# *Final Design Report*

**Team 09: Improving Flight Stability of Remote Biologging Tag-Deployment Systems**

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## EXECUTIVE SUMMARY

The critical issue is the endangerment of whales, with a notable gap in understanding how human activities impact whale populations. To gain insights into whale behavior and biomechanics, researchers deploy biologging tags on whales. These tags, crucial for studying whales in their natural settings, collect data on undisturbed whale behavior. However, traditional tag deployment methods have proven unreliable and potentially disruptive to whales. Ocean Alliance introduced a less invasive, remote drone tag deployment system, aiming for more accurate and reliable tag placements. Nevertheless, controlling the tag's stability as it falls towards the whale remains a significant challenge. If the tag rotates and misaligns its suction cups upon landing, it fails to adhere correctly to the whale and gather data. Proper attachment is necessary for accurate data collection.

Our requirements and specifications were developed by our team with direct input from our project sponsor, Professor K. Alex Shorter. The primary requirements we focused on were the flight drop stability and the suction, two requirements that are vital to the immediate success of the drop. Other lower priority requirements were included in order to address reliability and longevity of our final product.

Using standard concept generation techniques, we created many fin attachment design ideas that we later categorized based on the number and complexity of their moving components. Our concept selection method funneled through our design concepts using our requirements and specifications, stakeholder feedback, and a Pugh Chart. We have finalized a spring-loaded eight fin design that we will pursue as our alpha design. The purpose of the springs is to provide a variable projected area to control the drag forces acting on the system. This will allow us to control the oscillatory motion of the tag as it falls. We also derived a mathematical model that approximates the response of our system. We created an engineering prototype made of PETG with linear springs and hinges to facilitate the movement of the fins.

We used an existing model of a shuttlecock to help us make sure that the primary video kinematic analysis method we chose for our verification plans would be satisfactory by comparing experimental system responses to proven theoretical system responses. The responses were similar, which meant that we could use the video kinematic analysis method to ensure that our alpha design satisfied all of our user requirements and specifications.

As of the semester's end, we developed a physical prototype that assists in stabilizing the DTAG’s descent to the whale. We also created a working mathematical model to inform the fin design. We conducted validation and verification tests to prove that our alpha design does indeed meet all of our user requirements and specifications.

**ABSTRACT**

Researchers use biologging tags to study the behaviour and biomechanics of whales and investigate how human interactions disturb whales' natural behavior. Safely and efficiently placing the tags onto free swimming whales can be difficult. Dropping the tags from aerial drones is promising, but unstable dynamics during free-fall can result in tag orientations at impact that negatively affect the quality of the tag attachment. Our objective is to improve attachment reliability by reducing oscillatory movement of the tag system during the drop.

**BACKGROUND**

Researchers attach biologging tags onto whales to collect data about their depth, speed, orientation, water temperature, acoustics, and video [1]. Many whale species are currently endangered, so understanding the behavior and biomechanics of whales can help researchers inform the public about how their actions negatively affect the well-being of whales [2]. For example, if it is found that the majority of whales tend to spend their time at a specific ocean depth at a certain time of the day, then the researchers can tell fisherman, boatmen, etc. to avoid those parts of the ocean to prevent possible injury to the whales.

Researchers collect the relevant data by attaching biologging tags onto the whales. An example of one of the many different kinds of tags is shown below in Figure 1 .

**Figure 1:** A white-colored biologging tag attached to the body of a marine animal [2].

The tags are used to track the animals' behavior through different sensors located in the tag housing, including accelerometers, magnetometers, hydrophones, and depth sensors [3].

**Benchmarking Previous Biologging Methods**

Many different tag deployment methods have been used to track and monitor animals. One method is to use pneumatic guns to shoot biologging tags onto the animal as depicted in Figure 2 below.

**Figure 2:** Researcher deploying a biologging device with a pneumatic gun from the deck of a vessel to tag an animal without physically contacting them [4].

Using the pneumatic gun is inherently inefficient because of the stringent proximity requirement of the gun having to be 5-20 meters from the whale when fired [4]. Achieving such closeness is difficult because the boat's speed must be tightly restricted and the boat must also not cause harm or distress to the whales when so close to them.

Another method of tagging animals is by approaching the animal with a long pole, at the end of which is a biologging tag with suction cups. The researcher slaps the whale with the pole hoping to have the suction cups stick to the whale's skin. The tag can then start collecting data. Figure 3 below displays the execution of the pole attachment method.

**Figure 3:** Biologging tag deployment with a long pole done by a Cascadia Research Collective scientist at close proximity to a blue whale [5].

The pole method is problematic because it is unreliable due to the unpredictable nature of the whale's surfacing habits and because of the precision needed to ensure proper suction of the tag to the whale. The researcher and the boat they are in also have to be very close, sometimes dangerously close, to the whale for this method to be effective especially because researchers seek data about the natural, undisturbed behavior of the animal.

A third tagging method uses measuring devices attached to a harness that goes around the body of the animal. Figure 4 below shows how the harness is fixed onto a dolphin.

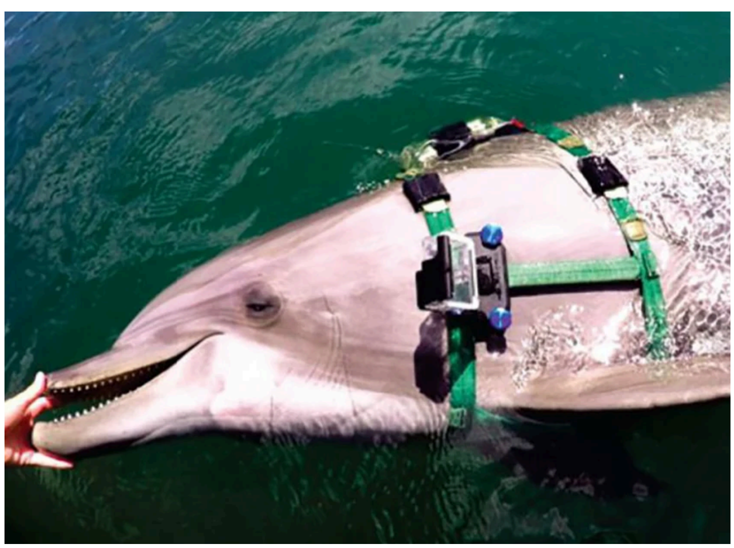


**Figure 4:** Dolphin wearing harness that contains electrical measurement devices, specifically a video camera used to record the hunting behaviors of the dolphin [6].

The dolphin harness is wrapped around the dolphin's body and over their flippers. The harness contains many devices for tracking their behavior. However, it is not a sensible concept for attaching to whales because the whales must be captured and that is not possible given their large size.

