
Drops tether only upon command	60.0	1	1	1	9	3	1	9	9	3	1	9	3	1	1	3	9	1
Fast disconnect time	20.7	3	1	1	3	1	1	9	9	3	1	1	3	1	1	1	9	1
Durable	20.7	9	3	9	9	3	9	9	9	3	1	3	3	9	3	9	9	1
Reusable	20.7	1	1	1	9	1	1	9	9	3	1	1	3	1	1	1	9	1
Weather resistant	20.2	1	1	1	1	1	1	9	3	1	1	1	1	1	1	1	9	1
Drone full range of motion	6.9	3	1	1	3	1	1	9	9	3	1	1	3	1	1	1	9	1
Not obstructing to camera	6.9	1	1	3	1	1	3	9	9	9	1	3	3	1	1	9	9	1
Cord cannot overheat	6.9	1	9	1	1	1	9	1	1	1	1	1	1	1	9	9	9	1
Fast cord storage time	6.9	9	1	3	1	9	3	1	1	1	9	1	1	9	1	3	9	1
Easy to attach and detach	6.9	3	1	3	9	9	3	9	9	9	3	9	9	3	1	9	9	1
Product Characterstic Importance		2,908	1,303	1,288	2,002	2,526	1,951	2,168	1,778	1,112	665	1,038	1,761	1,274	1,747	2,639	4,032	448

Figure 19. Functional Requirement vs. Product Characteristics section of HOQ.

A table of the final product characteristic importance values found in the HOQ reorganized by rank from highest to lowest importance is shown below in Table 4.

Table 4. Summary of Product Characteristic Importance.

Product Characteristic	Importance Value
Weight of tether (minimize)	2,908
Cord diameter (min)	2,639
Length of cord (max)	2,526
Type of connection to drone	2,168

Product Characteristic	Importance Value
Connection material price (min)	2,002
Cord insulation (max)	1,951
Connection actuator moving parts (min)	1,778
Weight of connector (min)	1,761
Line voltage (max)	1,747
Power flow capacity (max)	1,303
Cable material price (min)	1,288
Reel actuator price (min)	1,274
Size of connection apparatus (min)	1,112
Signal to disconnect	1,038
Size of cord storage system (min)	665
ABSOLUTE MAXIMUM VALUE	4,032
ABSOLUTE MINIMUM VALUE	448

HOQ Summary and Findings. From our HOQ, we found that there are nuanced trade-offs to consider when analyzing our designs. For instance, maximizing the power flow capacity of the cord - the wattage that can be transferred through the cord - is negatively impacted by reducing the weight and size of the cord. By our product characteristic importance values, we can see that minimizing the weight and size of the cord would be more important to satisfy than maximizing the power flow capacity if we need to decide a side of the trade-off to focus on to satisfy our functional requirements. These insights helped to justify certain design decisions in our concept interaction and design screenings and will be utilized moving forward as we begin to make trade-off decisions for our final design.

Final Design Screening

In our final design screening, we utilized a Pugh chart to compare the top three designs in each function against each other and to our requirements, taking into account the respective weighting of each requirement from our AHP analysis. These Pugh charts utilize one of the three designs as a baseline (chosen randomly). Then, the other two designs are compared to the baseline for a specific requirement to determine if they are better, a value of 1, worse, a value of -1, or the same, a value of 0 as the baseline. Once all the requirements have been compared, the values are multiplied by the respective requirement weighting and then summed to determine the final total. The design with the highest total is determined to be the best design for our requirements. The first Pugh chart, shown on the next page in Table 5, calculates the top design out of our three connection and disconnect method designs with the tensile chosen as the baseline.

Table 5. Connection and disconnect method top three designs Pugh chart

Requirement	**Weight**	**Connection and Disconnect Method Design:**		
		Tensile	**Electromagnet**	**Pin**
Safety of tether drop	74.0	-	0	0
Below max weight regs	74.0	-	-1	-1
Highest altitude possible	62.7	-	0	0
Stays fully charged while tethered	60.7	-	0	0
Drops tether only upon command	60.0	-	1	1
Fast disconnect time	20.7	-	1	1
Durable	20.7	-	0	-1
Reusable	20.7	-	1	1
Weather resistant	20.2	-	-1	-1
Drone full range of motion	6.9	-	0	1
Not obstructing to camera	6.9	-	0	-1
Cord cannot overheat	6.9	-	0	0
Fast cord storage time	6.9	-	0	0
Easy to attach and detach	6.9	-	1	1
Total (Including Weighting):		**-**	**14**	**-6.67**

As seen above, the winner is the electromagnet design with a score of 14. One important note here, is that the weightings for the requirements are in the 20s to 70s, and the top score this chart could produce is a 448 or -448 if all requirements were marked as 1 or -1 respectively. Therefore, when looking at a winning score of 14 versus the baseline of 0 versus a -6.67, the difference is relatively small. This indicated that these three designs are very similar in terms of their performance in our Pugh chart, but ultimately, the electromagnet is the best design.

The second Pugh chart, shown below in Table 6, calculates the top design out of our three cord safety mechanism designs with the airbag chosen as the baseline.

Table 6. Cord safety mechanism top three designs Pugh chart

Requirement	**Weight**	**Cord Safety Mechanism Design:**		
		Airbag	**Parachute**	**Large Radius**
Safety of tether drop	74.0	-	1	-1
Below max weight regs	74.0	-	1	1
Highest altitude possible	62.7	-	0	0
Stays fully charged while tethered	60.7	-	0	0
Drops tether only upon command	60.0	-	0	0
Fast disconnect time	20.7	-	0	0
Durable	20.7	-	0	1
Reusable	20.7	-	0	1
Weather resistant	20.2	-	-1	1
Drone full range of motion	6.9	-	0	0
Not obstructing to camera	6.9	-	0	0
Cord cannot overheat	6.9	-	0	0
Fast cord storage time	6.9	-	0	0
Easy to attach and detach	6.9	-	0	1
Total (Including Weighting):		**-**	**127.78**	**68.44**

As seen above, the winner is the parachute design with a score of 127.78. This score is much higher than the baseline of 0 and almost double the large radius design score, indicating that the parachute design is much more equipped to fulfill our requirements. Although the parachute scored the highest, our initial gut check tells us that the parachute will be harder to redeploy and not as reliable as we would like. This is explored further in the Engineering Analysis section.

The third Pugh chart, shown below in Table 7, calculates the top design out of our three cord storage system designs with the hand crank reel chosen as the baseline.

Table 7. Cord storage system top three designs Pugh chart

Requirement	**Weight**	**Cord Storage System Design:**		
		Hand Crank Reel	**Motorized Reel**	**Spring + Ratchet Reel**
Safety of tether drop	74.0	-	1	1
Below max weight regs	74.0	-	0	0
Highest altitude possible	62.7	-	0	0
Stays fully charged while tethered	60.7	-	0	0
Drops tether only upon command	60.0	-	0	0
Fast disconnect time	20.7	-	0	0
Durable	20.7	-	0	-1
Reusable	20.7	-	0	0
Weather resistant	20.2	-	0	0
Drone full range of motion	6.9	-	0	0
Not obstructing to camera	6.9	-	0	0
Cord cannot overheat	6.9	-	0	0
Fast cord storage time	6.9	-	1	1
Easy to attach and detach	6.9	-	0	0
Total (Including Weighting):		**-**	**80.89**	**60.22**

As seen above, the winner is the motorized reel design with a score of 80.89. Again, this score is much higher than the baseline of 0 and significantly higher than the spring and ratchet reel design, indicating it is the best choice for our requirements.

FIRST SELECTED CONCEPT DESCRIPTION: THE ALPHA CONCEPT

In our chosen alpha concept, we employ an electromagnetic connection system, coupled with a parachute mechanism to slow the descent of the tether, and a motorized reel for the purpose of efficiently reeling in the tether. This section delves into the intricate workings of each component and provides a comprehensive overview of our rationale behind adopting this particular design concept.

Connection Point and Disconnect Method Design

Our selected design for the connection point and disconnect method is centered around the utilization of an electromagnet to manage the tether connection. At the upper section of the connector, attached to the drone body, four electromagnets are incorporated, each with the capability to be remotely activated. Additionally, two holes at the center facilitate the electrical connection with the tether.

Contained within the upper segment of the connector on the drone body are essential components, including a power source, the electromagnet control system, a radio signal component, and electrical connections and wiring. The lower segment of the connector is designed to be affixed to the tether and contains four permanent magnets, along with two prongs for the electrical connection.

The connection process is facilitated by the interaction between the four electromagnets on the upper part of the connector and the corresponding four permanent magnets on the lower part. This magnetic connection provides a secure and stable linkage until the point when the tether is detached. A visual representation of this design concept can be found below in Figure 20.

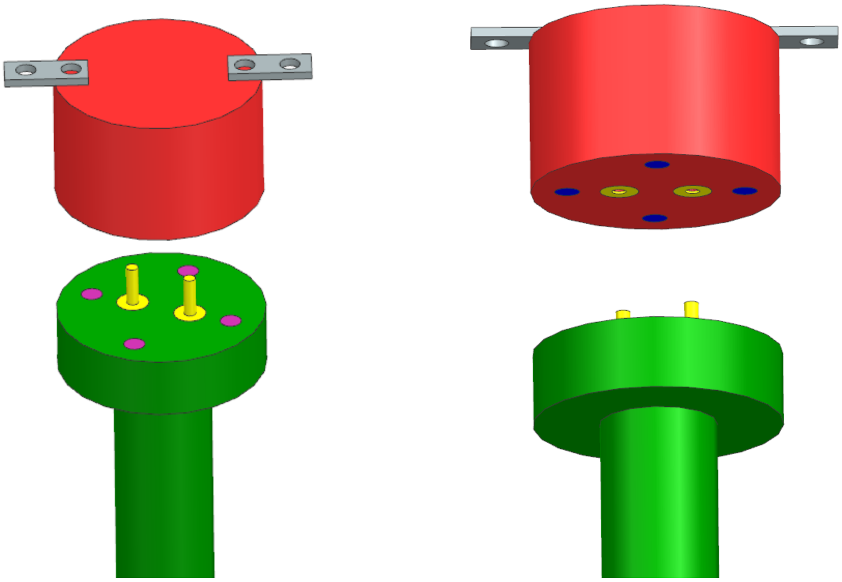


Figure 20. CAD of the electromagnetic connector

Cord Safety Mechanism Design

Our selected design for the cord safety mechanism incorporates a parachute to effectively regulate the descent of the tether upon detachment from the drone. This mechanism involves a structure consisting of two components: the capsule door rigidly linked to the upper part of the connector and the capsule body firmly connected to the lower part of the connector.

Contained within this capsule is the parachute itself, which will deploy when the capsule door and capsule body separate during the tether's descent. As the tether descends, the capsule body descends in tandem, creating a separation that facilitates the expansion of the parachute. When the capsule door separates from the capsule body, the loop on the door assists in pulling out the parachute to ensure it deploys correctly. This deployment serves the crucial function of significantly decelerating the tether's fall. A visual representation of this design concept and how it attaches to the electromagnet connector is presented below in Figure 21.

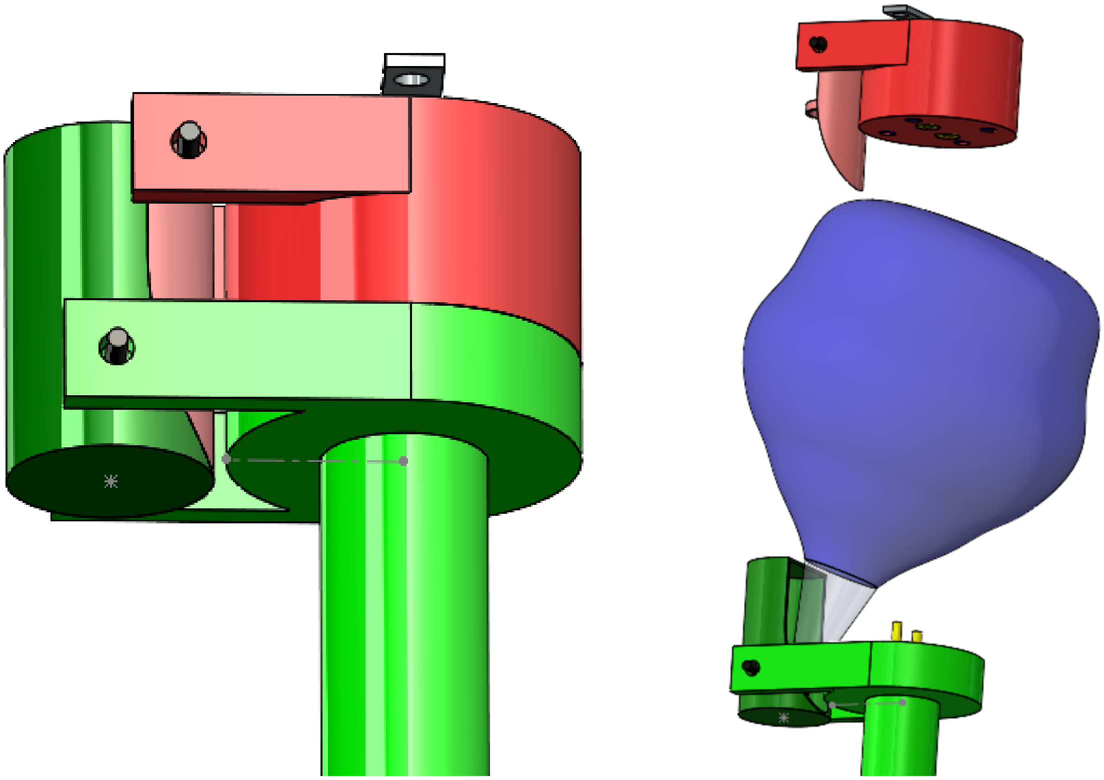


Figure 21. CAD of the connector with deployable parachute safety mechanism

Cord Storage System

The cord storage system we have opted for is a motorized reel. This system encompasses a motor with the reel itself, along with other electrical components that provide a housing for the tether when it is disconnected from the drone. A visual depiction of this design is illustrated on the next page in Figure 22 below.

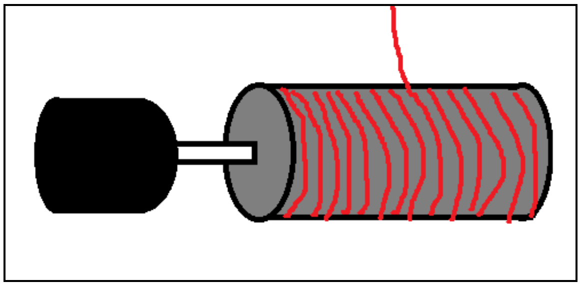


Figure 22. Drawing of the motorized reel

Overall Thoughts on the Alpha Concept

The selection of our alpha concepts stemmed from a thorough evaluation based on the outcomes of our Pugh chart, in which we systematically compared each design with our requirements and applied a weighted assessment system. The selected alpha concept was not influenced or reviewed by our sponsor, but this will be a crucial next step in the process. Furthermore, the values used in constructing our Pugh charts, AHP, and HOQ were established collaboratively as a team and were not manipulated to cater to the preferences of our sponsor or section instructor, ensuring an unbiased approach to the design selection process.

Next Steps for the Alpha Concept

Looking ahead, we will introduce a new requirement stemming from the potential impact of an electromagnet on the overall performance of other electrical components within the drone. This new requirement carries significant weight, prompting us to reevaluate our HOQ in order to determine its priority relative to other project requirements. Furthermore, the inclusion of an electromagnet could potentially necessitate a reconsideration of our alpha concept for the connector, especially after meeting with our sponsor at Vayu. If it becomes evident that the integration of an electromagnet is unfeasible or poses design challenges, we must be prepared to adapt and modify our connector design accordingly to accommodate this new requirement while maintaining the overall integrity of the system. One thing to note, currently we do not have a bill of materials or preliminary manufacturing plans because our alpha concept will change following an upcoming meeting with our sponsor at Vayu regarding the above considerations.

ENGINEERING ANALYSIS

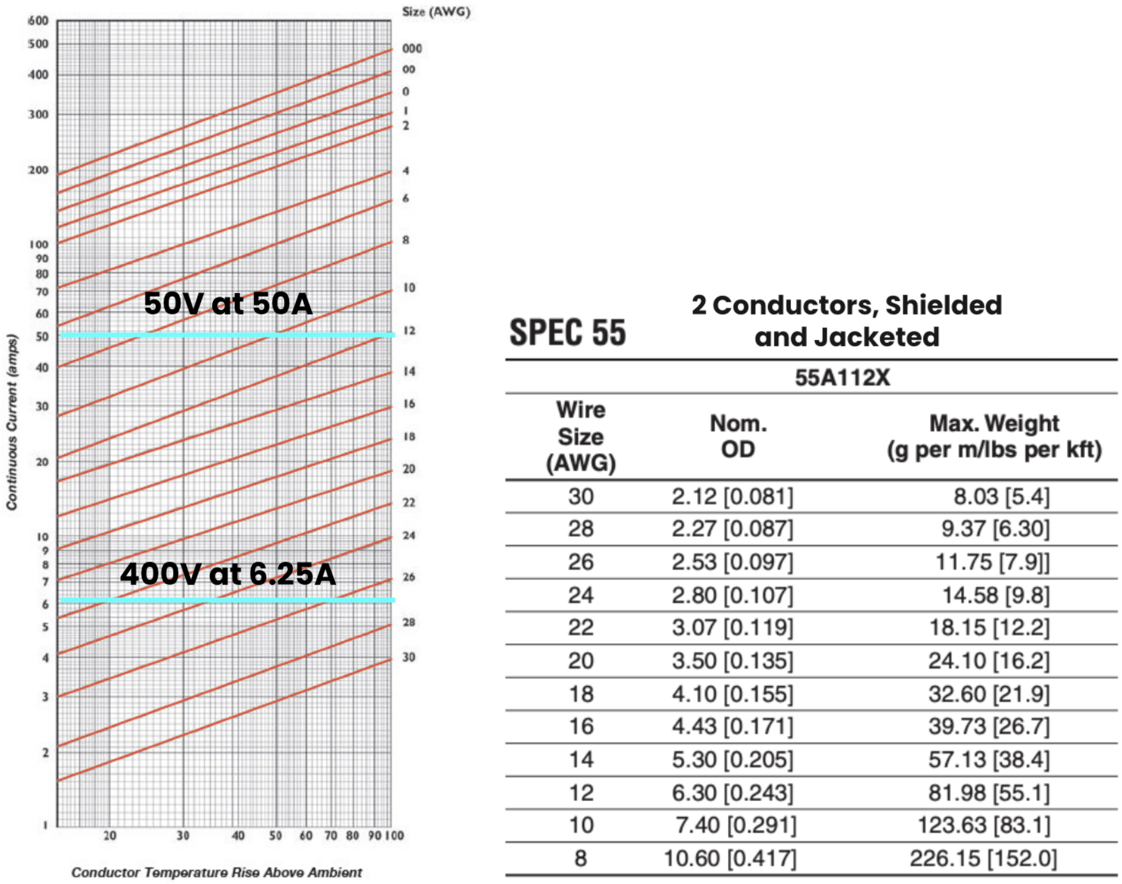
First Principles Calculations

In order to conduct preliminary analysis on whether our design would function as intended, we conducted a few first principles calculations before building any prototype. This included power supply and cord calculations and safety mechanism calculations including impact force and parachute specifications.

Power Supply and Cord Analysis. In order to power the drone from the ground, a voltage and current that runs through the tether needs to be determined. With the tether needing to supply 2,500W of power to the drone, the first option is to supply 50V from the ground through the cord and directly to the drone battery, as the drone battery operates at 50V.

$$P = I \cdot V \tag{1}$$ [24]

Using Equation 1, this means the tether would need to have 50A of current running throughout. A second option would be to reduce the current significantly by supplying 400V through the tether and then using two onboard DC DC converters to reduce the voltage to 50V in order to charge the drone battery. Using Equation 1 again, this means the tether would need to have 6.25A of current running throughout. To determine the pros and cons of each option, we looked at two major factors, temperature under use and weight. For temperature, Figure 23 below shows a graph comparing the current running through a cord to the temperature rise of the cord above ambient for different gauge wires (shown as the red lines). For a certain chosen operating voltage, we can pick a proper gauge size so that the temperature rise is low enough to prevent the cable from melting. For the 50V system running 50A, the wire gauge needed is gauge 10 or 8 wire is needed, found by using the below graph. For the 400V system running 6.25A, the wire gauge needed to maintain low temperature rise is gauge 22, 24, or 26 wire, found by using the below graph.