The current tag deployment system developed by Ocean Alliance uses remote-controlled drones to drop the biologging tags (DTAGs) onto the whale (Figure 5 below). The drones have the ability to move to the whale at speeds of 50 km/hr and work at distances up to 500 meters away from the researcher's boat [7]. Like the pneumatic gun and long pole methods, this method also uses suction cups to attach the DTAG to the whale.

**Figure 5:** Picture of a researcher sending the drone off to the whale. The four suction cups can be seen between the researchers hands [7].

However, unlike the previous methods, there is no risk of hurting or disturbing the whale by approaching it too closely by boat because the drones can drop the tags remotely from above the whale. The speed of the drone also assists in getting the DTAG attached to the whale during the brief time the whale has surfaced. However, this method is unreliable because the stability of the DTAG during its descent is hard to control. As explained later, this makes it difficult to ensure that the DTAGS stick completely to the whale's skin.

Table 1 below compares the advantages and disadvantages of each of the tagging methods described above.

**Table 1**: Comparison of the advantages and disadvantages of each of the tagging methods.

| Tagging Method | Advantages | Disadvantages |
|---|---|---|
| Pneumatic Gun | • Fast | • Close-range<br>• Invasive<br>• Inaccurate |
| Long Pole | • Low cost | • Close-range<br>• Invasive<br>• Inaccurate |
| Harness | • Guaranteed data collection<br>• Multiple attempts possible | • Close-range<br>• Requires capture<br>• Invasive |
| Drone | • Long-range<br>• Non-invasive<br>• Accurate | • Unreliable due to aerodynamic instability |

Given that the drone tag deployment method has the fewest disadvantages, we seek to improve this method such that the disadvantages are completely eliminated.

Our project is to come up with a way to stabilize the descent of a DTAG in free-fall. We will validate the stabilizing attachment by creating a dynamic model that can approximate the motion of the tag as it falls onto the whale. The rationale behind modeling the flight system is not only to understand the dynamics of the tag-drop, but more importantly to ensure that parameters of our flight stabilizing mechanism are adjusted accordingly to ensure a stable flight trajectory. This model will help us verify that the new fin attachment we develop does indeed stabilize the DTAG during the tags' descent. The sponsor for this project is Dr. Alex Shorter, professor of Mechanical Engineering at The University of Michigan.

**Understanding Suction and Stability**

It is important to understand the mechanics of suction cups because the DTAGs have suction cups that attach to the surface of the whale. It is this attachment that we seek to improve because the primary objective of our project is to get the DTAGs to attach effectively.

The suction cups have a seal along their outside edge that, upon compression of the suction cup, pushes out the air enclosed by the suction cup, creating a vacuum. The air pressure inside the suction cup is now less than the outside air pressure, which draws the seal closer to the surface to which it is adhered (the whale's skin). The seal only works this way when most of the seal is flush with the whale's skin [23].

The quality of the suction between the suction cup and the whale is dependent on the impact force of the cup hitting the whale and the angle at which the cups hit the whale [23]. The impact force must be large enough to ensure significant compression of the air enclosed by the suction cup. Otherwise, all of the air initially enclosed by the suction cup will not be pushed out and a vacuum will not be created. This will result in a pressure differential too small to draw the seal of the suction cup to the whale [23]. The impact angle must be as close to perpendicular to the surface of the whale to ensure that the air beneath the cup is forced out by the impact force. If there is any kind of misalignment that causes the suction cup seal not to be flush with the whale's skin, it is possible that the DTAG will not stick properly to the whale [23].

The impact force can be controlled by changing the drop height of the DTAG, changing the weight of the DTAG or any attachments, and changing the drag acting on the flight system during flight [23]. In the context of our project, the drop height is difficult to change because we are time-bound. The DTAG must reach the whale while the whale is still surfacing. Once the whale goes back underwater, the DTAG can no longer be attached to the whale. Increasing the drop height increases the risk of the whale returning underwater while the DTAG is still falling. Changing the weight of the DTAG or any attachments is possible, although it is important to consider the welfare of the whale so we must not increase the system weight too much. This means that the best way for us to control the impact force of the DTAG onto the whale is by manipulating the drag forces that act on the flight system.

Upon observation of the falling DTAGs, our sponsor and his research team noticed that the DTAGs oscillated back and forth during their descent to the whale. It was concluded that this oscillation was the chief reason for the misalignment issues mentioned above. Finding a way to dampen oscillatory motion during free-fall will solve the issue. We seek to create some sort of fin attachment to the DTAG that will assist the DTAG in reaching aerodynamic stability before reaching the whale.

We determined that a concrete conceptual definition of stability must be developed before creating the fin attachment. The first condition for stability was that the DTAG's response must reach steady-state about the vertical orientation regardless of any initial angular perturbation.

After experimenting with free-falling shuttlecocks (details of the experimental procedure can be found in the Preliminary Stability Study With Shuttlecocks section of the Appendix), we found that the shuttlecocks always eventually reached steady state about the vertical orientation no matter how severe the initial angular perturbation was. This led us to the primary condition for stability: the system must reach a steady-state condition about vertical orientation regardless of any initial angular perturbation. Our system is time-bound, so for our project, the DTAG must reach steady-state about the vertical orientation before the tag reaches the whale. Regaining vertical orientation as quickly as possible is important because in the event that any sudden perturbations (a gust of wind, a splash of water, etc.) unexpectedly act on the system, we want the fin attachment to already be in a stable configuration so that the late perturbations do not compound an already unstable configuration.

**Understanding The System**

To begin with, we would like to make a demonstration of the system that we are going to model. Figure 6 below describes a brief overview of the system and the forces that play a role in the aerodynamic trajectory of the system.

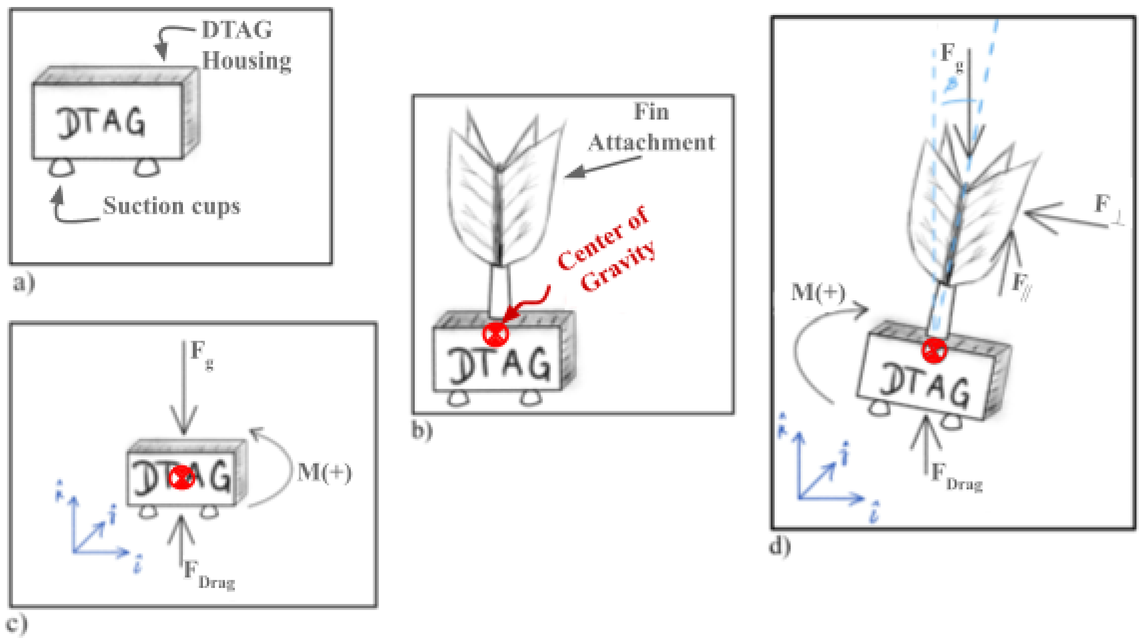



**Figure 6:** Self-created drawings depicting: (a) DTAG, (b) DTAG and fin attachment, (c) free-body diagram of DTAG, and (d) free-body diagram of DTAG and fin attachment. $F_{drag}$ is the force of drag on the DTAG, M(+) is the moment acting on the system, $F_{//}$ & $F_{\perp}$ are the forces parallel and perpendicular to the fins respectively. Angular deviation from vertical, denoted as β (in blue), serves as the critical parameter for assessing stability within our analysis.

The free-body diagrams aim to compare forces on a body with and without a fin attachment. Figure 6c shows a positive moment (M(+)) acting on the body, highlighting a significant contrast to Figure 6d, where a perpendicular resistive force ($F\perp$) counters M(+), particularly when the flight trajectory veers off vertical. This results from increased aerodynamic forces on the fin due to greater airflow interaction, aiding in trajectory correction and enhancing aerodynamic stability about the vertical axis.

**Standards and Sources**

To improve upon previous methods of biologging deployment, we turned to research about drone deployment systems. One of our main sources for background information is a research paper published in the Royal Society Open Science Journal [7]. The paper contains information about the efficacy of using a drone tag-deployment system to attach biologging tags onto whales. Our primary sponsor, Professor K. Alex Shorter, is one of the authors of the paper. Having him as our sponsor is advantageous because he can provide us with extra insight into the problems faced by the research team when they used the drones during their testing. We will also get access to video data collected by the research team which we will use to understand the kinematics of the tag-drop.   We also used research from a paper that sought to derive mathematical models for the motion of badminton shuttlecocks [8] to inform the development of our mathematical model for the DTAG.

The DTAGs for which we are designing fins have their own built in data memory system [3]. When the tag is recovered from the water, it is plugged into a computer for data analysis. This means that we are not concerned with signal processing standards because the fins that we will design/develop for our project will not contain any of the critical data collection components.

**DESIGN PROCESS**

So far this semester, we have adopted a hybrid design process that balances systematic methodology with iteration, inspired by the stage-based model. This process includes stages of development as shown below in Figure 7.

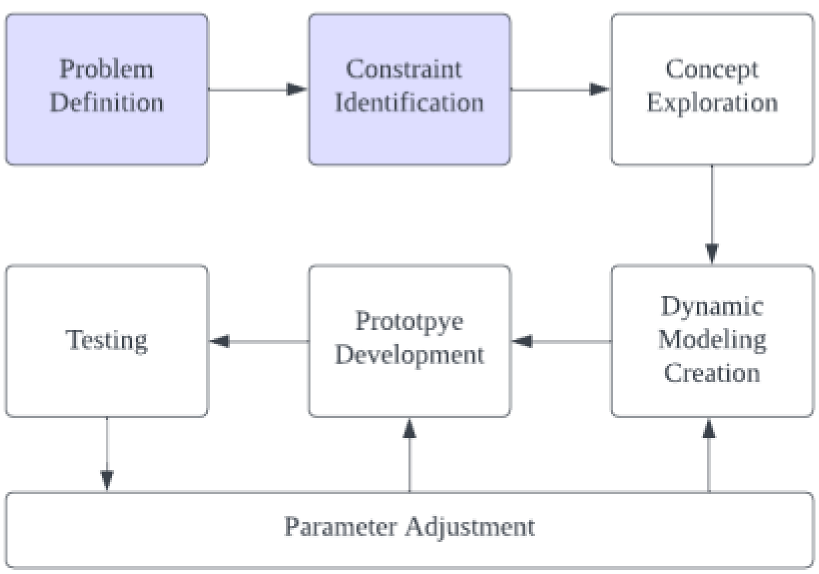


**Figure 7:** Illustration the flow and current status of the design process, represented as a flow chart. The first two blocks, "Problem Definition" and "Constraints Identification ", are shaded in blue to indicate that these stages have been completed already.

After examining Wynn and Clarkson's research, we contemplated several models, such as the reflective practice model for its iterative nature and the linear design model for its problem-solving principles . These models were selected for their potential to foster a deep understanding of the design problem through repeated cycles of action and reflection.

The stage-gate model stands out as particularly relevant for our project because it introduces clarity at each step, from concept to completion, ensuring that each stage is thoroughly evaluated before moving on to the next. This model supports our need for a systematic design process and for validation of our design solutions since we plan to dynamically model the tag dropping and then experimentally validate the dynamic model. Below, Figure 8 depicts the conventional model used in our ME 450 class.

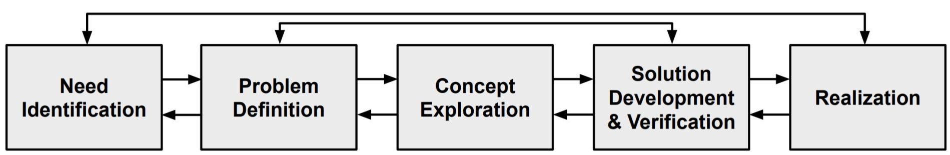



**Figure 8:** Illustration of the standard design process that is taught in the ME 450 class. The figure is meant to be used to compare our design process model with the model taught to us in the ME 450 class.

Our approach modifies the standard design process by integrating less feedback loops. Also, we made a few changes to the step content to fit in our model and verification structure. A process with fewer feedback loops can make the design process less complex and more practical since the early stage problem definition is clear. The modification of steps is necessitated by the nature of our project, which stresses the dynamic modeling over the ideation and concept generation phases of our project.