SPEC 55 **2 Conductors, Shielded and Jacketed**

55A112X

Wire Size (AWG)	Nom. OD	Max. Weight (g per m/lbs per kft)
30	2.12 [0.081]	8.03 [5.4]
28	2.27 [0.087]	9.37 [6.30]
26	2.53 [0.097]	11.75 [7.9]]
24	2.80 [0.107]	14.58 [9.8]
22	3.07 [0.119]	18.15 [12.2]
20	3.50 [0.135]	24.10 [16.2]
18	4.10 [0.155]	32.60 [21.9]
16	4.43 [0.171]	39.73 [26.7]
14	5.30 [0.205]	57.13 [38.4]
12	6.30 [0.243]	81.98 [55.1]
10	7.40 [0.291]	123.63 [83.1]
8	10.60 [0.417]	226.15 [152.0]

Figure 23. Graph comparing the current running through a cord to the temperature rise of the cord above ambient for different gauge wires[25] (left) and cable specifications for different gauges of SPEC 55 cable[26] (right)

Looking at Figure 23, for the 50V system with the required wire gauge of 10 or less, the 100 ft cord would weigh a minimum of 8.31 lbs. This would significantly reduce the payload capability of the drone. For the 400V system, with the required wire gauge of 26 or less, the 100 ft cord would weigh around 0.79 lbs. This drastic weight reduction indicates that the 400V option is considerably better than the 50V option at satisfying our requirements and specifications.

The on board DC DC converters needed for the 400V option have a weight to them that also should be accounted for. One possible option for these converters is the Vicor Corporation Bus Converter Module DC DC Converter[27]. This model has one output of 50V and 35A and requires an input of 260V to 410V, perfect for a 400V input. However, due to the current output of only 35A, two converters will be needed, running in parallel. The total weight of these two converters comes out to 0.18 lbs.

Looking at the overall weight of both systems, the 50V option weighs around 8.31 lbs while the 400V option weighs only 0.97 lbs (including the converters). Based on this analysis, we determined that the best option would be the 400V system in order to reduce the overall weight of the tether system. One potential challenge with this system is that the two onboard DC DC converters will generate some amount of additional heat. This can be offset by additional heat sinks, but the component will need to be tested first to determine the heat generation.

Safety Mechanism Analysis. It is important to roughly understand the forces and impulses that the system will be under to design a safety mechanism that properly preserves the cord and maintains the safety of its users. We can find a rough estimate of the impact force to a point mass (that would represent the critical tether components like the plug head) using basic kinematic equations[28] and the impulse-momentum theorem[29].

$$1.\ v = v_0 + at$$

$$2.\ x = x_0 + v_0 t + \frac{1}{2}at^2$$

$$3.\ v^2 = v_0^2 + 2a(x - x_0)$$

$$4.\ \vec{F}\Delta t = m\Delta\vec{v}$$

Figure 24. Kinematics equations of motion for constant acceleration[28] (24.1-3) and the impulse-momentum theorem[29] (24.4)

We assume that the tether head could have a maximum possible weight of 10 lbs for a worst-case scenario, and the tether head free falls under constant Earth gravitational acceleration (a = 32.17 ft/s^2) from a height (x-x_0) of 100 ft (so v_0 = 0). From this, we can rearrange Equation 24.3 into

$$v_{bf} = \sqrt{v_0^2 + 2a(x - x_0)} \qquad (24.5)$$

.

where v_{bf} is the velocity right before impact and v_0 is the initial velocity. Plugging in our values, we find that $\boldsymbol{v_{bf}}$ **= 80.2 ft/s**.

Using this value, we can isolate the net force F on impact in the impulse-momentum theorem (Equation 24.4). Isolating F gives us…

$$F = \frac{m}{\Delta t}(v_f - v_i) \tag{24.6}$$

…where m is the mass, Δt is the duration of impulse, and v_f and v_i are final and initial velocities, respectively. By separating Δv into $v_f - v_i$, designating v_i as v_{bf}, assuming v_f after impact is 0, and an estimated impact time Δt of 0.05 s, we can find the estimated impact force the tether head would experience, assuming the mass stays constant as it falls (i.e. the cord weight is fully hanging in the air until impact). This force is calculated to be $\boldsymbol{F_{impact}}$ **= 498.7 lbf or 2220 N**. Since the velocity is not slowed by air drag, the mass is well over our estimated cable weight and doesn't reduce as the cord hits the ground before the tether head, this impact force is an overestimate. If we design to withstand this force, the system will have a large safety factor in actual testing. For reference, this force is approximately half of the weight that OSHA-compliant Type I Construction hard hats are rated to withstand (1000 lbf)[30].

To understand the drag force provided by a parachute of a certain area, we can look at a simple free body diagram of the system. NASA has broken down the analysis into a simple system, as shown in Figure 25 below.

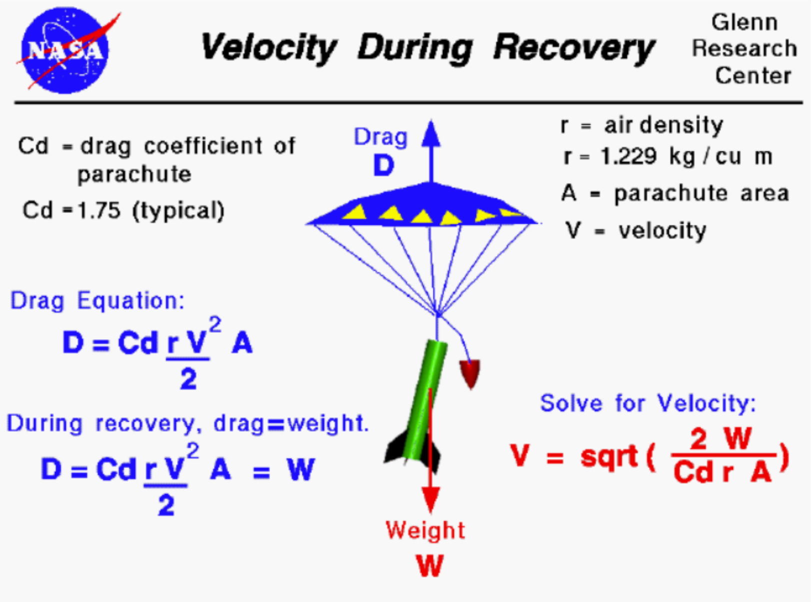


Figure 25. Parachute drag analysis by NASA[31]

From this, we can use their "drag = weight" equation to determine the area of a parachute, and if we assume the parachute is circular for simplicity, we can find a relationship between the weight of the object and the corresponding diameter needed to safely descend. This takes the form of Equation 25.1 as shown below…

$$d = \sqrt{\frac{\frac{8}{\pi}W}{C_d r V^2}} \tag{25.1}$$

…where d is the diameter of the parachute in meters, W is the weight of the payload in kg, C_d is the drag coefficient, and C_d, r, and V are pulled from Figure 25.

We assume that a reasonable target descent velocity V will be 4.5 m/s, as this is a velocity that durable model rockets are made to withstand[32]. Although NASA quotes 1.75 as a "typical" coefficient of drag for a parachute, there are many different factors that go into determining a parachute's drag coefficient. If we were to use a proprietary parachute for manufacturability and simplicity reasons, there could be drag coefficients of a much wider range than a single value based on the catalog a business has prepared[33]. If we assume a best-case scenario of a parachute with a drag coefficient of 2.3 versus a worst-case scenario parachute with a 0.6 drag coefficient, we can plot two functions of Equation 25.1 that show best- and worst-case parachute diameter. Below is Figure 26, a graph of these two scenarios, converted to imperial units for our purposes.

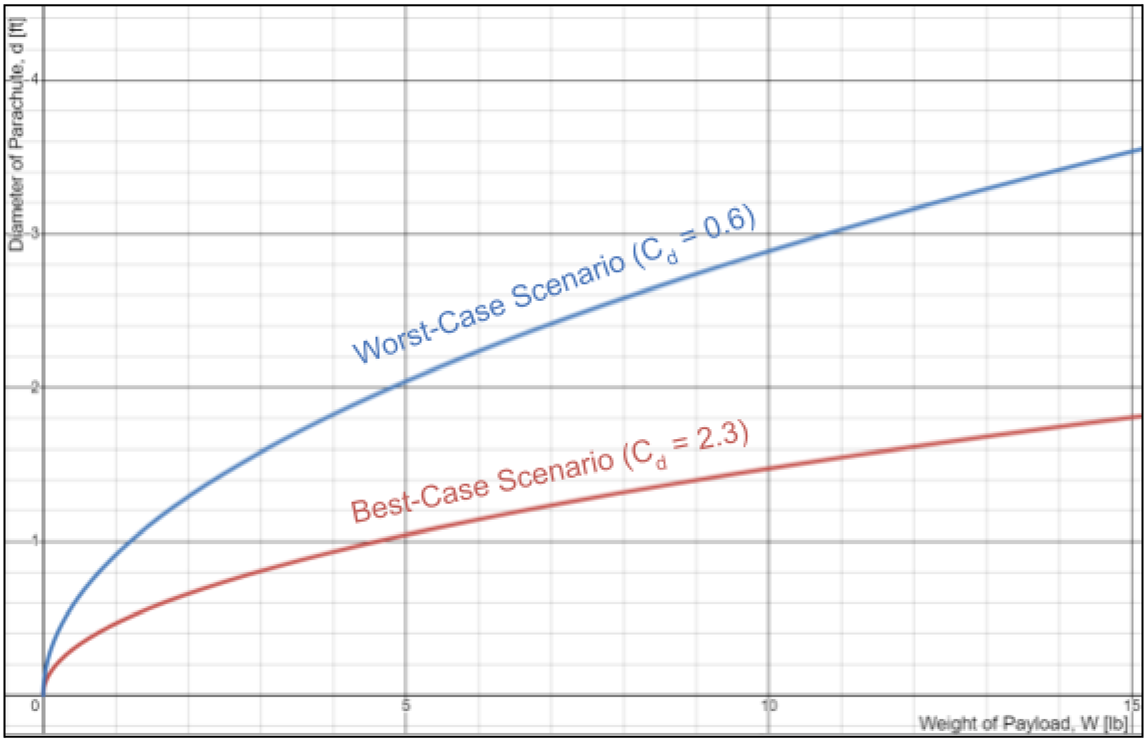


Figure 26. Plot of Parachute Size and Weight Analysis

The drag coefficient not only depends on the size of the parachute, but the way in which it opens and stays open. We assume that the parachute will be perfectly circular through its entire deployment, but that is rarely the case. Complications may occur in the lengthy process it takes to properly package a parachute for safe deployment before each use; the durability of the tether would fall on the user. There is also the possibility that, if not properly deployed away from the drone, the parachute cords or the parachute itself can get caught in the drone rotors and cause the entire system to fail. This does not satisfy our requirements for being unobstructive to the drone and simple to set up, and thus we should move to a different safety mechanism concept.

First Prototype Design

After generating design concepts and selecting electromagnets as our connection mechanism, we transformed our alpha concept into a manufacturable prototype. The CAD model for this prototype is shown below in Figure 27. Notable aspects of this design include a two pin Mil-Spec connector (AS610-02PN[34] as the plug and AS010-02SN[35] as the receptacle). This was chosen due to Vayu's familiarity with automotive harness connectors, its high voltage rating, and its low axial friction. In short, a safe and reliable electrical connection can be made which we predicted would fall out from its own weight when commanded. The electromagnet purchased from McMaster-Carr (1" diameter by ¾" height, 24V, 1.4W, part number 5698K212) had an advertised pulling weight of 26 lbs[36]. Our choice for this magnet is that it would have plenty of strength to hold up the tether head, which at this point was estimated would weigh no more than 10 lbs with 100ft of cable.

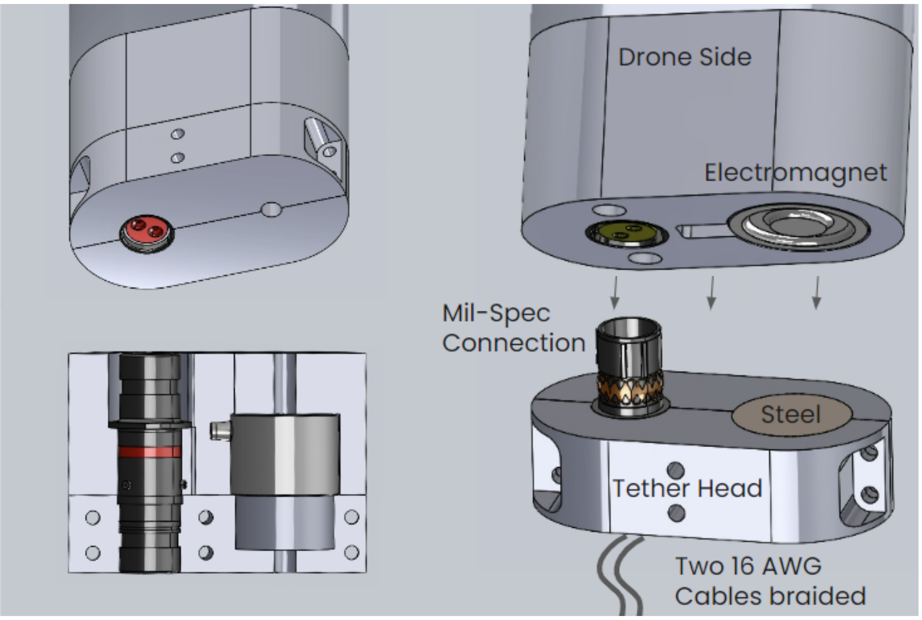


Figure 27. CAD model of the first prototype design

Electromagnet Load Test. Conducting an electromagnet load test involves evaluating the holding capacity of an individual electromagnet unit. The electromagnet we used operates at 24 volts and is designed to hold a force of 26 pounds. During the experimental procedure, a 24-volt DC power bank energized the electromagnet, which was securely affixed within a table vise. A steel rod, tethered to a crane scale, was used to measure the force the electromagnet could hold before failure. Refer to Figure 28 for a visual depiction of the experimental setup.

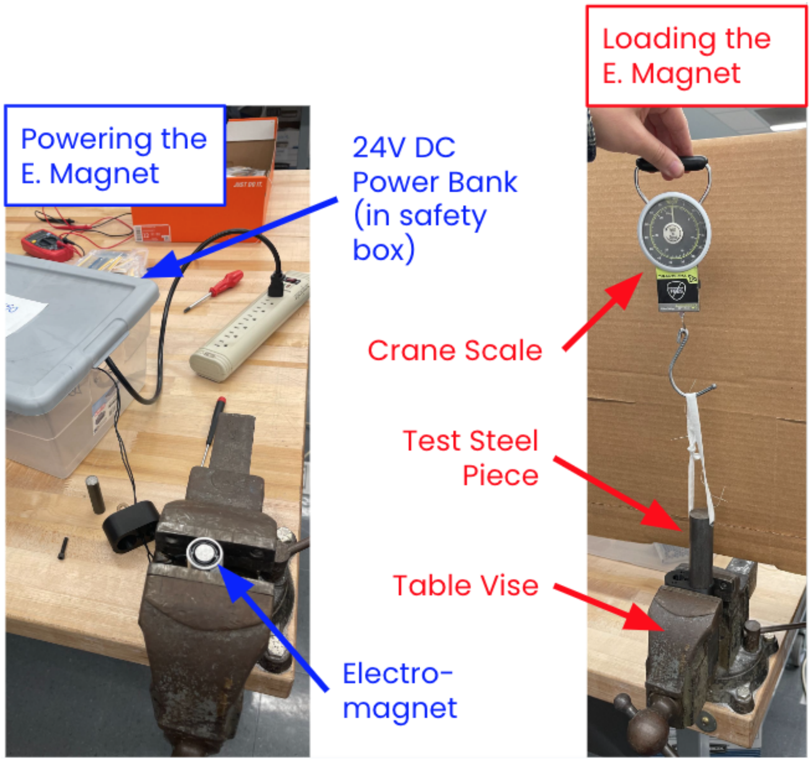


Figure 28. Electromagnet load test setup

The results of our examination indicate that the average load strength of an individual electromagnet is 13.44 lbs, with a force range spanning from 9 lbs to 17.5 lbs. This falls considerably short of the specified rated force of 26 lbs. Additionally, our observations revealed that the electromagnet became warm upon prolonged testing, and even after power was shut off, a residual magnetism remained. The removal of the steel rod from the depowered electromagnet required an additional force of approximately 1.8 lbs. Furthermore, our testing outside of the test setup showed that the geometry of the metal in contact with the electromagnet is an important factor, where a quarter-inch steel plate exhibited greater strength in adhering to the electromagnet compared to a one-inch diameter steel rod. Figure 29 illustrates a graphical representation of the load results obtained during this experimentation.

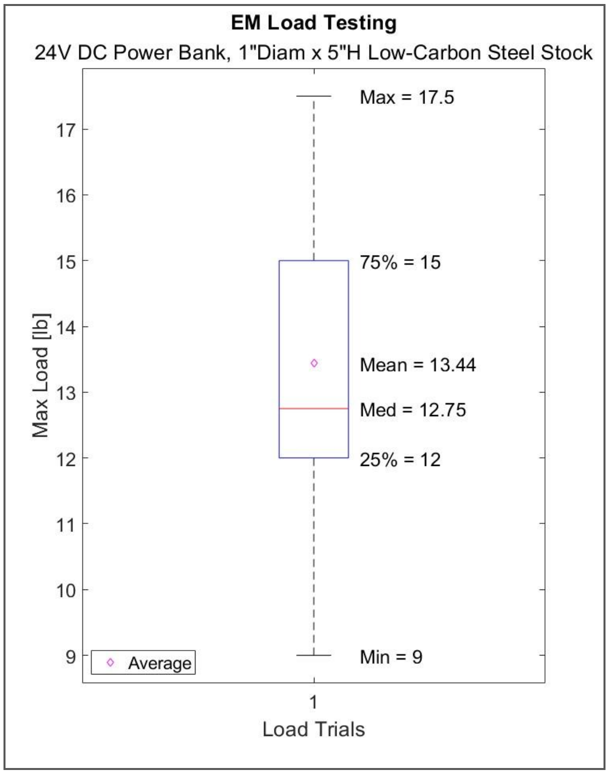


Figure 29. Graph showing the results of the electromagnet load test

Second Prototype Design

For our second prototype, we revisited the concept generation phase to address several issues identified in the previous design. These issues primarily centered around asymmetry-induced moments, insufficient magnetic holding force, and residual magnetism. To confront these challenges, modifications were made to the drone head by integrating two electromagnets on each side of the connector. Furthermore, we relocated the male side of the connector to the drone end. Lastly, in order to address the safety mechanism for the drone, we introduced a foam football drop box covering the tether head.

Regarding the tether head, we explored two concepts for testing purposes: one involved permanent magnets opposing the electromagnets, while the other utilized a plain steel plate against the electromagnets. Both of these designs are shown below in Figure 30. Our rationale for these choices stemmed from initial theories. We hypothesized that the permanent magnets might provide a stronger attractive force to the electromagnet core when inactive, transitioning to a robust repelling force when the electromagnet was activated. This repelling force would overcome any friction held in the connector, a concern we had before physically acquiring the connector part. In contrast, initial tests revealed the steel plate's superior attraction to the powered electromagnets, possibly due to its enhanced utilization of flux extending beyond its surface area.