**DESIGN CONTEXT**

The context of our design plays an important role in our project because we must consider the relevant stakeholders who will influence our project. We conducted a stakeholder analysis to organize the stakeholders of our design and categorize them by their interests in different aspects of the project. The potential impacts of the project on the stakeholders as well as the influences of the stakeholders on the project are also discussed. We deliberated on the environmental impacts, ethical design practices, and the inclusivity challenges that we anticipate stumbling upon during the course of our project.

**Stakeholder Analysis**

The project is driven by the societal need for marine conservation, specifically focusing on whales. It addresses global concerns about biodiversity and the health of marine ecosystems. It appears the project sponsor prioritizes societal impact, particularly environmental conservation and education over profit. The project's success seems to be measured not just by traditional metrics but also by its positive environmental and societal contributions.

The prioritization of social and environmental impact over profit will undoubtedly shape the design process. It necessitates a focus on sustainable materials, ethical manufacturing practices, and solutions that offer long-term benefits to marine life and ecosystems. The project might also incorporate educational elements to raise public awareness about marine conservation. The people, places, or things that will be either positively or negatively affected by the manufacture, distribution, use, or disposal of our product have been categorized as either primary, secondary, or tertiary stakeholders based on their relationship with and influence on our project in Figure 9 below.

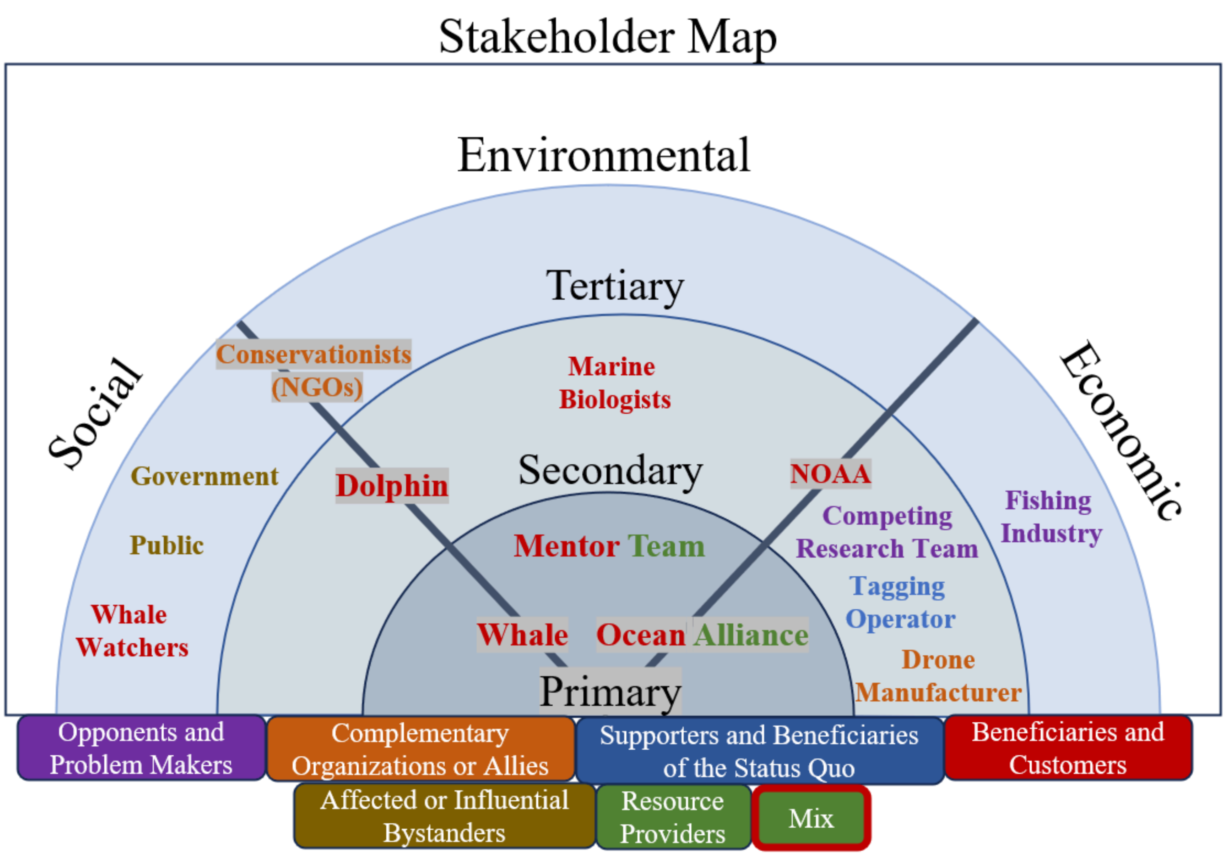



**Figure 9:** Stakeholder map dividing our stakeholders into three groups: primary, secondary, and tertiary. Each group contains three categories that separate the stakeholders by their interest/benefit: social, environmental, and economic. RP refers to Resource Providers, SB to Supporters & Beneficiaries of the Status Quo, CA to Complementary Organizations and

Allies, BC to Beneficiaries and Customers, OP to Opponents and Problem Makers, and AB to Affected or Influential Bystanders.

As can be seen in the figure the primary stakeholders in our project are the mentor team (RP, BC), Ocean Alliance (RP, BC), and whales (BC) because they are directly related to or influenced by the project. Secondary stakeholders refer to stakeholders who are part of the problem context but may not experience the problem themselves, and thus include marine biologists (BC), dolphins (BC), National Oceanic and Atmospheric Administration (BC), competing research teams (OP), tagging operators (SB), and drone manufacturers (CA). Tertiary stakeholders are defined as stakeholders that are outside of the immediate problem context but may influence the success of our potential solution. We include conservation non-governmental organizations (CA), governmental bodies (AB), the public (AB), whale watchers (BC), and fishing industries (OP) as the tertiary stakeholders.

The primary and secondary stakeholders, especially Ocean Alliance, marine biologists, dolphins, and whales, will benefit directly from the conservation efforts. The tertiary stakeholders like conservation non-governmental organizations and the general public will see indirect benefits through enhanced marine ecosystem health and increased awareness. There could be indirect negative effects on stakeholders like the fishing industry, which might face new regulations or restrictions based on the project's findings. Manufacturing and disposal of the project's components might also impact the environment if not managed sustainably.

**Ethics**

The ethics involved with this project are focused on animal welfare and the conservation of whales. It is important that we track whales because the data could be used to learn about their seasonal habitats, which will make it easier for us to protect them from unexpected and potentially harmful interactions with humans [9]. Using this information, researchers can justify seasonally closing off areas and can understand how human impact affects the animals' behaviors [9]. It is important that humans are not negatively impacting the whales' lives under water, so this tracking allows us to understand in what ways we may influence them.

Ethical considerations related to the design of the flight mechanism attached to the DTAGs that are dropped onto the whales with the use of drones include minimizing the disturbance of the DTAG on the whale while also ensuring that proper suction is achieved, as well as ensuring that the fin system is able to float post-deployment. This is important for several reasons. First, ensuring that our interactions with the whales are as small as possible is vital to the ethicality of our project, as we do not wish to interfere with the whales' environment. This might pose an issue because reducing the force of impact of our tag-drop to minimize whale disturbance will likely correlate with a decrease in success rates of tag-whale suction which would imply that we would have to perform more drops onto whales, thus disturbing whales more than necessary.

Finally, a very important ethical consideration involves the flight systems' ability to float back to the surface post-deployment and be easily visible to allow for researchers to locate and retrieve the flight system for reuse.

In our team, we find that our collective ethics closely align with the professional ethics expected by the University of Michigan and potential future employers. Our shared values emphasize principles such as honesty, integrity, and responsibility, which guide our actions and decisions throughout the design process. As a team, we share a strong commitment to environmental responsibility and animal welfare. These principles are particularly relevant to our project, as it revolves around biologging and interactions with whales. We believe in conducting research and design with the utmost consideration for sustainability and the ethical treatment of wildlife. Additionally, open communication, collaboration, and transparency are core values that we collectively prioritize. Effective teamwork and interdisciplinary cooperation are essential aspects of our project, and these values play a significant role in ensuring our success. In a professional context, we recognize the importance of adhering to the ethical standards set by the University of Michigan and potential future employers. This includes upholding academic integrity, respecting intellectual property rights, and following ethical guidelines in research and design, which we collectively endorse and uphold.

Our ethics must be maintained throughout the whole project, including in our discussions with our sponsors and stakeholders where power dynamics between us and them may influence the outcome of our solution. Our project sponsor naturally has more power over us because they can steer the project in any direction they choose. We all have more power over the whales because the whales will not have a say in the final design of our product. However, we will make sure to consider the point of view of the whales so that they do not end up being negatively affected by our decisions.

**Inclusivity**

As a team, we have addressed any and all considerations in relation to inclusivity in order to ensure that all members of the team feel comfortable and included. We believe that encouraging the expression of feelings, opinions, and concerns within our team will allow all of us to perform better as a team. Specifically, we discussed two specific inclusivity concerns that we felt we should keep in mind throughout the duration of our project: possible language barriers and the predominance of men in the team. We believe that it is very important for us to ensure that all members have the same ground to express their opinions and that any confusion within the team should be addressed to establish clarity for any issues that may arise. It is also important that the female in our team are treated as equals and with equal respect as all others in our team. Diversity is a wonderful thing to have in an engineering environment as it allows for the introduction of varied creativity.

## USER REQUIREMENTS AND ENGINEERING SPECIFICATIONS

The generation of engineering targets was fairly straightforward for our design project. This is because our project is built on the work of a previous project team as well as Professor Shorter's research lab. We have access to a record of the performance achieved by prior iterations of this very same flight system, serving as a valuable reference for our team's improvement efforts. Leveraging these historical performance metrics, we find it uncomplicated to establish engineering targets for our design, commencing with the primary objective of surpassing the accomplishments of its predecessors. In conjunction with the foundational performance criteria inherent to our design, our team has thoughtfully outlined additional, more detailed requirements to measure specific facets of our system's overall performance.

The requirements of most importance include aerodynamic stability, proper suction, and reusability. These requirements are critical to the overall success of our design because they address the objectives of our product in a quantifiable manner. Our engineering requirements and specifications serve as a general outline that, if generated appropriately, can streamline our design process and lead it to success. These requirements and specifications are delineated in Table 2 below.

**Table 2:** Requirements and specifications ranked on importance (1-9 from most to least important) in relation to performance outcomes and sustainability.

| Rank | Requirement | Specification | Evaluation Method(s) |
|---|---|---|---|
| 1 | Aerodynamic Stability | Attain a steady-state vertical orientation given any initial angular condition (0-180 degrees) in free-fall conditions [8] | Kinematic Analysis and Empirical Testing |
| 2 | Controllable System Response | Settle about vertical equilibrium given a 15 degree perturbation with a settling time < 0.6 seconds within 5% error margin [10][7][11]<br><br>Overshoot (Mp) < 15% of initial perturbation angular offset [11] | Video Motion Kinematic Analysis |
| 3 | Proper Suction | 2.8 N < Impact Force < 5 N applied by suction cup onto whale [12] | Accelerometer Data & Video Motion Kinematic Analysis |
| 4 | Easy Drone Fit | Tag fits within drone - clearance between fin attachment and edge of drone grips < 1 [cm] | Ruler/caliper |

| | | | |
|---|---|---|---|
| 5 | Impact Resistant | Material selected to withstand 5 N [13] | Compressive Testing and Empirical Testing |
| 6 | Reusability | Resist degradation > 5 years [14]<br><br>Force of buoyancy > 2 times weight of fins<br><br>Resistance to fatigue > 30 cycles (impacts) [15][16] | Standard Material Properties, Empirical Testing, First Principles |
| 7 | Low Cost | Cost per Prototype < $5 | Granta Edupack |

The requirements are a complete set of functions that the end design must take into account. All requirements have quantifiable specifications that are able to be tested by video motion kinematic analysis, accelerometer data, dimensional measuring tools, and first principle analysis. The engineering specifications associated with each requirement are reasonable to implement into our design. Below we will delve into our thought process behind the generation of each of the requirements, and the justification behind each specification.

**Aerodynamic Stability**

For our specification we have decided to define the stability of our system given two conditions. First, that the system is able to regain a vertical orientation given a 15 degree perturbation with a settling time less than 0.6 seconds with a 2% error margin. This quantity was selected under the assumption that we will be modeling the flight mechanism with the use of a second order differential equation, which requires its linearization for analysis purposes, which will be done using the small angle approximation. This would imply that our model will follow the regime of the small-angle approximation in its results, and thus the model must hold these small-angle assumptions to be true throughout its trajectory in order to be appropriately represented by our generated model.

Furthermore, given that the definition of stability in the context of this system is very subjective to our intended performance outcomes, we have deemed it appropriate to require a settling time of < .6 seconds given that the minimum impact force of ~2.8 N is achieved with ~.6 seconds of airtime. This would imply that our system must regain a vertical orientation, and have a low oscillation amplitude, in order to properly allow the tag to successfully suction onto the whale. Having our specification be .6 seconds is conservative given that larger impact forces work under the assumption of longer air travel times.

Our last specification addressing aerodynamic stability incorporates the concept of overshoot. Overshoot, along with the previously mentioned settling time, is a system frequency response characteristic which is used to assess the performance of a system. Ensuring that our system overshoot is limited to a certain quantity is vital in the stability of our system.