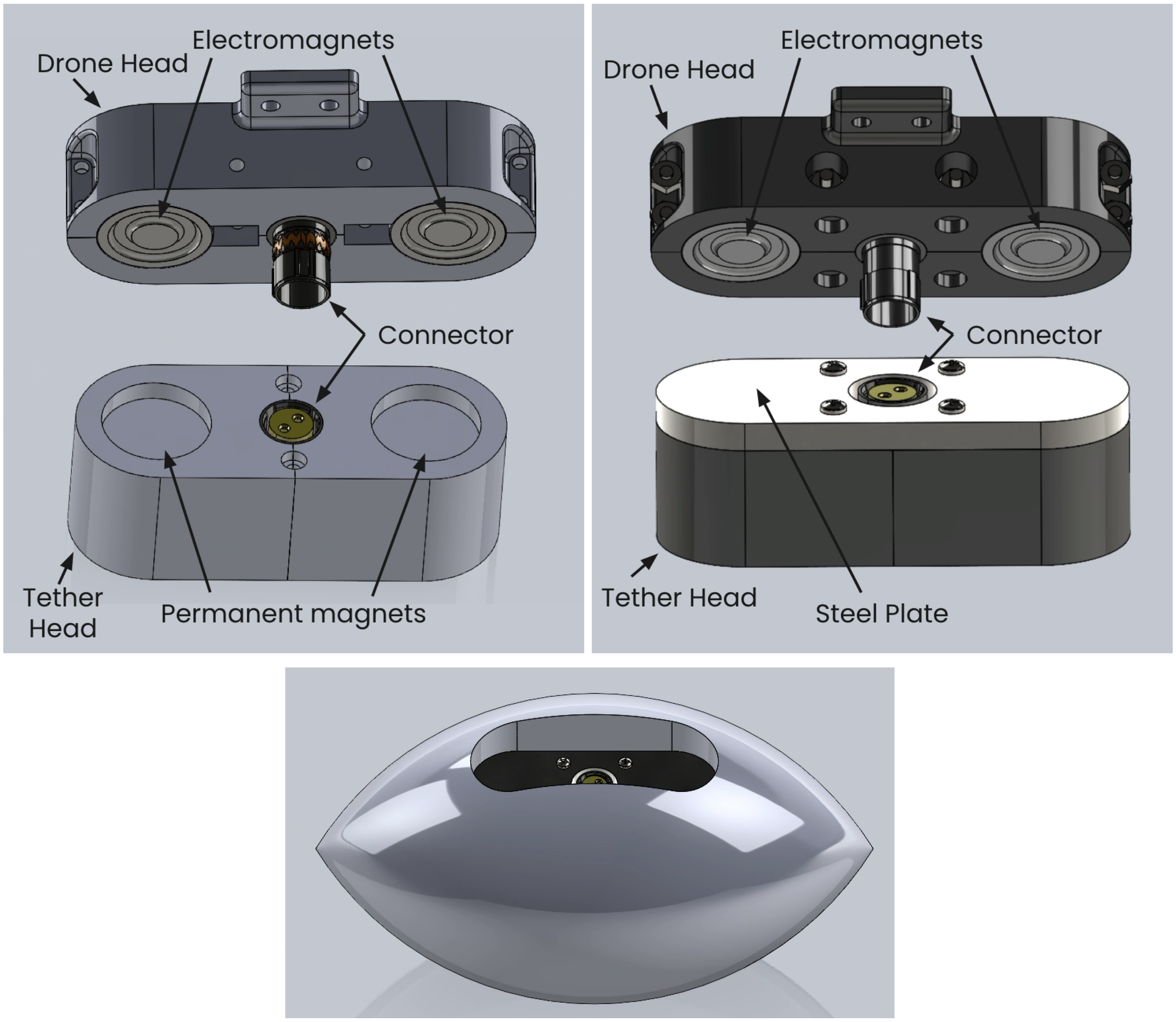


Figure 30. Permanent magnet design (left), steel plate design (right), and foam football drop box safety mechanism (bottom)

Permanent Magnet Test. In order to test the permanent magnet design, we assembled the prototype, using cyanoacrylate glue to hold the magnets onto the tether head 3D printed part. Our initial tests highlighted the complete failure of this permanent magnet solution. The magnets had relatively little hold on the powered-off electromagnet, and when the electromagnet was powered, the magnets were not repelled, and the system did not detach as thought. Due to these revelations, we abandoned the permanent magnet design, as it did not work as intended. Also, upon receiving the connector part, there was very little friction in the connection, diminishing the need for this concept to work. From this point, we moved forward with the steel plate design.

Overall Load Test. In order to test the overall load the steel plate design could hold, we conducted an overall load test. For this test, we assembled our symmetrical connector steel plate design and powered the two electromagnets with a 24V DC power bank. The drone head of the system which holds the electromagnets was securely fastened to a table vise, while the tether head was connected to a crane scale to determine the load capacity until failure. The test setup is shown below in Figure 31.

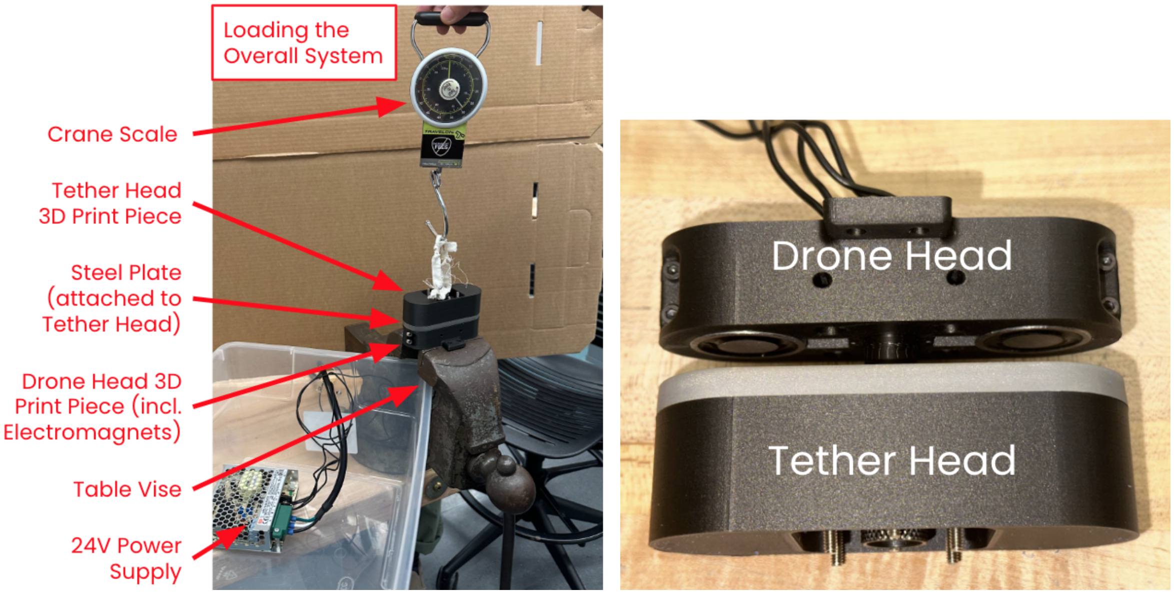


Figure 31. Overall load test setup (left) and assembled steel plate second prototype design (right)

Our testing yielded a mean load strength of 29.29 lbs, with a force range spanning from 27 to 31 lbs. Residual magnetism was also observed in this test. It is important to highlight that, during this assessment, the connector pins were intentionally omitted, potentially discounting additional friction that might occur during separation with the pins.

Furthermore, estimating a system weight of approximately 3.5 lbs (100 ft of 16 gage cable at 2.67 lbs and tether head weight of 0.83 lbs) and employing two electromagnets with a steel plate, the resulting safety factor was approximately 8.4, indicating a substantial safety factor when looking at the overall load the system can hold. Figure 32 below shows a graphical representation of the overall load test results.

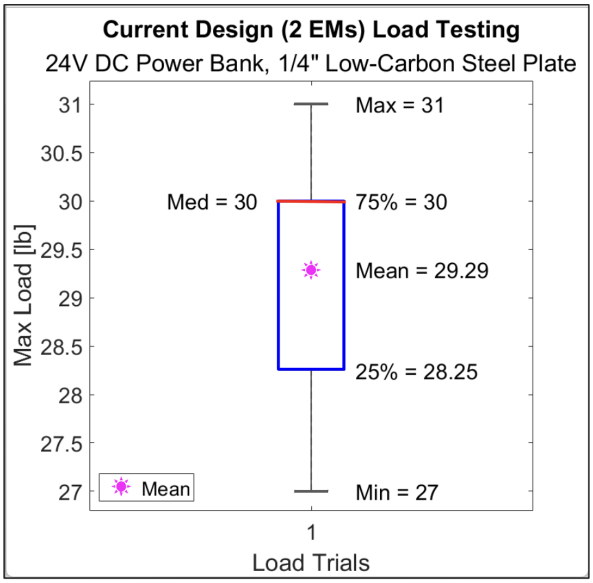


Figure 32. Graph showing the results of the overall load test

From a comparison of our initial final electromagnet load tests, there is a clear improvement in the consistency and magnitude of the connection force. Figure 33 below shows the side-by-side graphical comparison of our results.

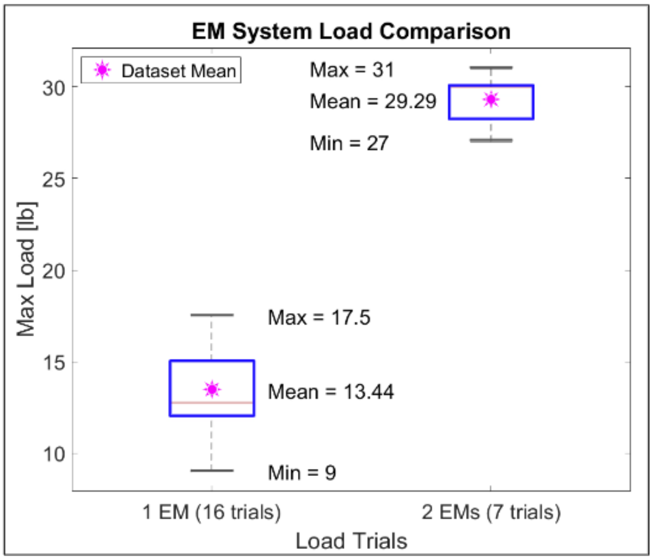
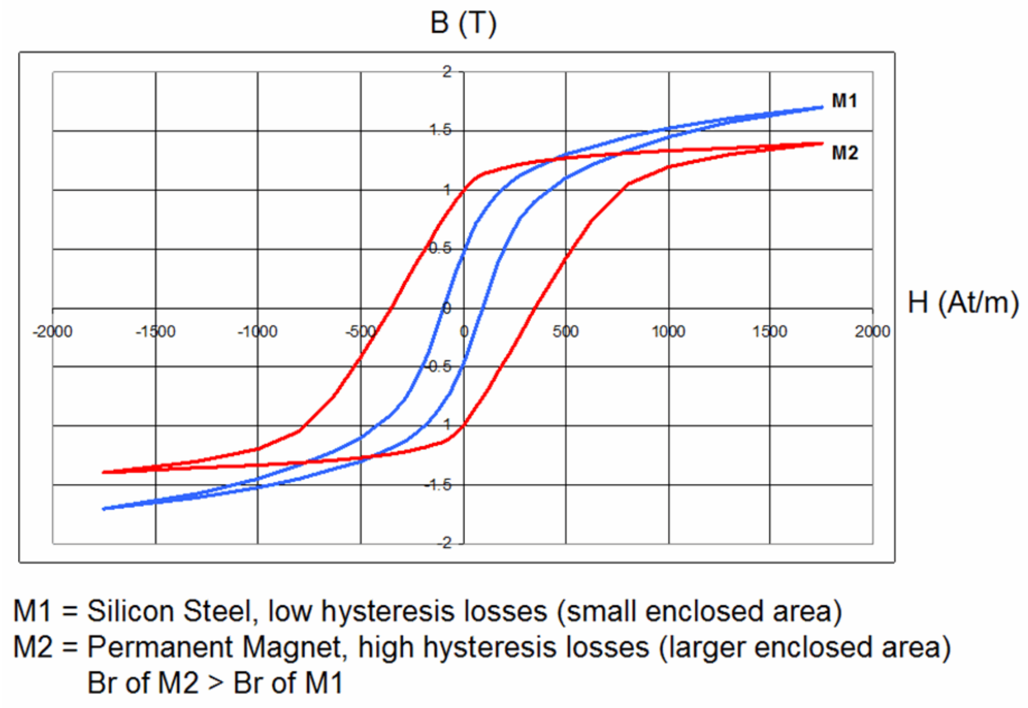


Figure 33. Graph comparing our single and overall load test results

Residual Magnetism. We encountered during both the single and overall electromagnet load tests that the steel plate would exhibit some residual magnetism, holding the connector together even when the electromagnet was turned off. This excessive residual magnetism hindered the systems ability to detach freely from the unpowered electromagnet on command. This prompted further research into the subject. We discovered that certain materials exhibit higher residual magnetism than others. Figure 34 below shows an example of two different materials and their residual magnetism.



M1 = Silicon Steel, low hysteresis losses (small enclosed area)
M2 = Permanent Magnet, high hysteresis losses (larger enclosed area)
Br of M2 > Br of M1

Figure 34. B-H curve[37] representing the relationship between magnetic flux density (B) and magnetic field strength (H) in two materials

A B-H curve represents the relationship between magnetic flux density (B) and magnetic field strength (H) in a material. It helps in characterizing a material's magnetic properties, particularly its magnetic hysteresis, saturation, and residual magnetism. By studying this curve, we can identify materials that exhibit lower residual magnetism and better suit our design needs. Based on initial research, one potential solution to this residual magnetism problem would be to choose a material such as a silicon steel or iron-nickel alloy[38] instead of low-carbon steel.

Two other options involve adjusting the thickness of the plate to aid in achieving the required pull strength or reducing the power output through the electromagnets to decrease the flux while ensuring the weight of the tether head allows for detachment. Considering our maximum pulling force already includes a safety margin, sacrificing some pulling load for a reduction in residual pulling load appears feasible and essential for resolving the issues encountered. This decision will be made after further testing with the new plate material.

Durability Drop Test. In order to ensure our drop box design was capable of protecting the tether head, we conducted a durability drop test. In conducting this test, our approach involved embedding our connector design into a foam football without any adhesive or additional securing material and then throwing the device into the air to simulate the device falling to the ground. The objective was to assess the impact of repeated drops on both the foam structure and the integrity of the connector. The connector was press-fit into the football, as depicted in Figure 35.

Figure 35. Connector inside the foam football drop box

Utilizing the airborne duration of the football, we calculated the maximum height achieved during each throw using Equations 24.1-3. Our testing revealed a maximum height of approximately 33 ft. Notably, the connector tended to dislodge from the football at heights of 23 ft or higher. Upon inspection of the connector after these drops, minor cosmetic scratches were observed, but the overall system remained operational. An illustrative example of the incurred damage is presented in Figure 36.

Figure 36. Minor damage to the steel plate on the connector

Although this test was helpful in determining preliminary considerations in how the drop box should properly attach to the tether head, it was imprecise in defining the height at which our overall system would fail. In order to properly test the durability of our system, a more repeatable procedure and a better way to attach the drop box to the tether head needs to be developed.

Actuation Cycle Test. The actuation cycle test was conducted to find three pieces of information. The first was to find the minimum cord weight that would correspond to the system dropping every time, overcoming all residual magnetism. The second was to verify the specification of detaches in < 3 seconds from command sent to mechanism to release from drone. The third and final was to verify the specification of ≥ 100 actuations before failure (“open” or “close”). The diagram we used to test for all three of these pieces of information is shown below in Figure 37.

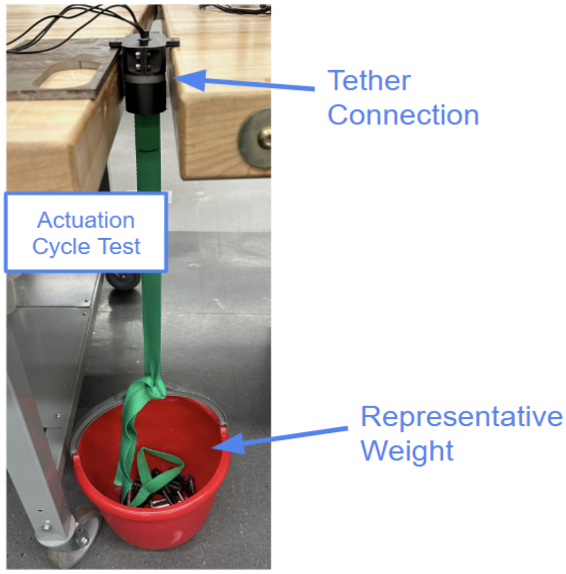


Figure 37. Actuation cycle test diagram

In order to find the minimum cord weight, we conducted a drop test of varying cord weights. We deemed that the system “dropped” when the system disconnected within 10 seconds of powering off the electromagnets. For eight different cord weights, we measured the representative cord weight using available shop weights, then counted the number of drops within 10 trials for that particular weight. The results of the representative cord weights we tested and their drop success rate out of 10 trials are shown below in Table 8.

Table 8. Increasing cord weight and drop success rate out of 10 trials.

Representative Cord Weight (lbs)	Drop Success Rate
0.80	0%
1.55	0%
2.50	20%
2.75	40%
2.85	40%
3.00	50%

Representative Cord Weight (lbs)	Drop Success Rate
3.50	60%
4.00	100%

At a representative cord weight of 4 lbs, we found that the system was disconnecting 100% of the time, indicating 4 lbs was the minimum cord weight needed to drop every time, overcoming residual magnetism. With this weight, we conducted an additional 18 trials to measure the time from sending the signal to power off the electromagnets to the tether disconnecting. Of the 17 trials that disconnected, the resulting graph in Figure 38 shows the important statistics of the detachment time test.

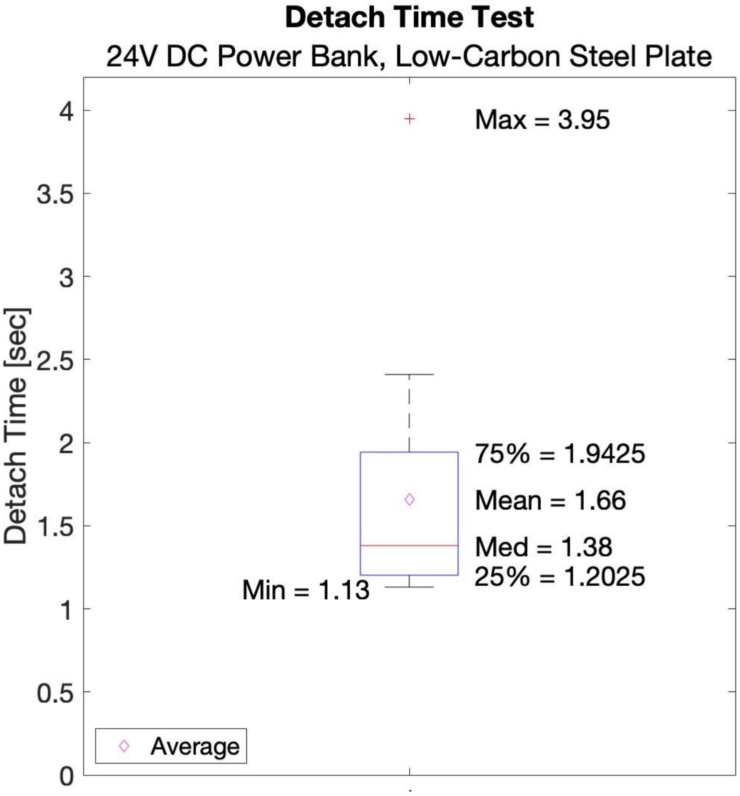


Figure 38. Detach time test results. Note that this is for 17 successful detach trials from 18 total trials.

With this representative cord weight of 4 lbs, we found that the system was disconnecting at an average of 1.66 seconds, which fit our requirement and specification of < 3 seconds. This test did bring our Drop Success Rate down from 100% to 96.4% for the 4 lb weight accounting for the one trial where the 4 lbs did not drop. After conducting these two above tests, we had successfully conducted a total of 50 drops with the system. This resulted in 50 “opens” or connecting and powering on the electromagnets and 50 “closes” or depowering the electromagnets and allowing the connector to drop. After these 50 drops or 100 actuations (counting open as one and close as one), the system did not reach failure and operated as normal, verifying our specification.

Ease of Attachment Test. Lastly, our ease of attachment test was performed in order to verify our specifications of 0 single use parts, 0 tools required to operate, and ≤ 3 steps to attach or detach. In order to perform this test, we conducted a usability test of using the prototype from the standpoint of an in the field user. This included taking the prototype from an unused state and then going through the motions of connecting the tether head and drone head together, powering the system, then depowering. For the first specification, 0 single use parts, this was verified as all parts of the prototype are reused every actuation and no parts are discarded. For the second specification, 0 tools required to operate, this was also verified as only hands are needed to connect the prototype together and disconnect, no tools are needed. For the third specification, ≤ 3 steps to attach or detach, this was also verified as there is only one step to attach or detach the connection; plug the tether head into the drone head. There are no other steps needed in the connecting of the prototype.

TETHER CONNECTION BUILD DESCRIPTION

In order to demonstrate the success of our project, we created a build prototype of the drone drop tether system. This build prototype was presented at the design expo on November 30th as a proof of concept for our overall design and allows us to conduct further verification testing. Shown below in Table 9 is the bill of materials for this build prototype.

Table 9. Build Prototype Bill of Materials

Part #	Description	Material	Make/Buy	Cost	Qty	Total Cost
Tether Connection						
1	Drone Head	Onyx	Make	$3 / gram	12 g	$36
2	Tether Head Right Side	Onyx	Make	$3 / gram	5 g	$15
3	Tether Head Left Side	Onyx	Make	$3 / gram	5 g	$15
4	Connector Receptacle	N/A	Buy	$58 Rayfast AS010-02SN	1	$58
5	Mil-Spec Connector Plug	N/A	Buy	$105 Rayfast AS610-02PN	1	$105
6	Electromagnet 24V 1” Dia ¾” Height	Iron/Steel	Buy	$60 McMaster-Carr 5698K212	2	$120
7	EM Contact Plate	Low Carbon Steel	Make	$15 McMaster-Carr 1388K384	1	$15
8	0.375” 10-32 Bolt	Black Oxide Alloy Steel	Buy	$0.15/ea McMaster-Carr 91251A340	2	$0.30
9	0.375” 4-40 Bolt	Black Oxide Alloy Steel	Buy	$0.10/ea McMaster-Carr 91251A108	4	$0.40
10	0.75” 4-40 Bolt	Black Oxide Alloy Steel	Buy	$0.16/ea McMaster-Carr 91251A305	2	$0.32

Part #	Description	Material	Make/Buy	Cost	Qty	Total Cost
11	1.125” 4-40 Bolt	Black Oxide Alloy Steel	Buy	$2.05/ea McMaster-Carr 91251A345	6	$12.30
12	4-40 Lock Nut	Steel/ Nylon	Buy	$0.04/ea McMaster-Carr 90631A005	12	$0.48
Tether Cable						
13**	100 ft of Two 16 gauge Cables Shielded and Jacketed	Copper/ Teflon	Buy	$300 TE Connectivity 55A1121-16-0/9-9	1	$300
Ground Station						
14**	Onboard EV Charger 3.3kW 180-430Vdc	N/A	Buy	$1600 Valeo	1	$1600
15**	Reel mechanism	N/A	TBD	TBD	1	TBD
Safety Device						
16	TPU enclosure	TPU	Make	$0.02 / g	10 g	$0.20
					Total Cost:	**$2,278**

*** indicates parts that will not be shown at Design Expo due to cost and time restraints*

Manufacturing Plan

The manufacturing of our build prototype can be completed with a 3D printer capable of printing ONYX, simple hand tools and electrical tools including screwdrivers, soldering irons, and super glue, and then one of the following machines in order of increasing accessibility to create the magnetic plate (CNC waterjet, CNC plasma cutter, CNC mill, CNC router, manual mill, or drill press). This plan does not include attachment of the safety mechanism, as this still needs to be developed.

Steps

1. Machine the magnetic plate out of low carbon steel using the waterjet cutter (or any other 2 axis CNC machining method available). Check dimensions.

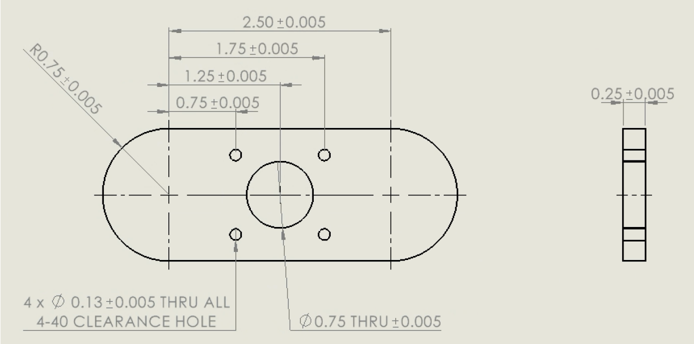


Figure 39. Magnetic Plate Drawing

2. 3D-Print the tether head and the two halves of the drone head using ONYX filament. Verify tolerances on the critical surfaces on the magnet slots and the connector.

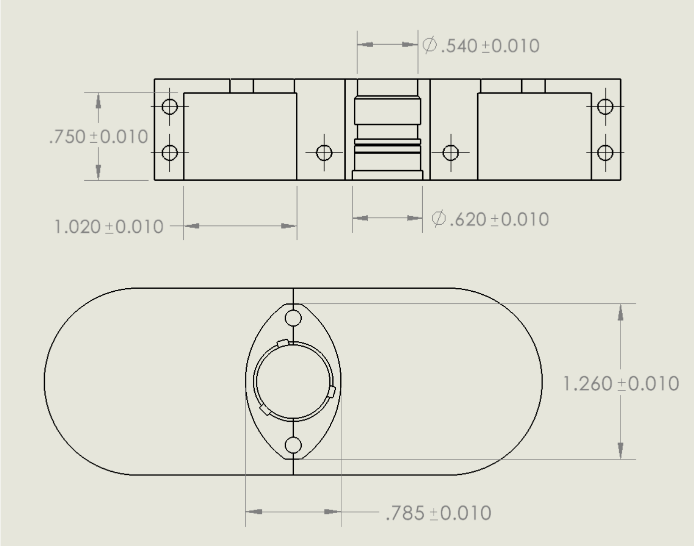


Figure 40. 3D Print Critical Dimensions

3. First, secure the receptacle into the 3D printed tether head using two 0.75 in 4-40 bolts and nuts, then secure the plate into the tether head using four 1.125 in 4-40 bolts and nuts.

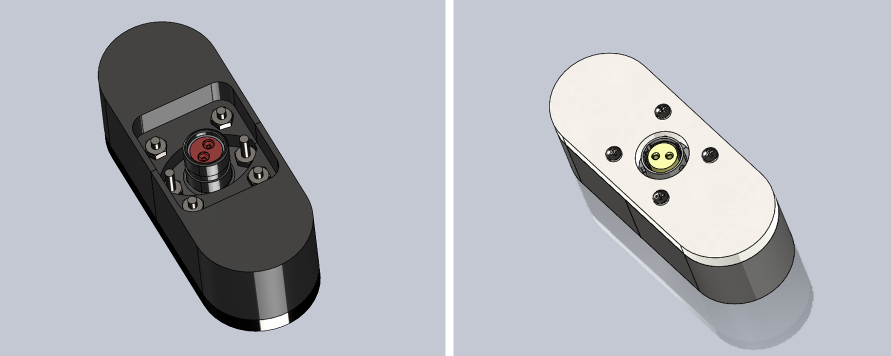


Figure 41. Tether Head Assembly

4. Insert the assembled tether head into the TPU drop box with the metal plate on the side open to the air. Secure with glue along the bottom and sides of the tether head.

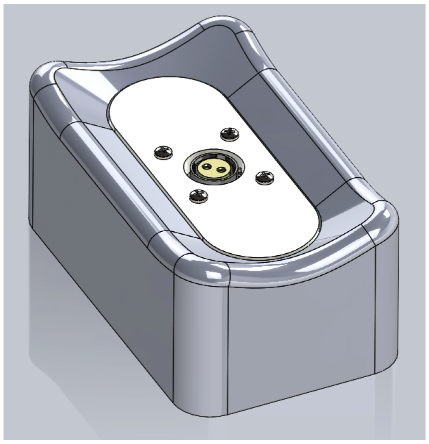


Figure 42. Tether Head with TPU Drop Box

5. Align the plug to be in proper orientation on the drone head and then super glue into position. Ensure it is rotated properly so that the tether head and drone head mate flush. Insert electro magnets then clamp two halves together using four 0.375 in 4-40 nuts and bolts for the four edge holes and two 1.125 in 4-40 nuts and bolts for the two inner holes.

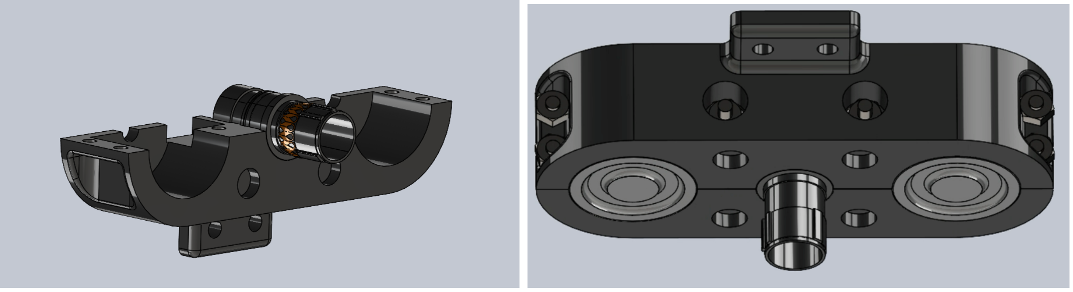


Figure 43. Drone Head Assembly

6. Solder tether cable to the connector pins and insert into the connector.

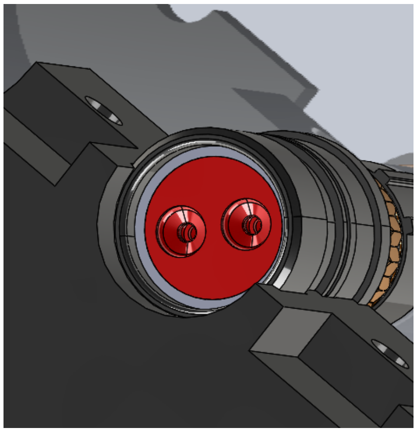


Figure 44. Cable Pins

Relationship to Final Design

The purpose of creating our build prototype is to conduct a series of verification and validation tests that we deemed more feasible and economical to be done empirically versus theoretically. Most importantly, we want to verify that the maximum pulling strength and residual pulling strength of the electromagnets are within proper ranges so as to not cause unintended tether drop or failure of tether drop when commanded, both of which are requirements of our design. A second important test that can be completed with a physical prototype is drop testing as well as reusability assessment. This is incredibly difficult to simulate due to the highly specific and random conditions imposed by drops. Further details pertaining to these test conditions and results to date are discussed in the verification and validation plan section. Results of these final tests will be used to inform changes made to our current design before submission of our final report after the expo.

FINAL DESIGN DESCRIPTION

Our most up to date design for the drop tether consists of 4 separate subsystems. First and most notably is the tether head and drone head. The design of this will be very similar to the build prototype presented at the expo with slight modifications made due to the results of verification and validation tests. The biggest change is in the magnetic plate. Originally, we prototyped this to use ¼” low carbon steel, but found that the residual magnetism is too high. For the final design, we suggest this plate to be made with ⅛” silicon steel instead.[43]

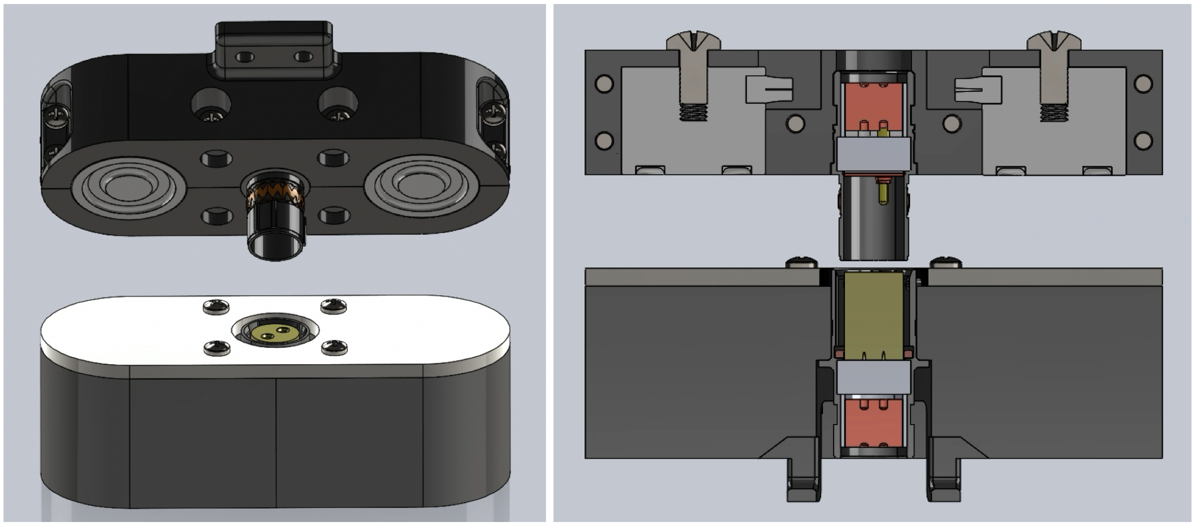


Figure 45. Tether Head and Drone Head Final Design

The next subsystem is the safety drop box. The foam drop box proved to be a cumbersome solution during our testing. Cutting the hole in the foam is very difficult to do accurately and is unlikely to be reproducible. In exchange, we are opting for a 3D printed TPU enclosure. TPU has excellent impact strength of 0.80 to 10.1 ft-lb/in[39] and is 3D printable, allowing for continued and low cost iteration of the thickness and density of the infill of the enclosure to give adequate drop protection, should the maximum height be increased down the road. The CAD screenshot below shows our final conceptual design for the enclosure. A sleeve shape with a chamfered opening allows for full protection of the tether head while maintaining access to plug into the drone head. The purpose of this drop box is to protect the connector assembly from the impact force of hitting the ground. The safety of the people comes from the barricaded radius provided by OSHA guidelines[16]. This drop box design is shown below in Figure 46.

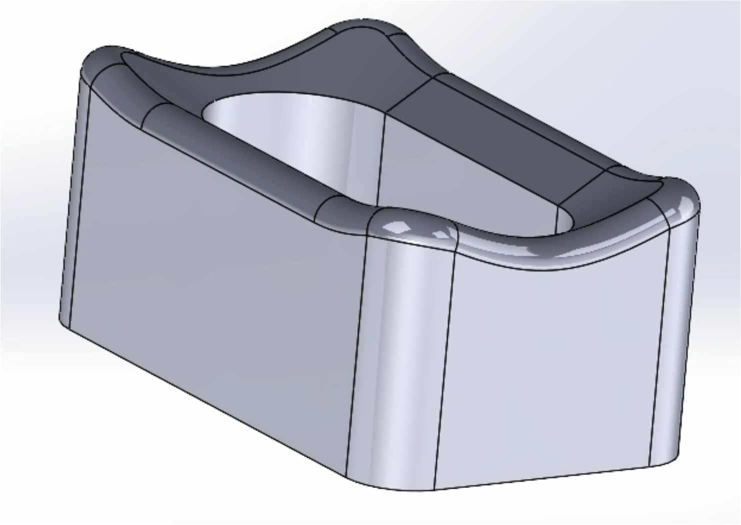


Figure 46. Safety Drop Box Final Design

For the cord subsystem, we selected a 16 gauge twisted pair cable with shielding and teflon jacket. Our initial calculations suggested that 22-26 gauge would be enough to maintain a safe operating temperature, but we decided to go with the higher gauge to ensure a safety factor. We have higher confidence that the thicker cable will operate at low temperature and be more resistant to abrasion and severing due to environmental factors. Our analysis indicated that with the current setup, 4 pounds of cable is required to achieve high detachment probability, so the length of the cable must be 150 feet instead of 100 feet in order to reach 4 pounds. This cable is shown below in Figure 47.

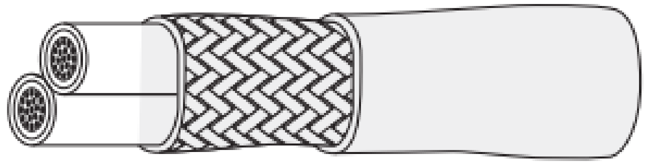


Figure 47. Chosen Tether Cable[26]

Due to the weight of the cable, a strain relief element is included in the tether head to prevent unwanted removal of the connector pins. For simplicity, we decided to make two loops that can be printed with the tether head itself so that additional parts or assembly steps are not needed. The two parts of the cable can each individually be wrapped around these loops in a way so that the pulling force remains symmetrical. This design can be seen below in Figure 48.

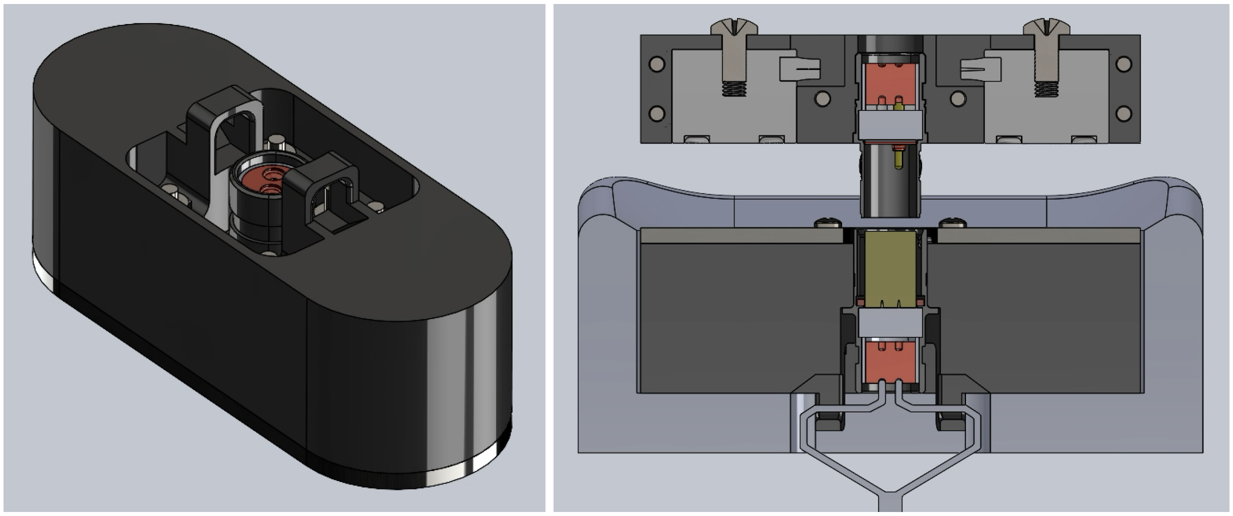


Figure 48. Depiction of Cable Strain Relief

The ground system is the final component of our design and received the least amount of attention due to time constraints and it was a lower priority requirement. We performed concept selection for this subsystem and decided that a motorized cable reel in combination with an onboard EV charger would accomplish the requirements of the overall system. Our suggestion for the EV charger would be the On Board Battery Charger for EVs (3.3kW 180-430Vdc) by Valeo. This unit retails for $1600 and has the capability to reach the required current and voltage of the end use situation. This is shown below in Figure 49.

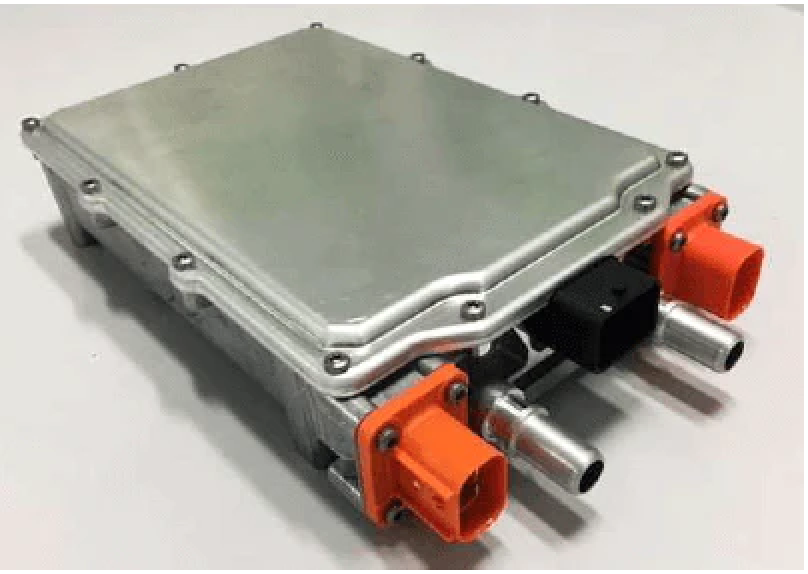


Figure 49. Suggested Ground Charger[40]

For the onboard system, we have created a more detailed circuit diagram for our suggested method for actuating the electromagnets. Our plan is to utilize the 50V DC bus to power the two electromagnets in series. A switch between the two electromagnets can be used to disconnect power and drop the tether. A switch is needed, as opposed to just connecting the electromagnets to the bus because without it, the batteries will power the electromagnets even when the power from the cable is turned off. We suggest using a remotely actuated switch that can be triggered either by the drone control interface or the ground charging station. A diagram of this can be seen below in Figure 50.