The presence of an overshoot that is larger than or even close to the magnitude of the initial perturbation deflection angle signifies a potential instability within the system, and such a characteristic should be diligently avoided in both our model and design process. This implies that the system's response to a disturbance not only exceeds the desired equilibrium state, but does so to an extent that mirrors or surpasses the initial deviation caused by the perturbation. Ensuring stability, therefore, requires careful tuning of the system's parameters to minimize overshoot, thus preserving the integrity and reliability of the system's performance in maintaining a steady and predictable operation following any external disturbances. These parameters are visualized for understanding in Figure 10 below.

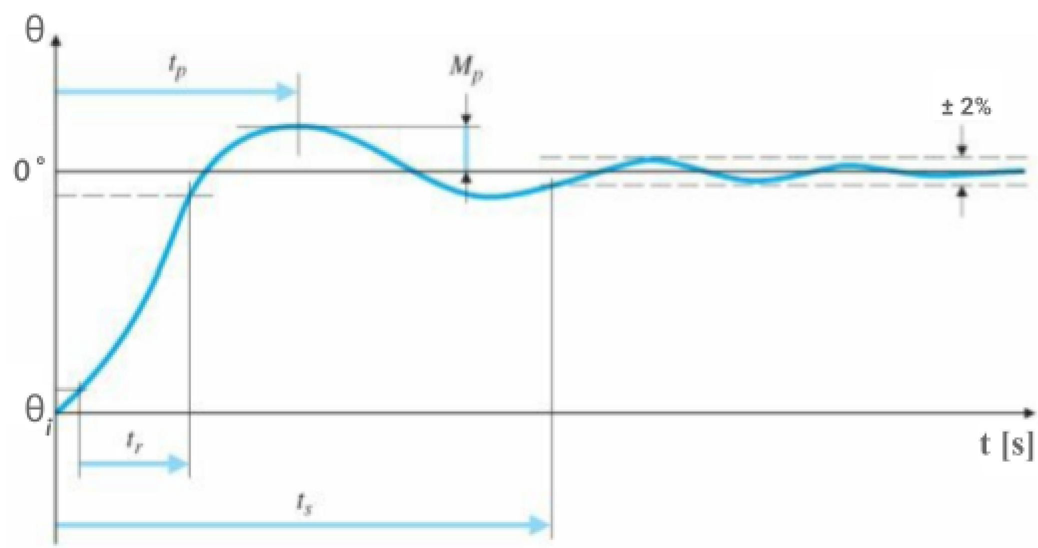



**Figure 10:** Visual representation of rise time ($t_r$), settling time ($t_s$), and overshoot ($M_p$) relating an example system response to an initial angular offset $\theta_i$ with oscillation about an equilibrium of 0 ° . The response function represents the angular displacement, β, described in Figure 8, previously included in the report [10].

In order to understand if our prototype is adhering to the performance parameters set within our specification, we will make use of video cameras and perform motion analysis of the frames, capturing the oscillatory motion of the flight system throughout its trajectory. We will then process this data to gather information on the frequency, amplitude, overshoot, and settling time of the systems' oscillations to assess the overall performance of our flight mechanism experimentally. This will allow us to determine whether or not the system falls within our quantifiable assumptions of the small-angle approximation, which will then allow us to validate other characteristics/parameters accurately. Given that our assumptions hold true, the stability of the system will be accurately quantifiable with the use of our generated dynamic model and will reflect in the performance of the prototype.

**Proper Suction**

The impact force of the suction cup onto the whale should be high enough to ensure proper suction of the suction cups to the skin of the whale. Based on Professor Shorter's research paper, we determined that the lower limit for impact force was 3.1 N. The paper stated an approximate 2.8N of minimum force for attachment [7], but we decided to hold our specifications to a more conservative estimate so that we have a higher success rate of proper attachment. This means that in order for the suction cups to properly attach to the surface of the whale, the suction cup had to fall on the whale with a force of at least 3.1 N.

However, it is also important for us to consider the well-being of the whale because the whale is a primary stakeholder. Based on a literature review we conducted, we decided to determine that the maximum impact force that the whale could tolerate without being disturbed was 5 N. This is why we chose 3.1 N as our minimum bound and 5 N as our maximum bound for impact force of the suction cup onto the surface of the whale. These impact forces will be measured using inertial measurement units (IMUs) and standard kinematic analysis with initial conditions gathered from video motion analysis.

**Easy Drone Fit**

The drone fit requirement is aimed at researchers utilizing drone-based systems for tagging animals. Our goal was to streamline the tag system's operation, ensuring it's straightforward to operate and quick to learn. We've tailored this requirement specifically to the drone's loading process.  Initially, the fin attachment was positioned beneath the drone, nestled within the landing gear's span. We believe it's reasonable to design subsequent versions of the tag-drop system to fit within the same XY plane constraints as the landing gear. The adherence to these design specifications can be verified using measuring tools such as rulers and calipers throughout the design phase. Figure 11 below shows how the current fin attachment design fits easily between the landing gear legs.

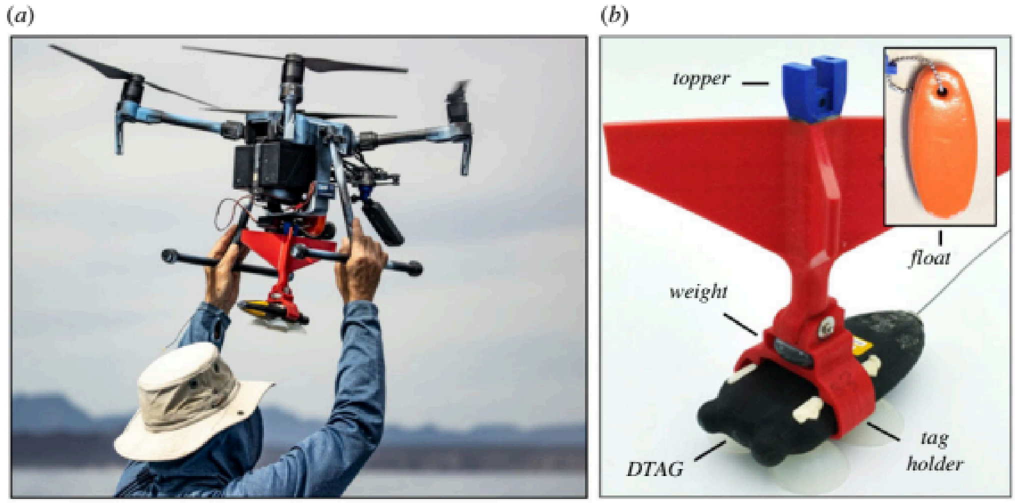



**Figure 11:** a) Current Drone tag deployment setup. b) Fin designed drop system with DTAG attached, along with a float [7]. The current red fin fits easily within the space enclosed by the landing gear

The current designed drop system implemented a four-winged aircraft which had a “topper” to connect the system to the drone, a “tag holder” for the DTAG to sit along, and a float device. The topper was used to connect the whole system to the drone, which was released using a remote controlled servo-pin release [7]. The tag holder used a spring pin release system so that the DTAG would detach from the drop system on impact to the whale. The float was used for retrieval purposes to keep the fins buoyant when sitting in the water for the researchers to pick up [7]. We aim to enhance the system's buoyancy through the development of a buoyant fin system, designed to eliminate the necessity for flotation accessories. Such accessories could disrupt the fin attachment's streamlined aerodynamics. By adopting this approach, we avoid incorporating additional systems that do not contribute to the aerodynamic stability of the system.