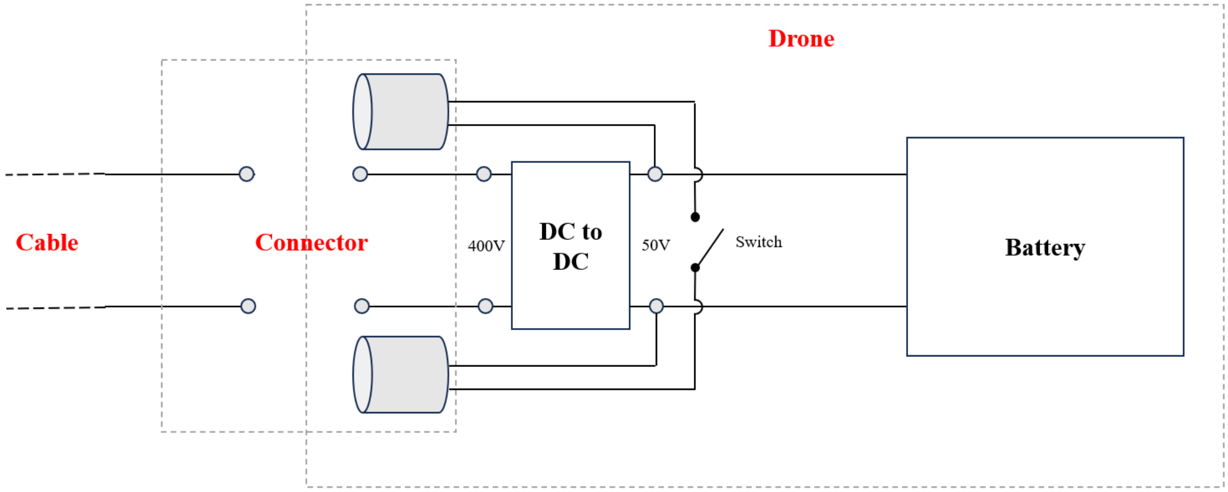


Figure 50. Electromagnet Actuation Design

VERIFICATION AND VALIDATION PLANS

For our design project, we have carefully created a list of requirements and specifications that explicitly lay out the criteria for a successful design solution, should it conform to them. Since we have gone through the concept generation process and now have a functional design, it is now time to evaluate the proficiency of the design in meeting the requirements. This is done through testing, or imposing the conditions that inspired the creation of each requirement on a model of our system and evaluating the response to ensure it passes. There are many empirical and first principle testing methods to achieve this goal, ranging from the deployment of a full scale prototype in a completely representative environment, to simple hand calculations completed with a variety of simplifying assumptions.

Methods for Testing Requirements

Each requirement we have drafted needs to be validated to an extent where we feel within appropriate certainty that the design will uphold its responsibility. There are several strategies we can use to expedite this process. In certain cases, each experiment or calculation done can test multiple requirements in tandem. For example, a connector actuation test can be used to validate fast disconnect time, durable, reusable, and easy to attach and detach. Additionally, we can build on our functional decomposition and conduct tests on prototyped parts of the overall system separately to avoid creating an expensive full scale prototype that could be destroyed in one of these tests. Finally, the simplest method of all for conducting testing is to use first principles calculations. This involves applying the related engineering fundamentals in their basic form to model the theoretical performance of the system and its reaction to a set of input conditions. This is incredibly useful because it gives us high quality information without the need for investing in material prototypes, something of emphasized importance early on in the iteration process.

Taking these strategies into consideration, we have conceived a list of required tests and calculations, shown on the next page in Table 10, that we feel will be sufficient to validate all of our requirements. A notable inclusion to this list is a test for interference with the onboard magnetometer, a hidden requirement that was uncovered during our DR2 presentation. For each of the tests, a summary of the related engineering principles is included as well as the subcomponents that are subject to redesign in the case of a failed test. Within the problem domain analysis and reflection section, we will touch on the knowledge gaps in our team that could present challenges for effectively completing certain tests.

Table 10. Requirements and specifications testing plan

Requirement	Specification	Experiments or Calculations	Engineering Fundamentals Involved	Component Subject to Iteration	Verification Results
Safety of tether drop	Entire system, including drop, operates within a barricaded 20 ft diameter circle	Drop test (measuring circle of drop points around system)	Dynamics, Health and Safety	Connector, Safety Mechanism, Cord, Reel	To be tested in the future
Adhere to maximum takeoff weight regulations	< 55 pounds	Weight calculation from CAD	Materials Science	Connector, Safety Mechanism, Cord	Passed, 4.65 lbs (4 lb cord, 0.5 lb tether head, and 0.15 lb TPU drop box) off drone + 0.532 lbs on drone
Enable as much altitude as possible	Tether length ≥ 100 ft	Drone lift force calculation	Dynamics	Connector, Safety Mechanism, Cord	Passed, only 4 lbs of cord for 150 ft versus estimated drone lift force of 10 lbs (provided by Vayu)
Drone should stay fully charged while in use with tether	Net zero decrease in battery State Of Charge (SOC) during use	Cable current carrying capacity, power loss, and heat generation calculation	E/M Physics, Heat transfer	Connector, Cord	Passed, 2500 W charging capability
Drops tether only upon command	0 unintended tether drops during normal use	Overall load test	Statics, E/M Physics	Connector	Passed, avg. max load of system is 29.29 lbs
Fast disconnect time when ready to detach	Detaches in < 3 seconds from command sent to mechanism to release from drone	Actuation cycle test (just looking at time to drop)	Controls, Usability	Connector, Safety Mechanism	Passed, avg. time of 1.66 seconds at 4 lbs cable weight
Durable	Can survive ≥ 50 drop uses	Drop test (looking at damage of system)	Dynamics, Mechanics of Materials	Connector, Safety Mechanism	To be tested in the future
	Maintains flat surface finish between steel plate and magnets. (Class B or better [19] and 3.2 μm Ra[20])	Drop test (looking at surface finish)	Dynamics, Mechanics of Materials	Connector, Safety Mechanism	To be tested in the future

Requirement	Specification	Experiments or Calculations	Engineering Fundamentals Involved	Component Subject to Iteration	Verification Results
Reusable	≥ 100 actuations before failure (“open” or “close”)	Actuation cycle test	Mechanics of Materials, Controls	Connector, Safety Mechanism	Passed, system fully operational after 100 actuations
	0 single use parts	Ease of attachment test	Controls, Usability	Connector, Safety Mechanism	Passed, 0 single use parts
Unobtrusive to drone operation, including sensors, motion, and camera	< 1% affect on drone magnetometer sensor	Magnetometer interference test	E/M Physics	Connector	To be tested in the future
	360° drone motion in yaw axis and ≥ 20° of pitch and roll	Flight simulation of tether elements on drone Real life flight test	Controls, Usability	Connector, Safety Mechanism, Cord, Reel	To be tested in the future
	≥ 180° horizontal motion of camera with unobstructed view and ≥ 90° vertical motion of camera with unobstructed view	CAD of camera FOV versus tether system in assembly Real life flight test	Controls, Usability	Connector, Safety Mechanism, Cord	To be tested in the future
	Failure mode of the system is disconnection of the tether	Drone lift force calculation Real life flight test	Controls, Usability	Connector, Safety Mechanism, Cord	Not passed, drone lift force is estimated at 10 lbs (provided by Vayu) versus 29.29 lbs of electromagnet holding force
	< 5 lb. onboard components	Weight calculation from CAD	Materials Science	Connector, Safety Mechanism, Cord	Passed, 0.532 lbs on drone
Weather resistant	Rating of IP67[11]	Mating surfaces ingress protection calculation (Refer to standard testing procedure)	Mechanics of Materials, Fluid Dynamics	Connector, Safety Mechanism, Reel	To be tested in the future

Requirement	**Specification**	**Experiments or Calculations**	**Engineering Fundamentals Involved**	**Component Subject to Iteration**	**Verification Results**
Cord cannot exceed a target temperature	When in use, the temperature must be ≤ 15°C more than the temperature of the drone	Cable current carrying capacity, power loss, and heat generation calculation Ground charging test	E/M Physics, Heat Transfer, Circuits	Cord	Passed, wire spec ensures no excessive temperature rise
Fast cord storage time	< 60 seconds	Reeling duration test	Controls	Cord, Reel	To be tested in the future
Easy to attach and detach	0 tools required to operate	Ease of attachment test	Controls, Usability	Connector, Safety Mechanism	Passed, 0 tools
	≤ 3 steps to attach or detach	Ease of attachment test	Controls, Usability	Connector, Safety Mechanism	Passed, 1 step

Verification Testing

To ensure our design meets our specifications, we performed a few of the above verification tests. These include the weight calculation from CAD, drone lift force calculation, cable current carrying capacity, power loss, heat generation calculation, overall load test, actuation cycle test, and the ease of attachment test. The outcomes of these tests are shown above in the testing plan table and the methods and discussion of these tests can be found in the engineering analysis section.

Moving forward, there are additional verification tests that can be conducted to ensure our design meets our specifications. These include a more comprehensive drop test, magnetometer interference test, flight simulation of tether elements on drone, CAD of camera FOV versus tether system in assembly, real life flight test, mating surfaces ingress protection calculation, ground charging test, and reeling duration test. These tests are laid out below.

Drop Test. For a more comprehensive drop test, we plan on testing a few aspects. The first is the radius of landing points for the connector when dropped from different heights all the way up to 100 feet. This should land within 20 feet as per our specifications, but our specification may need to change based on the radius we find. The second aspect we are looking at is the damage to the overall system, ensuring that the system can survive more than 50 drops from 100 feet and still function. Lastly, we will look at the surface finish of the metal plate, ensuring that it meets our specification and it still mates correctly with the electromagnet. This test will include 50 drops from 100 feet in order to test all three specifications with enough certainty. The prototype should be dropped on concrete or a hard material in order to test for the worst case scenario.

Magnetometer Interference Test. For the magnetometer interference test, the prototype will be placed in close proximity to the drone in order to see if there is any physical or magnetic interference with any of its components. If there are issues, we will determine an optimal mounting location on the drone that mitigates interference.

Flight Simulation of Tether Elements on Drone. This test will be conducted to verify the specifications of 360° drone motion in yaw axis and ≥ 20° of pitch and roll. This test involves creating a computer simulation using CAD of the connection mechanism and the tether itself attached to a model of the drone in order to see how the connection and tether affect the drones ability to rotate and move.

CAD of Camera FOV versus Tether System in Assembly. This test will be conducted to verify the specifications of ≥ 180° horizontal motion of camera with unobstructed view and ≥ 90° vertical motion of camera with unobstructed view. This test involves creating a computer simulation using CAD of the connection mechanism and the tether itself to see how the FOV from the camera of the drone is affected by the connection and tether. Using this simulation, we will be able to see if the camera can move and maintain an unobstructed view based on where the connection is mounted on the drone.

Real Life Flight Test. This test will be conducted to verify the specification of failure mode of the system is disconnection of the tether, and further verify the specifications of 360° drone motion in yaw axis and $\geq 20°$ of pitch and roll, $\geq 180°$ horizontal motion of camera with unobstructed view and $\geq 90°$ vertical motion of camera with unobstructed view. A real life flight test will be used to verify the failure mode of the system by purposefully conducting a failure scenario, such as the drone suddenly flying up and forward without powering off the electromagnets. Furthermore, the real life flight test will be used to further verify the drone motion and camera motion by specifications by including a usability test of these functions. During the flight test, the drone will be moved in the yaw, pitch, and roll to ensure the specifications above are met and the camera will be moved vertically and horizontally to ensure the specifications above are met.

Mating Surfaces Ingress Protection Calculation. This test will be conducted to verify the specifications of rating of IP67. The IP67 rating states that sealed devices must resist dust exposure and withstand submersion in up to 40 inches of water for 30 minutes[44]. In order to ensure this specification, the prototype will be put through the IP67 rating test by submerging it in 40 inches of water for 30 minutes in its connected and disconnected form[45].

Ground Charging Test. This test will be conducted to further verify the specifications of when in use, the temperature must be $\leq 15°C$ more than the temperature of the drone. This would involve powering the tether cable with the 400V going into the DC DC converters to then charge the drone battery (the drone would be strapped down with the propellers running). Then the cord temperature would be measured to ensure it stays within our specifications.

Reeling Duration Test. This test will be conducted to verify the specifications of < 60 seconds to reel in the tether. Once a reeling prototype is created, this will be a simple test of timing how long from tether disconnection it takes to fully reel in the cord into the storage reel.

Validation Plans

Our preliminary validation strategies are designed to confirm the alignment of our final design with the defined problem. Several steps can be taken to validate the effectiveness of our mechanism.

To begin, a comprehensive review of our problem statement will be conducted. This step ensures that our design is appropriately addressing the identified problem. Any potential discrepancies or oversights can be rectified through this examination. Furthermore, engaging in discussions with our project sponsor is a crucial aspect of validation. By doing so, we seek to validate that our design aligns with the expectations and requirements of both our sponsor and their end-users. This dialogue allows us to gain valuable insights and ensures that the design meets the desired criteria. Throughout this validation process, soliciting and receiving feedback from our sponsor is essential. This feedback loop provides an opportunity to address any concerns or suggestions, fostering continuous improvement. It enables us to refine the design based on the practical insights offered by those closely associated with the project.

Additionally, it is crucial to engage in ongoing discussions with customers. Their input is valuable, considering they are the ones purchasing the product. Through the implementation of end-to-end testing, we can confirm that the design aligns with their expectations and incorporate any suggestions or comments they may provide.

In essence, this multi-faceted validation approach not only safeguards against misalignment with the initial problem but also establishes a dynamic feedback mechanism with our sponsor and the customers, ensuring that our design is not only technically sound but also aligns with the practical needs and expectations of the stakeholders involved.

PROJECT PLAN

In this section, we will talk about our project timeline and the important milestones we achieved during the course or were unable to achieve, and some lessons we have learned.

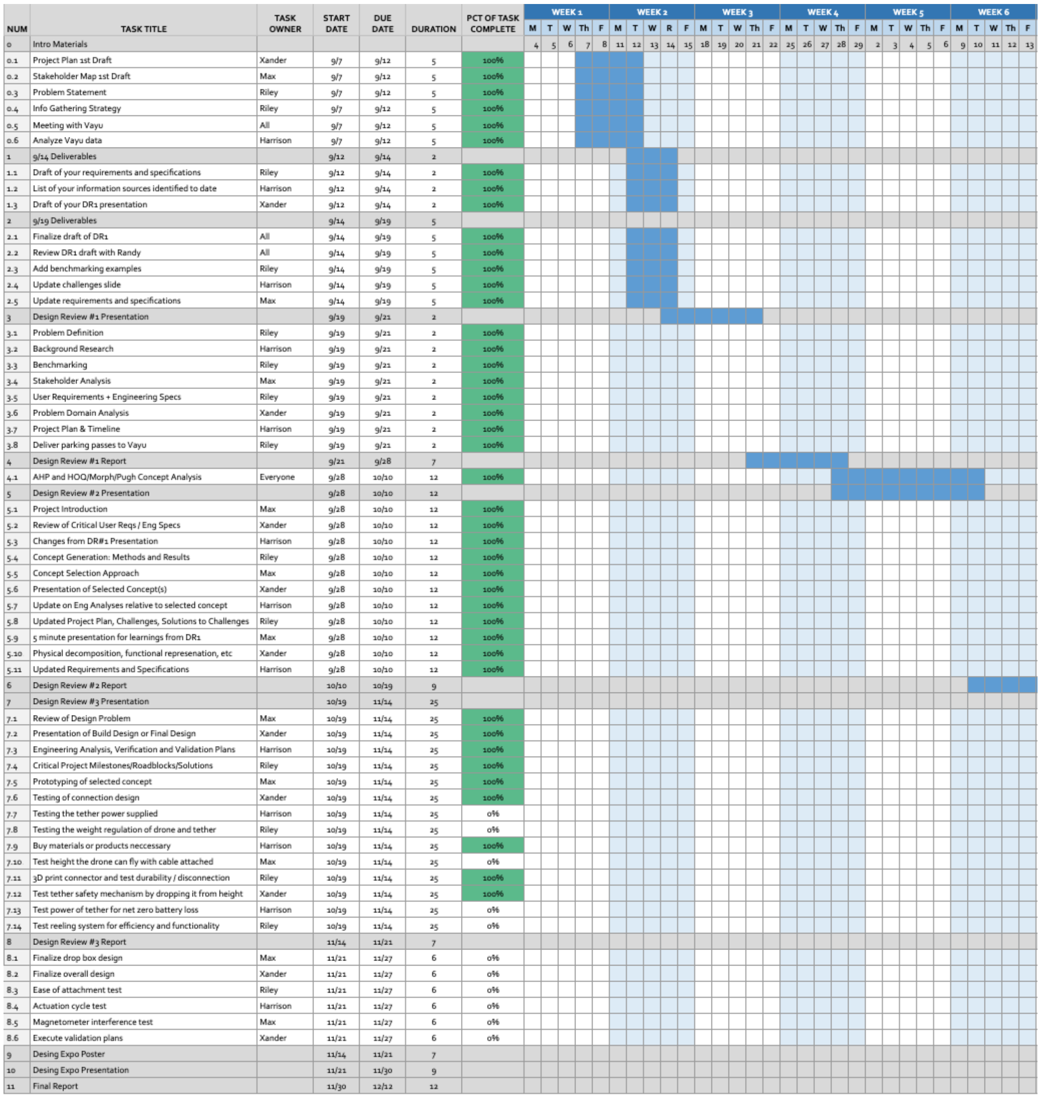
Project Scope and Feasibility

The scope of our semester-long project underwent adjustments due to various constraints. Primary among these is the limitation of our budget, which proved insufficient to acquire all the necessary components for the comprehensive design. Key elements such as procuring high performance cable, along with its associated onboard electrical components such as the DC DC converters, and the motorized reeling system, have been impacted by this financial constraint. Additionally, the inherent risks associated with testing the wire at 400V were too high for us to conduct a test safely on campus.

As a result of these challenges, we shifted our focus to the development of the connector and the drop box mechanism. The allocated budget of $400 from the ME 450 resources was adequate for the completion of these specific components. Leveraging the 3D printers available at Vayu's facility has proven valuable in advancing our design process. Furthermore, ongoing communication with our project sponsor has played a pivotal role in soliciting feedback and implementing necessary modifications to our design.

Project Schedule

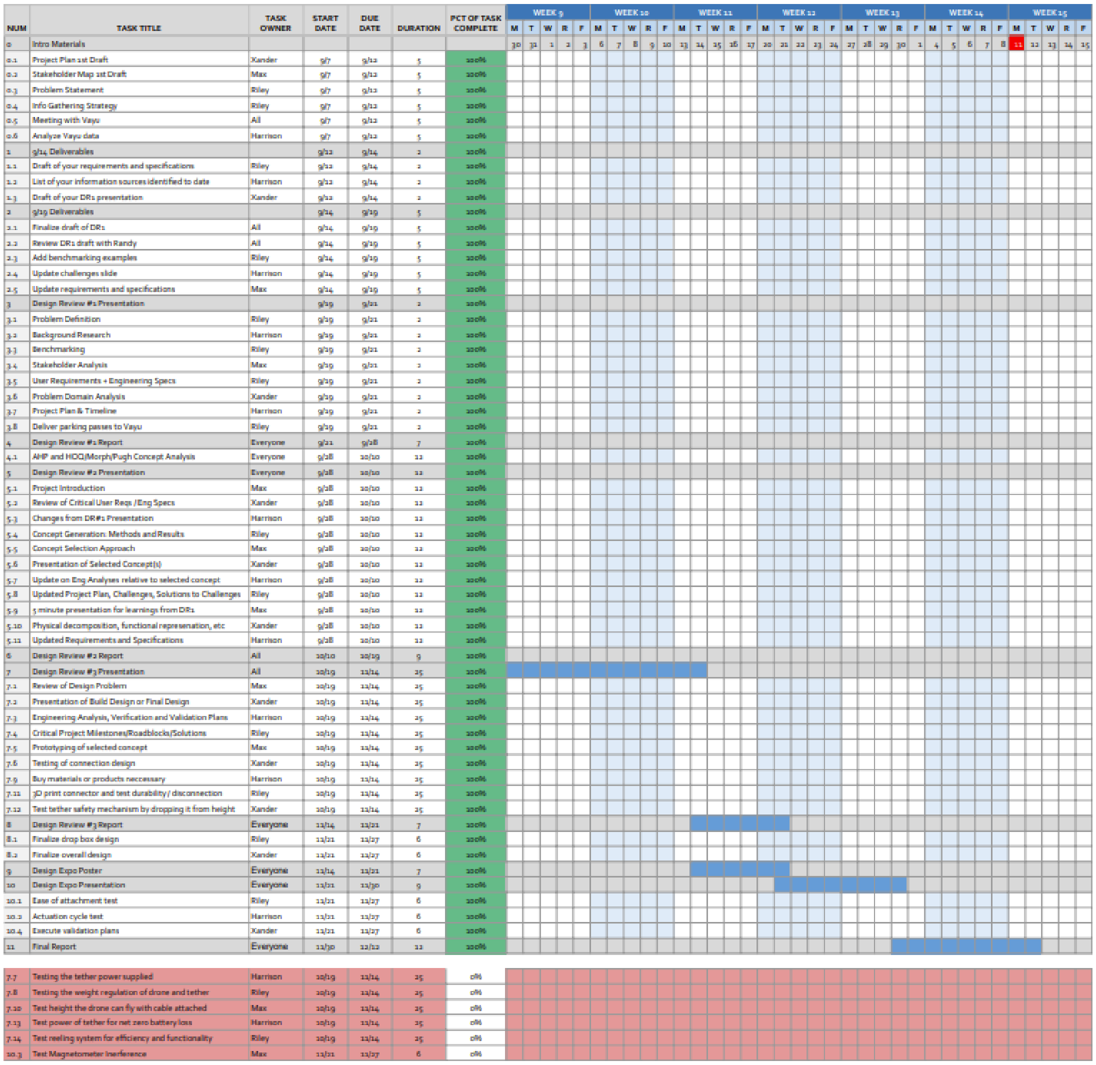
A comprehensive review of our project schedule has been established, aligning with the major milestones provided by the ME 450 staff. This structured timeline guided our project's progression and ensured that we remained on track for successful completion. Each team member was assigned specific tasks that helped us reach our final goal, which have been documented below in our Gantt chart in Figure 51. This task allocation ensured accountability and streamlined our workflow. The critical path to project completion followed the Gantt chart and the associated task assignments.



NUM	TASK TITLE	TASK OWNER	START DATE	DUE DATE	DURATION	PCT OF TASK COMPLETE
0	Intro Materials					
0.1	Project Plan 1st Draft	Xander	9/7	9/12	5	100%
0.2	Stakeholder Map 1st Draft	Max	9/7	9/12	5	100%
0.3	Problem Statement	Riley	9/7	9/12	5	100%
0.4	Info Gathering Strategy	Riley	9/7	9/12	5	100%
0.5	Meeting with Vayu	All	9/7	9/12	5	100%
0.6	Analyze Vayu data	Harrison	9/7	9/12	5	100%
1	9/14 Deliverables		9/12	9/14	2	
1.1	Draft of your requirements and specifications	Riley	9/12	9/14	2	100%
1.2	List of your information sources identified to date	Harrison	9/12	9/14	2	100%
1.3	Draft of your DR1 presentation	Xander	9/12	9/14	2	100%
2	9/19 Deliverables		9/14	9/19	5	
2.1	Finalize draft of DR1	All	9/14	9/19	5	100%
2.2	Review DR1 draft with Randy	All	9/14	9/19	5	100%
2.3	Add benchmarking examples	Riley	9/14	9/19	5	100%
2.4	Update challenges slide	Harrison	9/14	9/19	5	100%
2.5	Update requirements and specifications	Max	9/14	9/19	5	100%
3	Design Review #1 Presentation		9/19	9/21	2	
3.1	Problem Definition	Riley	9/19	9/21	2	100%
3.2	Background Research	Harrison	9/19	9/21	2	100%
3.3	Benchmarking	Riley	9/19	9/21	2	100%
3.4	Stakeholder Analysis	Max	9/19	9/21	2	100%
3.5	User Requirements + Engineering Specs	Riley	9/19	9/21	2	100%
3.6	Problem Domain Analysis	Xander	9/19	9/21	2	100%
3.7	Project Plan & Timeline	Harrison	9/19	9/21	2	100%
3.8	Deliver parking passes to Vayu	Riley	9/19	9/21	2	100%
4	Design Review #1 Report		9/21	9/28	7	
4.1	AHP and HOQ/Morph/Pugh Concept Analysis	Everyone	9/28	10/10	12	100%
5	Design Review #2 Presentation		9/28	10/10	12	
5.1	Project Introduction	Max	9/28	10/10	12	100%
5.2	Review of Critical User Reqs / Eng Specs	Xander	9/28	10/10	12	100%
5.3	Changes from DR#1 Presentation	Harrison	9/28	10/10	12	100%
5.4	Concept Generation: Methods and Results	Riley	9/28	10/10	12	100%
5.5	Concept Selection Approach	Max	9/28	10/10	12	100%
5.6	Presentation of Selected Concept(s)	Xander	9/28	10/10	12	100%
5.7	Update on Eng Analyses relative to selected concept	Harrison	9/28	10/10	12	100%
5.8	Updated Project Plan, Challenges, Solutions to Challenges	Riley	9/28	10/10	12	100%
5.9	5 minute presentation for learnings from DR1	Max	9/28	10/10	12	100%
5.10	Physical decomposition, functional represenation, etc	Xander	9/28	10/10	12	100%
5.11	Updated Requirements and Specifications	Harrison	9/28	10/10	12	100%
6	Design Review #2 Report		10/10	10/19	9	
7	Design Review #3 Presentation		10/19	11/14	25	
7.1	Review of Design Problem	Max	10/19	11/14	25	100%
7.2	Presentation of Build Design or Final Design	Xander	10/19	11/14	25	100%
7.3	Engineering Analysis, Verification and Validation Plans	Harrison	10/19	11/14	25	100%
7.4	Critical Project Milestones/Roadblocks/Solutions	Riley	10/19	11/14	25	100%
7.5	Prototyping of selected concept	Max	10/19	11/14	25	100%
7.6	Testing of connection design	Xander	10/19	11/14	25	100%
7.7	Testing the tether power supplied	Harrison	10/19	11/14	25	0%
7.8	Testing the weight regulation of drone and tether	Riley	10/19	11/14	25	0%
7.9	Buy materials or products neccessary	Harrison	10/19	11/14	25	100%
7.10	Test height the drone can fly with cable attached	Max	10/19	11/14	25	0%
7.11	3D print connector and test durability / disconnection	Riley	10/19	11/14	25	100%
7.12	Test tether safety mechanism by dropping it from height	Xander	10/19	11/14	25	100%
7.13	Test power of tether for net zero battery loss	Harrison	10/19	11/14	25	0%
7.14	Test reeling system for efficiency and functionality	Riley	10/19	11/14	25	0%
8	Design Review #3 Report		11/14	11/21	7	
8.1	Finalize drop box design	Max	11/21	11/27	6	0%
8.2	Finalize overall design	Xander	11/21	11/27	6	0%
8.3	Ease of attachment test	Riley	11/21	11/27	6	0%
8.4	Actuation cycle test	Harrison	11/21	11/27	6	0%
8.5	Magnetometer interference test	Max	11/21	11/27	6	0%
8.6	Execute validation plans	Xander	11/21	11/27	6	0%
9	Desing Expo Poster		11/14	11/21	7	
10	Desing Expo Presentation		11/21	11/30	9	
11	Final Report		11/30	12/12	12	

Figure 51. Project plan Gantt chart drafted for the Drone Drop Tether Project[42]

As our projections and goals shifted over time, our project plan changed to match it. Figure 52 below shows our updated project plan.



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2.4	Update challenges slide	Harrison	9/14	9/19	5	100%
2.5	Update requirements and specifications	Max	9/14	9/19	5	100%
3	Design Review #1 Presentation		9/19	9/21	2	100%
3.1	Problem Definition	Riley	9/19	9/21	2	100%
3.2	Background Research	Harrison	9/19	9/21	2	100%
3.3	Benchmarking	Riley	9/19	9/21	2	100%
3.4	Stakeholder Analysis	Max	9/19	9/21	2	100%
3.5	User Requirements + Engineering Specs	Riley	9/19	9/21	2	100%
3.6	Problem Domain Analysis	Xander	9/19	9/21	2	100%
3.7	Project Plan & Timeline	Harrison	9/19	9/21	2	100%
3.8	Deliver parking passes to Vayu	Riley	9/19	9/21	2	100%
4	Design Review #1 Report	Everyone	9/21	9/28	7	100%
4.1	AHP and HOQ/Morph/Pugh Concept Analysis	Everyone	9/28	10/10	12	100%
5	Design Review #2 Presentation	Everyone	9/28	10/10	12	100%
5.1	Project Introduction	Max	9/28	10/10	12	100%
5.2	Review of Critical User Reqs /Eng Specs	Xander	9/28	10/10	12	100%
5.3	Changes from DR#1 Presentation	Harrison	9/28	10/10	12	100%
5.4	Concept Generation: Methods and Results	Riley	9/28	10/10	12	100%
5.5	Concept Selection Approach	Max	9/28	10/10	12	100%
5.6	Presentation of Selected Concept(s)	Xander	9/28	10/10	12	100%
5.7	Update on Eng Analyses relative to selected concept	Harrison	9/28	10/10	12	100%
5.8	Updated Project Plan, Challenges, Solutions to Challenges	Riley	9/28	10/10	12	100%
5.9	5 minute presentation for learnings from DR1	Max	9/28	10/10	12	100%
5.10	Physical decomposition, functional represenation, etc	Xander	9/28	10/10	12	100%
5.11	Updated Requirements and Specifications	Harrison	9/28	10/10	12	100%
6	Design Review #2 Report	All	10/10	10/19	9	100%
7	Design Review #3 Presentation	All	10/19	11/14	25	100%
7.1	Review of Design Problem	Max	10/19	11/14	25	100%
7.2	Presentation of Build Design or Final Design	Xander	10/19	11/14	25	100%
7.3	Engineering Analysis, Verification and Validation Plans	Harrison	10/19	11/14	25	100%
7.4	Critical Project Milestones/Roadblocks/Solutions	Riley	10/19	11/14	25	100%
7.5	Prototyping of selected concept	Max	10/19	11/14	25	100%
7.6	Testing of connection design	Xander	10/19	11/14	25	100%
7.9	Buy materials or products neccessary	Harrison	10/19	11/14	25	100%
7.11	3D print connector and test durability / disconnection	Riley	10/19	11/14	25	100%
7.12	Test tether safety mechanism by dropping it from height	Xander	10/19	11/14	25	100%
8	Design Review #3 Report	Everyone	11/14	11/21	7	100%
8.1	Finalize drop box design	Riley	11/21	11/27	6	100%
8.2	Finalize overall design	Xander	11/21	11/27	6	100%
9	Design Expo Poster	Everyone	11/14	11/21	7	100%
10	Design Expo Presentation	Everyone	11/21	11/30	9	100%
10.1	Ease of attachment test	Riley	11/21	11/27	6	100%
10.2	Actuation cycle test	Harrison	11/21	11/27	6	100%
10.4	Execute validation plans	Xander	11/21	11/27	6	100%
11	Final Report	Everyone	11/30	12/12	12	100%
7.7	Testing the tether power supplied	Harrison	10/19	11/14	25	0%
7.8	Testing the weight regulation of drone and tether	Riley	10/19	11/14	25	0%
7.10	Test height the drone can fly with cable attached	Max	10/19	11/14	25	0%
7.13	Test power of tether for net zero battery loss	Harrison	10/19	11/14	25	0%
7.14	Test reeling system for efficiency and functionality	Riley	10/19	11/14	25	0%
10.3	Test Magnetometer Inerference	Max	11/21	11/27	6	0%

Figure 52. Updated project plan Gantt chart as of 12/11/23. Note that the tasks in red at the bottom of the plan are the tests we were not able to complete before the end of term.

DISCUSSION

Problem Definition

If we had more time to define our problem before beginning our design process, we believe that more effort spent on failure modes would have aided us in creating a better solution. It became apparent to us towards the end of our project that failure modes often are difficult to brainstorm and usually present themselves during testing of the product. One way to mitigate this issue is to conduct thorough benchmarking. Other people have faced similar issues in the past when designing similar projects and by analyzing the solution they created, it can inspire the creation of requirements for your own design. The most impactful example of where this could have saved us a lot of headache is with the residual magnetism in the plate. It did not occur to us that residual magnetism even existed until we discovered it when testing our prototype. Being equipped with this knowledge before designing would have been extremely beneficial.

Design Critique

Evaluating our design honestly, our team believes that there are some clear strengths and weaknesses. Starting with the strengths, the drone head and tether head prototypes are incredibly simple to manufacture. All parts are 3D printed except for the metal plate, which requires some form of 2D machining such as a CNC mill or waterjet, and can even be made by hand drilling the holes if needed. Another strength of our design is its complete non-dependency on moving parts. This was a conscious decision that we made because we felt that it would increase the reliability and user-friendliness of the system. Moving to weaknesses of our design, the biggest flaw is the residual magnetism in the metal plate. This had the unexpected side effect of keeping the tether head and plate connected even when the electromagnets are off, resulting in a light pulling force of a few pounds to make it drop on command. It is our understanding that no matter the situation with the electromagnets, there will always be a residual magnetism in the plate, but there are strategies to decrease this force. One would be to select a material with lower residual magnetism, such as a purer form of iron or a special electrical alloy such as silicon steel[43]. A second strategy would be to tune the geometry of the plate to have just enough pulling force when the magnet is on and then have a lower residual force in return. Our safety factor at the moment is quite high at 8.3, and we think there could be room here to reduce it, while still having ample connection force for the tether.

Challenges and Risks

During the project, we came across a few major challenges. The first was our budget constraints, which impose limitations on the components we can incorporate into our final prototype. The allocated budget of $400, provided by ME 450, prohibited the acquisition of certain essential components, such as the 100 ft cord and the motorized reeling system. To address this challenge, our strategy involves the development of mockups and the reliance on robust calculations to support our ongoing testing, despite the prototype’s incomplete state.

Another noteworthy challenge pertains to cord testing. While the procurement of a 100 ft cord is unfeasible within our budget constraints, it is crucial to acknowledge the safety concerns associated with testing it at 400 V without the correct power supply and high voltage safety training. To mitigate this risk, we conducted careful calculations and ensured the cord specifications met all of our needs.

Our design has one main risk that we ultimately decided to accept. The dropping of the tether head from heights near or exceeding 100 ft has major safety concerns for anyone or anything that gets struck by it. Simple hand calculations that we performed revealed that the impact force would be half the rated force of a grade 1 hard hat and could cause serious injury in many cases. We would like to reiterate here that drop testing is a serious requirement in the future when a more complete prototype is created so that a safe operating radius can be identified and communicated to the user. An additional risk is the high voltage (400V) that is used in the charging cable. Clear warnings will need to be printed on the delivered products and software will likely be needed to ensure that a disconnected tether will not be sending power to the pins of the cable. Our efforts to reduce risk in this area included attaching the female side of the connector on the tether head as well as solely using components that are rated above 400V and the 6.5A current we expect.

Lessons Learned

Throughout the design process, we have gained a wealth of valuable insights and experiences. A significant lesson learned is that our initial estimation of the project's progression rate was considerably over-optimistic. This realization prompted us to make strategic cuts and prioritize specific components over others. For instance, our final prototype did not include the reel and cord due to budget constraints and safety considerations, and we focused on finalizing the connector and safety mechanism.

Additionally, some verification tests will remain incomplete as we lack the necessary components and time for testing. Another key lesson centers around the unexpected challenges that physical testing can unveil, challenges not anticipated through prior research and analysis. An illustrative example is the residual strength of the electromagnet when the power is turned off. The presence of residual magnetism requires additional force to disconnect the connector from the drone side, an aspect that we only learned about through physical testing.

REFLECTION

Relevant Factors

Numerous factors are relevant to our project. With public health, safety, and welfare, our product holds significance as it enhances the capabilities of surveillance drones. This improvement contributes to heightened safety measures but also raises concerns about privacy infringement. On a global scale, our design stands out as a new entry in the marketplace. The innovative feature of swiftly transitioning from surveillance to pursuit makes it particularly sought after by other drone surveillance companies. Considering social impacts tied to our design, minimal concerns arise regarding the manufacturing process or disposal. The entire design is both reusable and easily manufacturable through 3D printers. Examining the economic impact, it is important to note that this product constitutes a costly addition of $2,278 to the drone and does not generate additional employment opportunities. To characterize the societal impacts comprehensively, we have crafted a stakeholder map to discern the individuals or groups affected by our product. This mapping exercise allows us to pinpoint key stakeholders and understand the broader societal implications of this design.

Team Dynamics

The positive impact of cultural, privilege, identity, and stylistic similarities and differences among team members is evident in how effectively our team executed the project. Each team member brings unique strengths which contribute to the successful completion of various tasks related to our design, such as CAD, research, calculations, and report writing. Additionally, diverse engineering skills and experiences, including those from Spark Electric Racing and the University of Michigan Solar Car Team, proved to be valuable assets for our team dynamics.

Similarly, the influence of cultural, privilege, identity, and stylistic aspects played a crucial role in shaping our design process and the final product, especially in collaboration with our sponsor, Vayu Aerospace. Our goal was to develop a product that aligns with Vayu's expectations, considering their significant role as sponsors and their knowledge about the project. Multiple meetings and incorporating their advice into our design iterations were instrumental in arriving at our final design, ensuring it met both our team's objectives and our sponsor's satisfaction.

Inclusion and Equity

The power dynamics between our sponsor and our team members played a vital role in shaping our final design. Vayu Aerospace generously provided us access to their facility and consistently offered constructive feedback, which we incorporated into each iteration. Leveraging the unique engineering skills and backgrounds of our team members facilitated the progress of our project, allowing us to work with each individual's strengths and complete the final design.

Given that the US-2 drone is a prototype with unknown buyers, we did not directly engage with end users during the communication process. Recognizing the potential value of their feedback, especially in refining the final design and exploring further iterations, we remained attentive to the diverse viewpoints of both stakeholders and team members. This inclusive approach enabled effective communication and informed decision-making as we navigated the design process.

Within all the ideas generated throughout the design phase, selecting specific concepts for implementation became essential. With input coming from both our sponsor and team members, we prioritized our own analytical analysis of our concepts first, then incorporated the feedback from Vayu Aerospace. Engaging in team discussions, we collectively determined the most effective path forward to enhance the overall design.

The cultural similarities and differences among team members played a role in advancing our design process. The diverse engineering backgrounds within the team led to the creation of numerous unique ideas, offering a rich array of options for consideration. This diversity allowed us to explore various possibilities and select the optimal choices for our design. Furthermore, the cultural similarities and differences with our sponsor significantly influenced our design approach, as we were crafting the product for their satisfaction. Integrating their distinct inputs became a crucial aspect of our decision-making, ensuring that the final design resonated with their expectations and requirements.

Ethics

Throughout the project's design process, several ethical considerations demanded our attention. A primary concern involved the safety implications of our tether drop, given the 100-foot descent. Recognizing potential risks to those in proximity to our system, we established a requirement aligned with OSHA guidelines, mandating a 20-foot barricaded diameter around our setup for safety. Environmental impact emerged as another ethical consideration, prompting us to create a fully reusable system to minimize waste. This commitment was integrated throughout our design process, leading to the formulation of a corresponding reusable requirement.

Introducing our product to the market reveals additional ethical concerns. Privacy became a focal point due to the extended surveillance capabilities and the transition to pursuit mode. The presence of the drone's camera raised privacy issues for those within its scope. Additionally, the noise generated by the drone during flight introduced potential concerns, especially for individuals residing or working in close proximity. Addressing these ethical issues may involve carefully selecting the drone system's location.