### High Impact Resistance

The impact resistance requirement is crucial since we want the tag-dropping system to be resistant to fracture. When the tag is deployed, the material of the tag-drop system must withstand the impact force of the tag onto the whale generated through impulse. The polymeric materials that we plan to research for the dropping system have trends in high flexibility and thus resistant to the impact according to the literature where the trend is depicted below in Figure 12 [13].

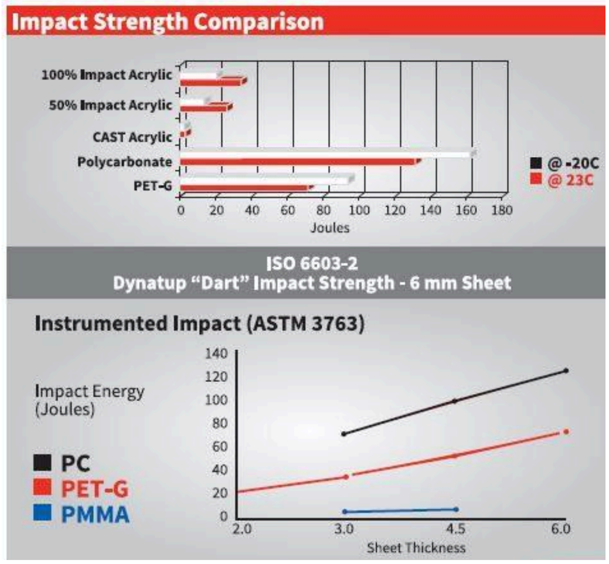



**Figure 12:** Illustrates the impact resistance performance of several polymer based materials. Showing their ability to absorb strong impacts [17].

Given a safety factor as large as 2.5 will allow us to be conservative in our design approach so that the material does not fracture given we run into unexpected loading conditions (eg. Tag unexpectedly drops from high altitude onto the boat's hard surface). To test this, we can see at what height the tag-drop will fracture by stepping through different drop heights of the tag and observing the damage done to the drop system.

### Reusability

The reusability requirement is crucial to ensure long-term functionality and sustainability. According to the material science study [14], we set a benchmark for the tag to resist degradation for five years, ensuring a consistent performance over multiple research expeditions. In addition, the tag's design will include a buoyancy force exceeding a specified multiple of the weight of the fins, ensuring it floats as it detaches from the tags, facilitating recovery and reuses. The material chosen for the fin should be highly fatigue resistant, capable of withstanding numerous cycles of impacts during multiple experiment iterations [15][16].

Selection of material will be determined through means of literature review, which we will use to narrow down the list of applicable materials. Our narrowed list of materials will then all be tested for buoyancy by the use of a weighed down fin system in salt water, which we can use to determine the net buoyancy of the system. Ensuring a safety factor of 2.5 times the weight of the fin system will truly ensure the recoverability of the fin attachment.

**Low Cost**

It is important for us to choose a prototype manufacturing method that is very cheap. This is because we plan on iterating through many designs to refine our dynamic model for stability. As a result, many prototypes will be made. Due to the iterative nature of our design and prototyping approach, we would prefer to choose a very fast manufacturing method that is inexpensive so that we do not exclude designs given they might be too expensive to pursue. After consulting our sponsor and conducting a literature review, we set a $5 limit on the cost to manufacture each fin attachment iteration. We expect to make around 20 iterations during our testing phase of our design process and we expect our sponsor to make 3-4 for his research applications. Based on the published prices for PETG (our selected material for the fin attachment), this would lead to a $100 expenditure for our team and a $15-$20 expenditure for the research team [5][6].

## CONCEPT GENERATION

We used multiple concept generation methods to explore the solution space of our project. These included the 77 cards design heuristics technique, the Morphological Analysis and Functional Decomposition technique, and the SCAMPER technique. Each member of our team used these techniques to develop 20-30 different fin attachment designs (please see APPENDIX for complete set of designs). We then had a collaborative brainstorming session where we shared our favorite ideas with each other, the result of which is shown below in Figure 13.

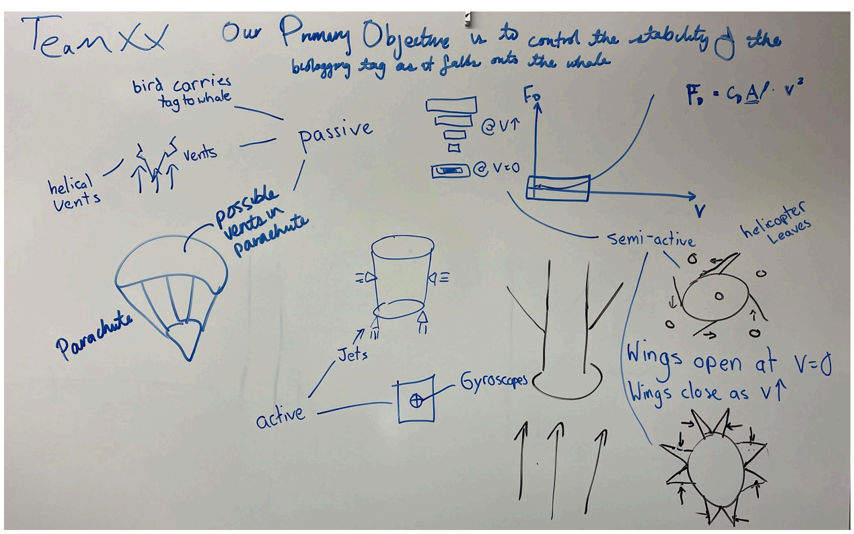



**Figure 13.** Brainstorming session results. We broke up the system into passive, semi-active, and active concepts.

During the initial phase of the collaborative session, we built upon each other's thoughts to develop new designs and no idea was turned down.  We then retrospectively categorized the ideas based on their primary functional components: passive designs, semi-active designs, and active designs.

**Active Designs**

We defined active designs as designs that had components that moved unassisted.  These included attaching a few jets onto the DTAG to help control the air stream around the DTAG (Figure 14a) and using mechanical gyroscopes to control the rotational velocity of the DTAG during free-fall (Figure 14b).