Our personal ethics closely align with the values upheld by professionals and prospective employers. The top consideration throughout the design process was safety, with a strong emphasis on preventing harm to users. Our aspiration is to develop a product that not only meets ethical standards but also gains pride and approval from ourselves and potential users alike.

RECOMMENDATIONS

1. Iterate on the TPU drop box and find a solution that has a satisfactory safety to form-factor compromise. Increasing the thickness of the TPU will give it better impact absorption capabilities at the cost of it being larger. Our decision on the dimensions was somewhat arbitrary and made based on intuition, but due to the simplicity of the drop tests and the rapid prototyping capabilities, we felt that this iteration would be relatively easy to execute.

2. Look into alternative components and designs for the electromagnets and tether head plate, respectively. Using higher-end components such as more powerful electromagnets or more expensive alloys for the plate could yield more desirable properties such as a smaller end product, more holding force when powered, and less residual magnetism. Reducing the thickness in the plate could provide the same effect. Our budget was limited, but we identified silicon steel as a good alloy replacement for the plate[43]. Our time is also limited and so we could not iterate on the plate further and conduct more tests before the end of the project.

3. Add a new mechanism or develop a procedure for disconnecting the cord from the drone. This could be something simple like a linear servo on the drone side that pushes the tether head off with pins, or it could be a procedure where the reel lightly pulls the cord down once the signal to drop has been sent. In our testing, the cord fell when unpowered with a cord weight of 4 lbs, but with lower weights, the system sometimes took several seconds and in rare cases would stay connected until we pulled it off by hand due to residual magnetism. Adding this further disconnect feature would significantly increase the probability of successful disconnection without the need for human interference.

4. Further test the design. The design in its current state has potential, but requires more rigorous and lengthy testing to determine its viability in the real world. For instance, there are aspects of the design that could interfere with onboard components on the drone - like the magnetometer - that we do not have enough information about, so developing an empirical test or simulation of the drone-tether system, as shown in the verification section above, would be crucial in understanding the design's validity, but this requires time and resources that we as a team do not have at the moment.

5. Iterate on the reel mechanism(s). This was a part of the project that was not critical to the tether's primary function and there would have been a considerable amount of time, money and effort needed to bring the reel to the same prototype state as the tether. Because of this, we decided to focus our efforts on only the tether connection and cord design, at Vayu's permission and approval. To fully implement the drop tether system, and to greatly increase user-friendliness, this part of the system should be further integrated, prototyped, and tested.

CONCLUSION

During this semester, significant progress has been made in advancing the US-2 Drone Drop Tether Project. Our connector design has been developed as well as a TPU 3D printed drop box design. The iteration of our prototypes encompass a single electromagnet connector, a repulsion-type electromagnet connector, and our current design, the symmetrical double electromagnet connector. For safety, our iterations included a parachute system, a foam football around the tether head connector, and now a TPU 3D printed drop box.

Verification of our design has been conducted through various verification tests, including an electromagnet load test, an overall load test, a durability drop test, an actuation cycle test, and an east of attachment test. These tests have yielded valuable insights, affirming that our design aligns with the requirements and specifications. Additional verification tests are required for future testing as laid out in the verification and validation section.

Furthermore, rigorous calculations have been computed to further verify our design. This includes analyses of the power supply and cord dynamics, as well as an examination of the safety mechanism. For the power supply, the system will run at 400 V with a corresponding 150 ft cord. Safety mechanism calculations have assessed the impact force on the connector (approximately 2220 N). An examination of the residual magnetism encountered during testing has been conducted, revealing variations in strength among different materials with our recommendation being a ⅛" silicon steel instead.

A comprehensive manufacturing plan has been devised, involving 3D printing for housing components, machining a metal plate, and utilizing super glue, soldering kits, and wire strain relief mechanisms to finalize the design.

Additional recommendations have been suggested to improve on the design. This includes more iterations on the drop box, exploring higher-end components, a physical mechanism to detach the tether connection, more system testing, and working on the reel design. These tasks can further finalize the design and ready it for customer use.

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We would like to thank Mike Carovillano, Preston Schipper, and Yoni Seevers from Vayu Aerospace for their assistance and sponsorship of our project, which included 3D printing components we needed on short notice, attending our design reviews in person, and overall creating an engaging project for us to work on. Additionally, we would like to thank our instructor Randy Schwemmin and the rest of the ME 450 instructional staff for aiding us in the completion of this project.

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TEAM BIOS

Harrison Kim

Harrison Kim is a senior at the University of Michigan. In May 2024, Harrison will graduate with the Bachelors of Science in Engineering (BSE) degree in Mechanical Engineering (ME). He grew up in Dexter, Michigan which is a small city local to his college campus in Ann Arbor, Michigan.

Harrison has an interest in mechanical engineering because he enjoys crafting innovative solutions and thrives in hands-on environments. Harrison has demonstrated his engineering skills as a former member of the University of Michigan Solar Car Team, where he actively contributed to the development of the suspension system. Additionally, his commitment to practical application was evident during an internship at Ford, where he engaged in Product Development. During his time there, he conducted rigorous testing of airbag systems through a combination of online simulations and real-world experiments, further enhancing his practical skill set.

Post-graduation, Harrison plans to have a career in the automotive industry. He aims to work on pioneering projects that will shape the future of transportation, emphasizing safety, efficiency, and sustainability.

Riley Hargrave

Riley Hargrave is also a senior at the University of Michigan and will graduate in May 2024 with a BSE in Mechanical Engineering. He grew up in Hopkinton, Massachusetts, a small town outside of Boston. Playing electric guitar and pickup soccer are Riley’s favorite pastimes.

Mechanical engineering was always an obvious choice for Riley, who enjoyed Math and Science courses in high school as well as messing around with passion projects at the workbench. After arriving in Michigan, Riley got involved with SPARK Electric Racing to pursue an itch to learn more about electric vehicles. As a member of this team, Riley learned how to design and manufacture battery packs and pivoted into the research world armed with this knowledge. His first internship was in a research lab at Michigan studying battery active material with professor Yiyang Li, and the following summer he went to Argonne National Lab to study new approaches to making solid-state batteries.

Post-graduation, Riley plans to pursue a Ph.D. focused on advanced battery technologies in the field of Materials Science. He envisions combining his mechanical engineering background with further education in materials science to help design better batteries for electric vehicles.

Max Gusukuma
Max Gusukuma is the third senior on the team at the University of Michigan and graduating in May 2024 with a BSE in Mechanical Engineering. He has lived all around the United States but likes to say his hometown is Bellingham, Washington, where he grew up to enjoy being in nature. He goes camping when he can, but when stuck at home he enjoys video and board games, horror movies, and working on personal origami projects.

In high school, Max had the opportunity to join his local FIRST Robotics Competition team, and from there he knew that he wanted to work on robots for his career. He loved working on the robot's mechanisms, so he decided that solving other mechanical problems was the job for him, and that mechanical engineering was the major he should study. In college, Max is an avid member of hands-on course and project teams, starting as a suspension engineer on U-M's Solar Car Team, then as a team leader in ME250 and ME350, before transitioning to Michigan Task Based Robotics to work on robots designed to compete in the VEX U Robotics Competition. He is now balancing supporting his mission-critical work in ME450 with his current position as vice president on MTBR that are set on winning VEX U world championships in 2024.

After graduation, Max wants to develop his industry practice and knowledge base by going into the workforce as a mechanical engineer at an exemplar company of its industry. Once he has a few years of experience under his belt, he wants to transition to a job focused on robotics.

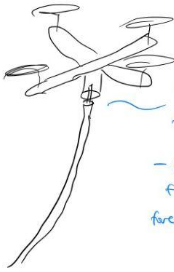
Xander Yanni
Xander Yanni is also a senior at the University of Michigan graduating in May of 2024. He is pursuing a dual degree with a BBA in Business and a BSE in Mechanical Engineering. Growing up in Washington state, Xander gained a love for the outdoors, including hiking, skiing, and boating. He has always been fascinated by new technology, especially drones, and has been pursuing drone photography since middle school. Now, his hobbies include film, digital, and drone photography, visiting national parks, and music production.

Xander found an interest in Mechanical Engineering after joining his high school FIRST Robotics team where he worked on designing and building various robot subsystems. Furthermore, he loves the more analytical side of engineering, including math and physics, data analysis, and problem solving. Xander found his interest in Business after joining his high school DECA team where he competed in various business scenarios, and after moving to the business side of his robotics team. In college, Xander joined BOND Consulting Group, a business consulting club on campus providing data based recommendations to Ann Arbor based clients.

Post graduation, Xander will be starting his career in management consulting specifically within business operations. As he starts working, he wants to pursue clients and work related to the supply chain and manufacturing industry.

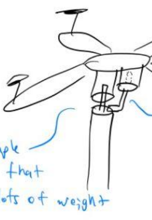
APPENDIX

Appendix A: List of Concept Generation Design Ideas



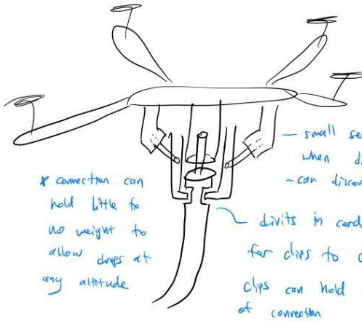
simple connection similar to plugging in a laptop

– will disconnect if drone flies up with enough force at max cord length



Same simple connector that can hold lots of weight

Small servo that pushes connection apart

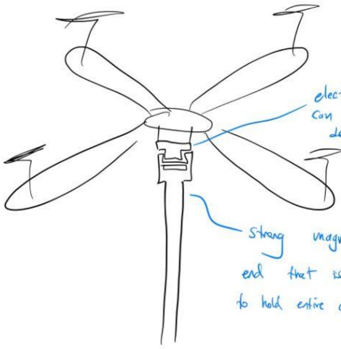


– small servos to pull clips apart when disconnection is wanted – can disconnect at any height

* connection can hold little to no weight to allow drops at any altitude

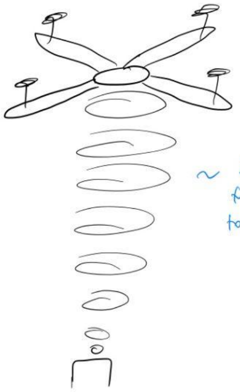
divits in cord or end piece for clips to clip into

clips can hold weight of cord instead of connection

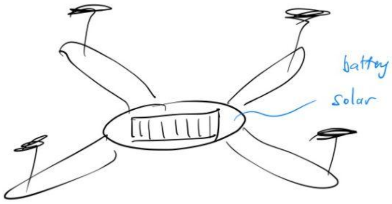


electro magnet that can activate and deactivate

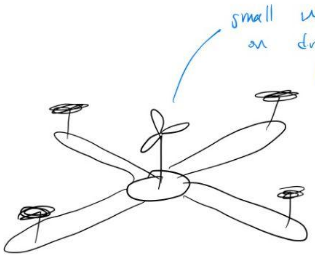
Strong magnet connection end that is strong enough to hold entire cord weight



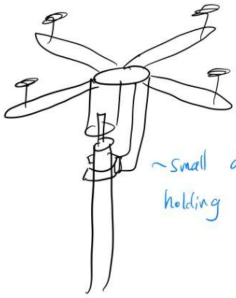
~ beam electricity from the ground to the drone



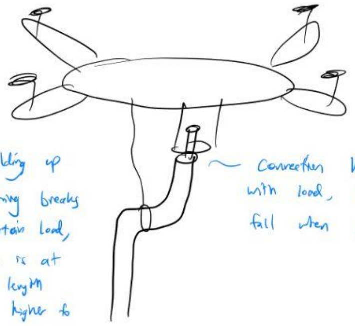
battery is solar powered



small wind turbine on drone generating power

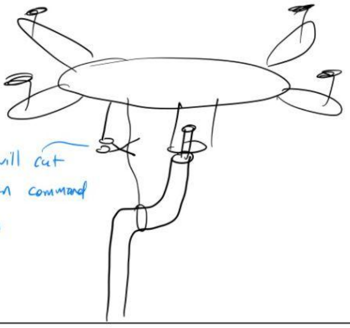


~ small actuating claw holding cord up

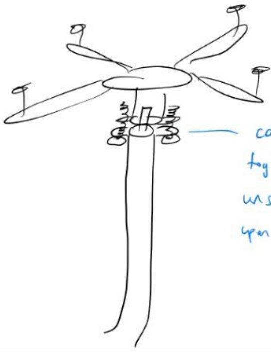


string holding up cord. String breaks at a certain load, when drone is at max cord length then flies higher to add load

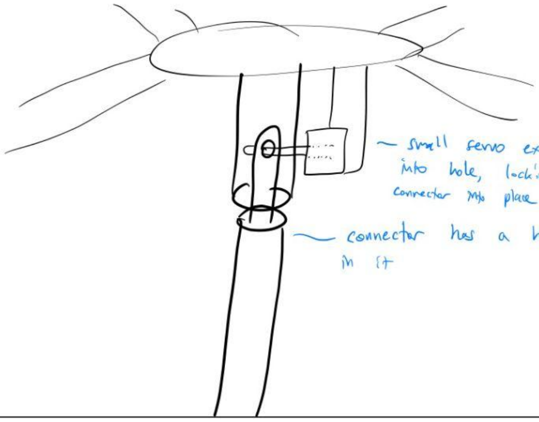
Connection will break easily with load, allowing cord to fall when string breaks



Scissors will cut string when command is given

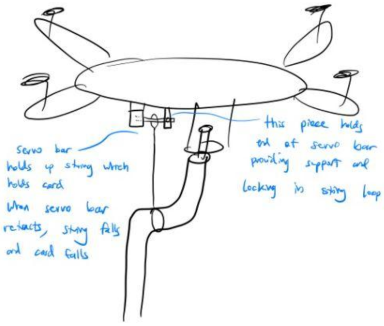


connection is screwed together. The screws unscrew themselves upon a command



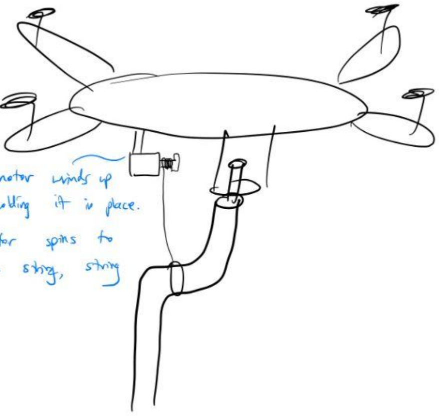
small servo extends into hole, locking connector into place

connector has a hole in it

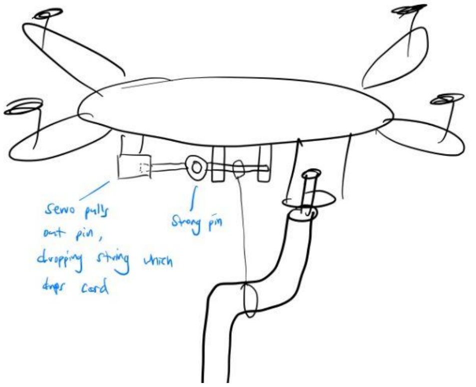


servo bar holds up string which holds cord
When servo bar retracts, string falls and cord falls

this piece holds end of servo bar providing support and locking in string loop

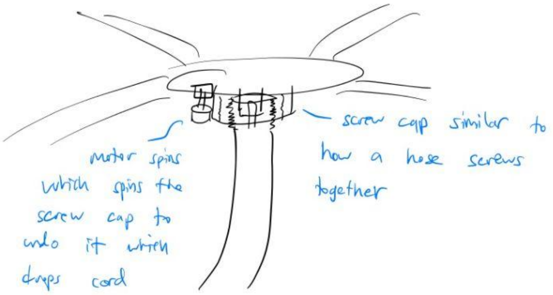


small motor winds up string holding it in place. When motor spins to undo the string, string falls



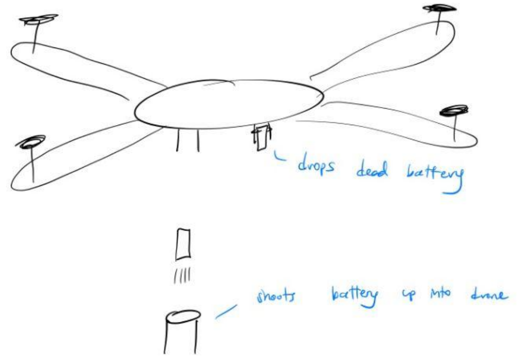
Servo pulls out pin, dropping string which drops cord

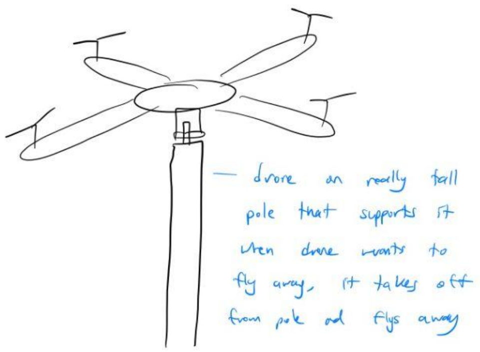
String pin

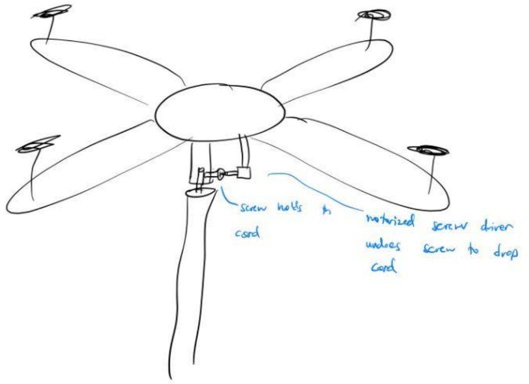


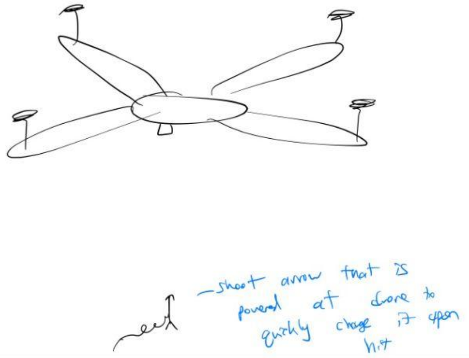
screw cap similar to how a hose screws together

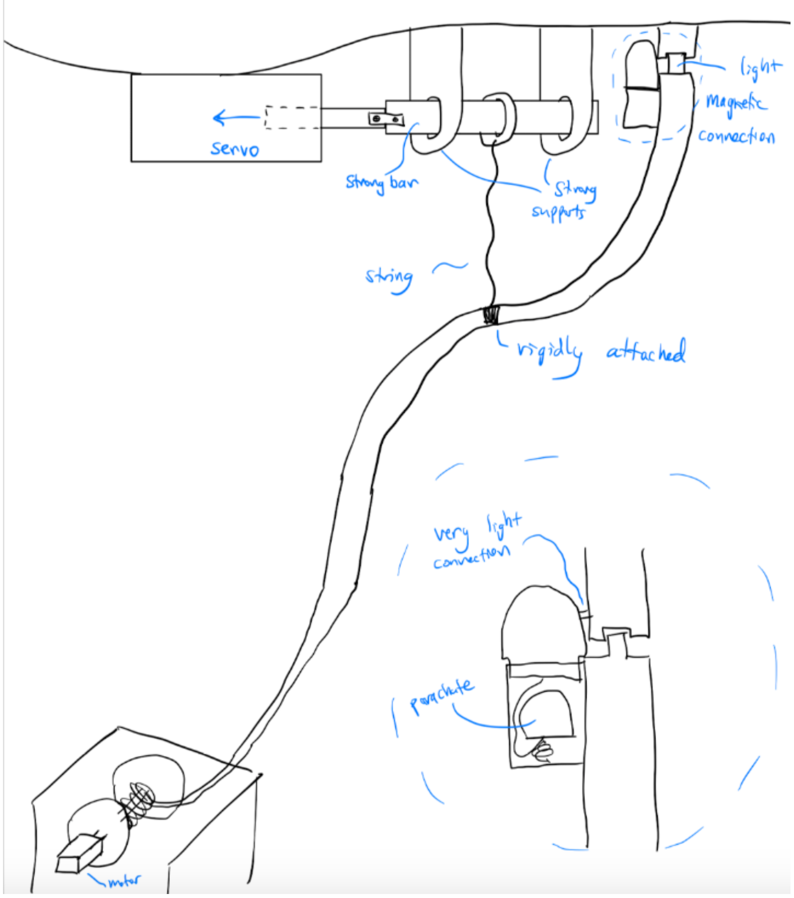
motor spins which spins the screw cap to undo it which drops cord


drops dead battery
shoots battery up into drone

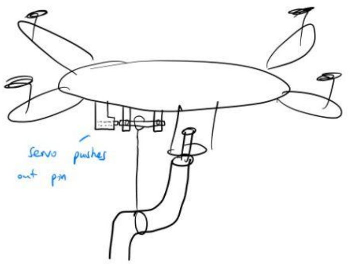

drone on really tall pole that supports it when drone wants to fly away, it takes off from pole and flys away


screw holds in card
motorized screw driver undoes screw to drop card

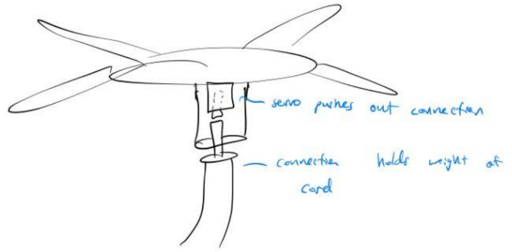

shoot arrow that is powered at drone to quickly charge it upon hit


servo
Strong bar
Strong supports
light
Magnetic connection
string
rigidly attached
very light connection
parachute
motor

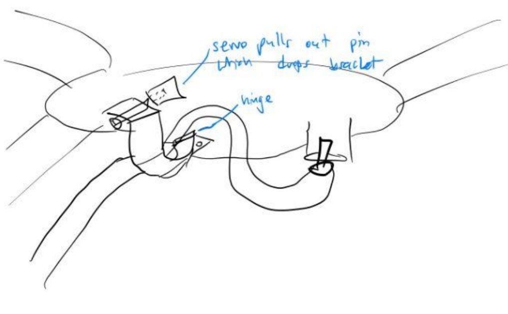
Morph chart : female/male connector + string + push something



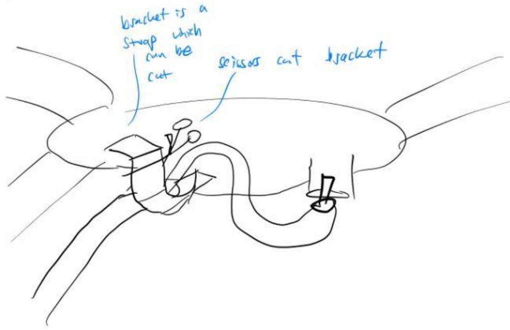
Morph chart : female/male connector + connection itself + push out



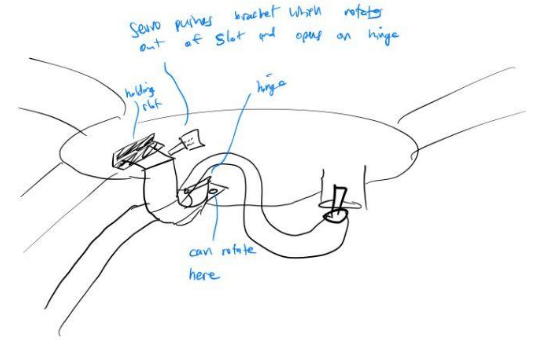
Morph chart : female/male connector + bracket for the cord + pull



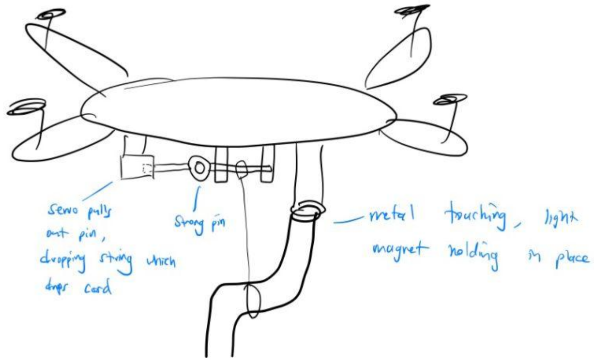
Morph chart : female/male connector + bracket for the cord + cut



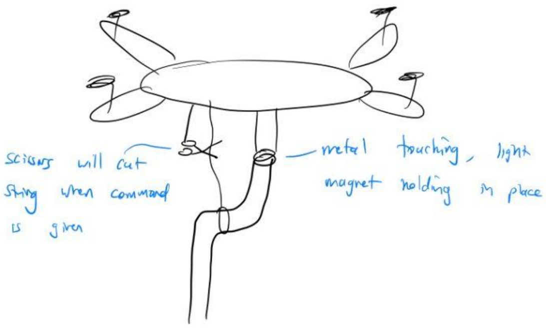
Morph chart : female/male connector + bracket for the cord + push



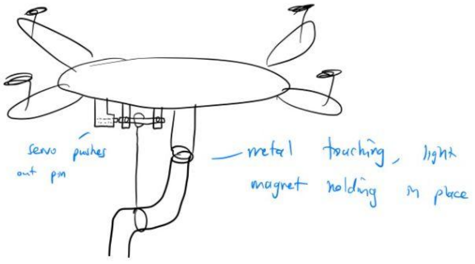
Morph chart : metal touching + string + pull



Morph chart : metal touching + string + cut



Morph chart : metal touching + string + push



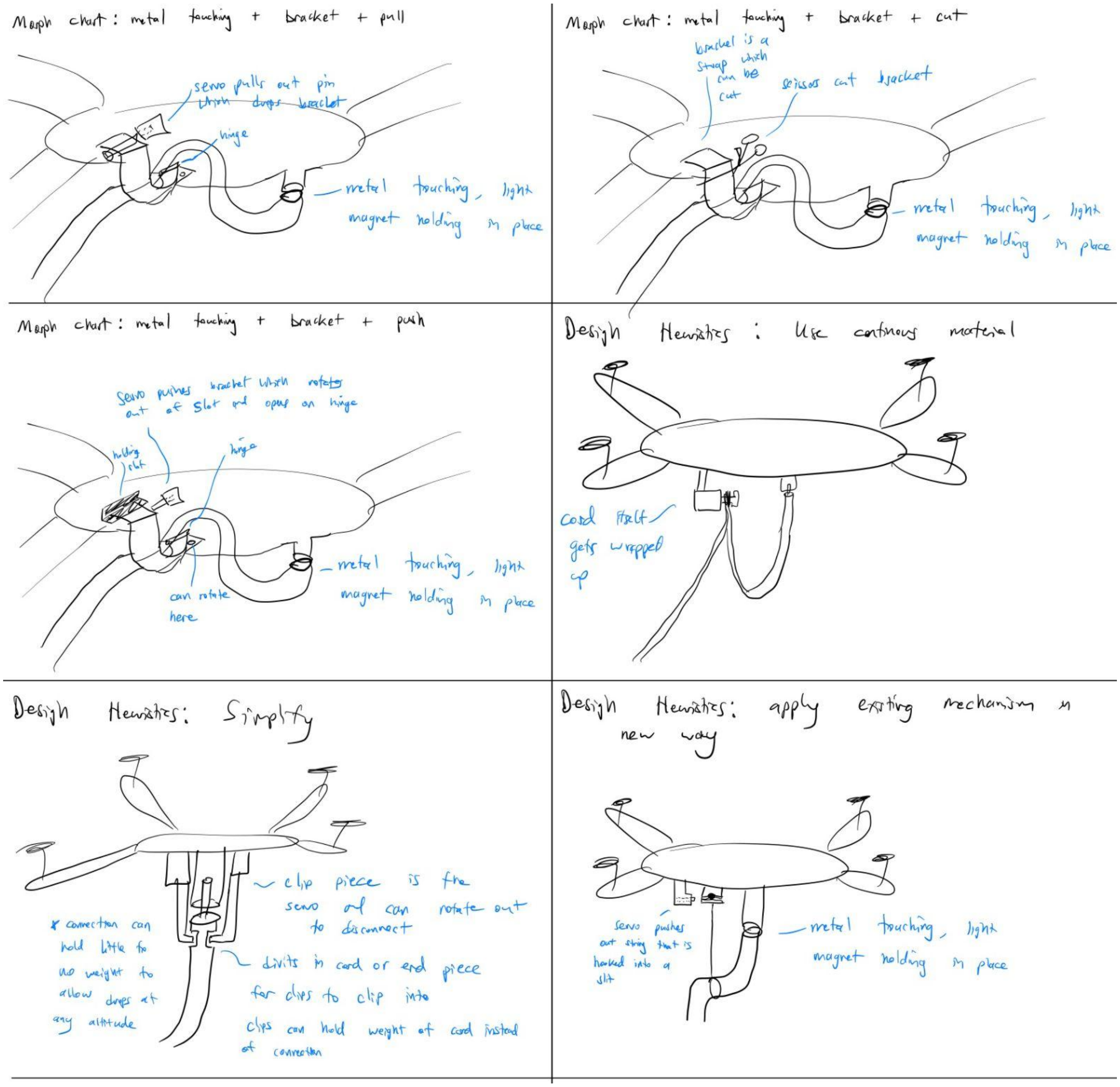


Figure 53. Xander's initial design ideas

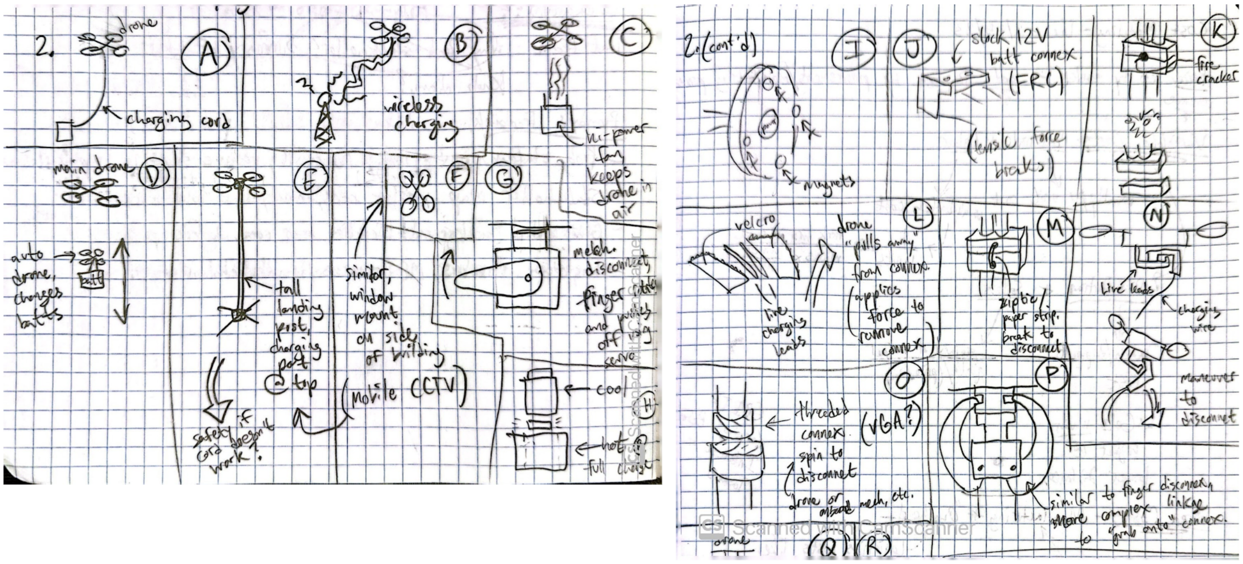


Figure 54. Max's initial design ideas

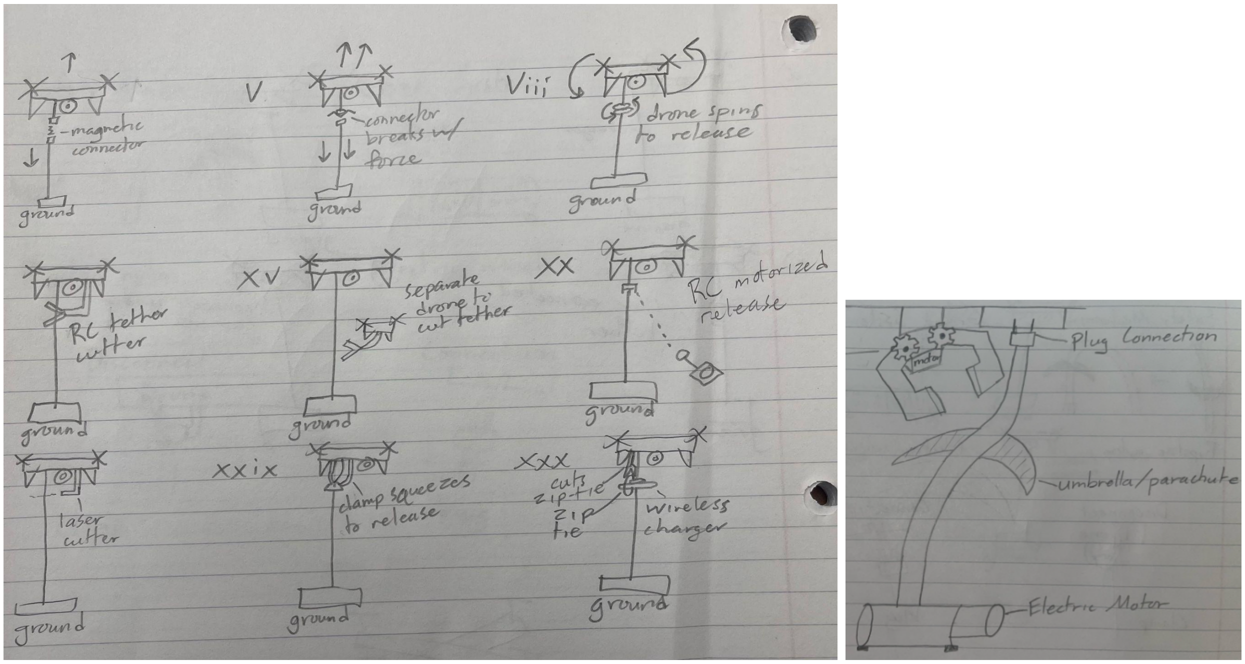
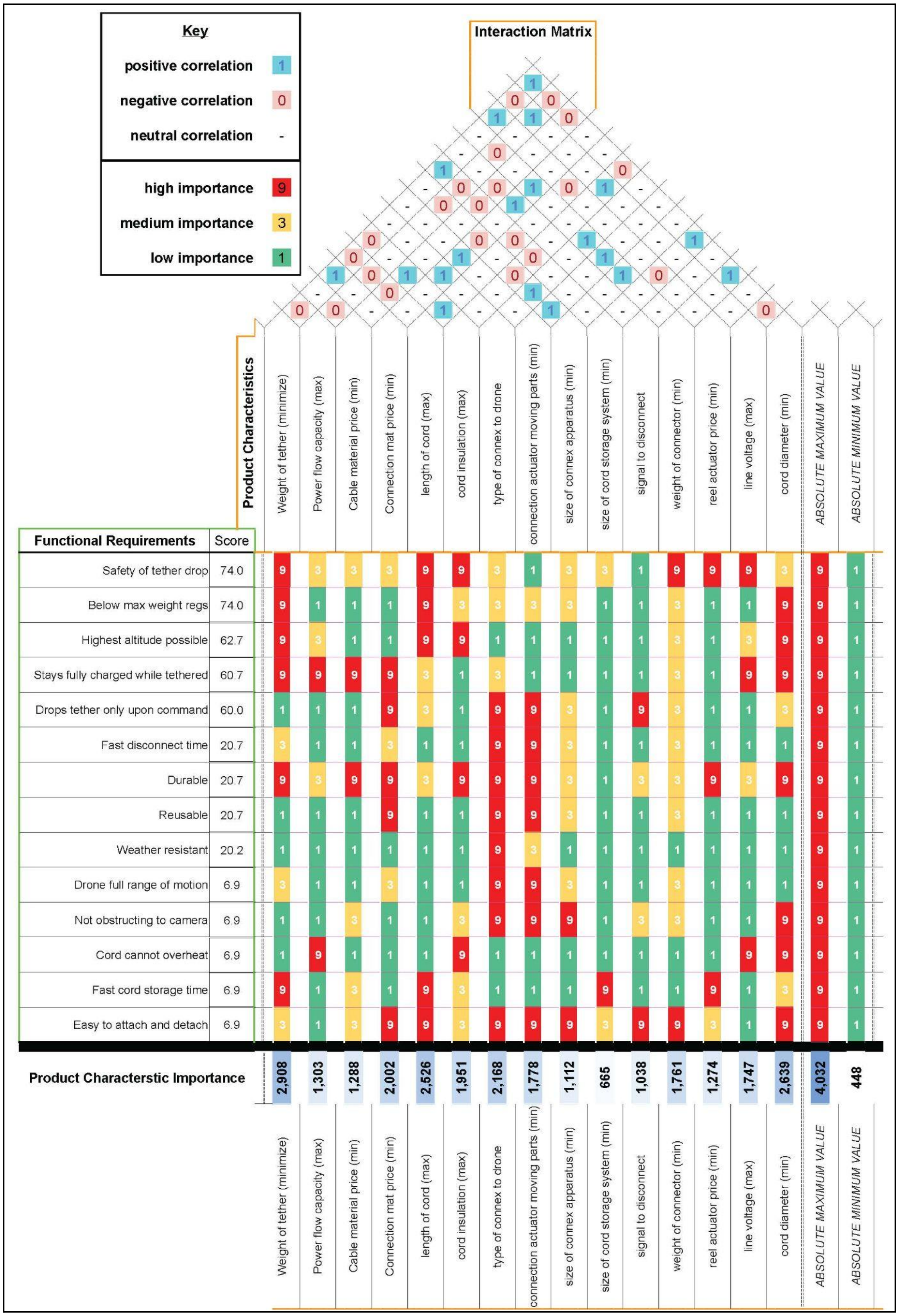


Figure 55. Harrison's initial design ideas

Appendix B: Full House of Quality Analysis



Functional Requirements	Score	Weight of tether (minimize)	Power flow capacity (max)	Cable material price (min)	Connection mat price (min)	length of cord (max)	cord insulation (max)	type of connex to drone	connection actuator moving parts (min)	size of connex apparatus (min)	size of cord storage system (min)	signal to disconnect	weight of connector (min)	reel actuator price (min)	line voltage (max)	cord diameter (min)	*ABSOLUTE MAXIMUM VALUE*	*ABSOLUTE MINIMUM VALUE*
Safety of tether drop	74.0	9	3	3	3	9	9	3	1	3	3	1	9	9	9	3	9	1
Below max weight regs	74.0	9	1	1	1	9	3	3	3	3	1	1	3	1	1	9	9	1
Highest altitude possible	62.7	9	3	1	1	9	9	1	1	1	1	1	3	1	3	9	9	1
Stays fully charged while tethered	60.7	9	9	9	9	3	1	3	1	1	1	1	3	1	9	9	9	1
Drops tether only upon command	60.0	1	1	1	9	3	1	9	9	3	1	9	3	1	1	3	9	1
Fast disconnect time	20.7	3	1	1	3	1	1	9	9	3	1	1	3	1	1	1	9	1
Durable	20.7	9	3	9	9	3	9	9	9	3	1	3	3	9	3	9	9	1
Reusable	20.7	1	1	1	9	1	1	9	9	3	1	1	3	1	1	1	9	1
Weather resistant	20.2	1	1	1	1	1	1	9	3	1	1	1	1	1	1	1	9	1
Drone full range of motion	6.9	3	1	1	3	1	1	9	9	3	1	1	3	1	1	1	9	1
Not obstructing to camera	6.9	1	1	3	1	1	3	9	9	9	1	3	3	1	1	9	9	1
Cord cannot overheat	6.9	1	9	1	1	1	9	1	1	1	1	1	1	1	9	9	9	1
Fast cord storage time	6.9	9	1	3	1	9	3	1	1	1	9	1	1	9	1	3	9	1
Easy to attach and detach	6.9	3	1	3	9	9	3	9	9	9	3	9	9	3	1	9	9	1
Product Characterstic Importance		**2,908**	**1,303**	**1,288**	**2,002**	**2,526**	**1,951**	**2,168**	**1,778**	**1,112**	**665**	**1,038**	**1,761**	**1,274**	**1,747**	**2,639**	**4,032**	**448**

Figure 56. Full HOQ resultant table