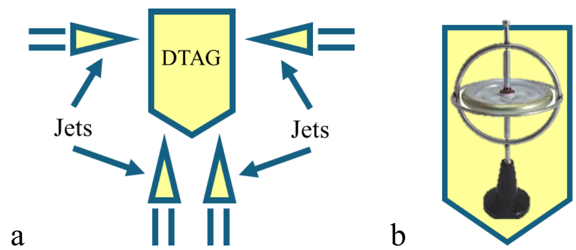



**Figure 14:** Diagrams of the active designs. **a)** The jet-controlled idea. **b)** The mechanical gyroscope idea.

The jet-idea was made with the idea that using stabilizers we could program the jets to go off and control the descent and orientation of the DTAG similar to how spacecraft land on the moon. The gyroscope idea was thought of when thinking about how gimbals operate. Gimbals fix its orientation regardless of the motion that is happening around it, so using the gyroscope it would self-orient to maintain the vertical axis. As it descended from the sky the gyroscope would fix its orientation so that the DTAG part would stay vertically oriented.

**Semi-Active Designs**

We defined semi-active designs as designs that had moving components.  However, the components moved only from outside influence (the environment, some manual perturbation, etc.) and not on their own.  Our alpha design, discussed later in detail, and the design shown in Figure 15 below were two of our main semi-active designs.

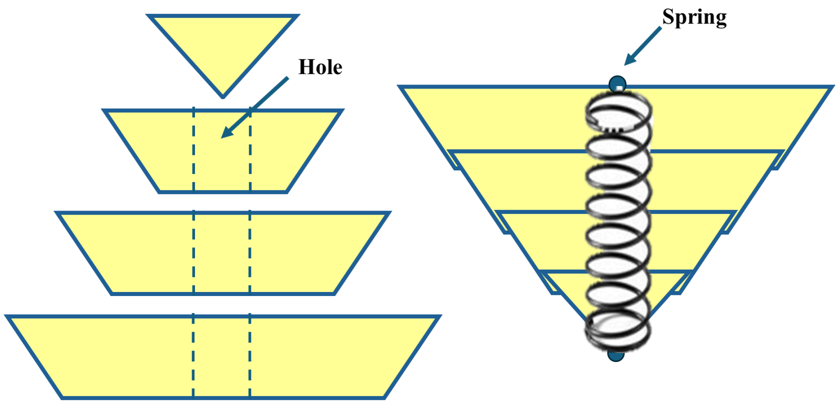



**Figure 15:** A diagram of the semi-active fin design.

The design above at rest has the shape of donuts resting inside of each other so that at rest it is the shape of a cylinder, and after it has gone through free fall and reaches higher velocities, it expands to form a Christmas tree like shape. With the idea of air resistance being dependent on the flux area and velocity, we figured it would change drag forces dependent on the speed of the system which could be beneficial.

**Passive Designs**

We defined passive designs as designs that did not have any components that moved unassisted. One passive design idea was to attach a parachute to the DTAG to stabilize its descent onto the whale (Figure 16a). Another idea was to make channel-shaped cutouts, out of a chunk of material attached to the DTAG to vent/control the flow of the air through the DTAG to naturally use the air to stabilize the system by equally and oppositely applying forces on the top side of the system (Figure 16b). A third idea was to train a bird to drop the DTAG onto the whale (Figure 16c).

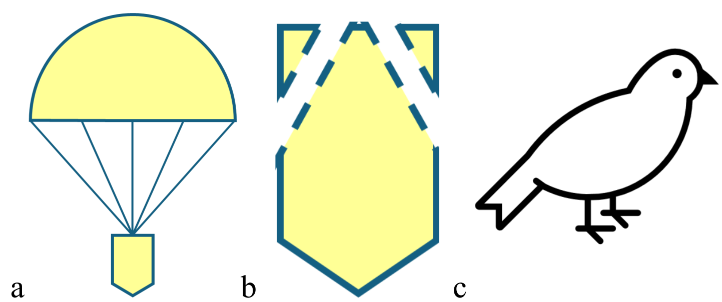



**Figure 16:** Passive design ideas to stabilize the descent of the DTAG to the whale. a) Parachute idea b) Vent idea c) Bird idea

## CONCEPT SELECTION PROCESS

The concept selection process was a thorough collaborative effort to figure out the main fin design that we would like to test and model. It was broken up into multiple stages to funnel out the designs that would not fit our expectations. Our initial stage was knocking out designs that did not satisfy our requirements and specifications. Then we looked for stakeholder feedback along with the feasibility of each design. A detailed description of these selection methods can be found in the Concept Selection - From Many Down To Six section of the Appendix. Using these initial stages we had a couple of designs that satisfied those rounds, and to finalize our selection process, we made a pugh chart that would give quantitative results to select the design most effective based on certain factors.

### Selection based on Pugh Chart

With the use of a pugh chart, we were able to compare our top options from the passive and semi-active concepts. The active solutions were thrown out due to the complexity of modeling and programming that would not be suitable for a semester's worth of time. The pugh chart was made with seven different criteria to consider and a weight associated with each factor. The weights for each criteria were given based on the subjective priority that each factor plays in our project.Then we used the passive four fin design as a baseline to compare the other designs to, due to its simplistic nature. The pugh chart can be seen below in Table 3.

**Table 3**: Pugh Chart for Design Selection

| Criteria | Weight (1-5) | Baseline: Standard 4-Fin Design | Spring Loaded Fin Design | Parachute | Vent | Christmas Tree |
|---|---|---|---|---|---|---|
| **Complexity** | 2 | 0 | -1 | -1 | 0 | -1 |
| **Cost** | 2 | 0 | -1 | -1 | 0 | -1 |
| **Material Availability** | 3 | 0 | 0 | -1 | 0 | -1 |
| **Modeling Accuracy** | 3 | 0 | 0 | -1 | -1 | -1 |
| **Reusability** | 4 | 0 | 0 | -1 | 0 | -1 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Performance** | 5 | 0 | 1 | 0 | -1 | 0 |
| **Ease of Use** | 3 | 0 | 0 | -1 | 0 | -1 |
| **Total** | | 0 | 1 | -17 | -8 | -17 |

Our first criterion was complexity, which we defined as a measure of how difficult it would be to get the prototype to an operational level. We considered the number of components and the ease of manufacturing when evaluating this criterion. This criterion was assigned a weight of two because the complexity of the design should be simple to make and function similar to the theoretical function. The standard fin design and vent design were considered the least complex out of the five designs we compared because the whole concept would be 3D printed with no extra components.

Our second criterion was cost. This criterion was assigned a weight of two because the cost is important, but most of our concepts will fall in the same range to manufacture given that most parts will be 3D printed. The more expensive something was to design, build, test, and implement, the lower the score. The standard fin-design and the vent design were deemed the cheapest (and hence the best-scoring designs for this criterion) because they would be 3D printed only.

Our third criterion was material availability. We evaluated each design based on how easy it would be to get access to the materials needed to make the design. This criterion was assigned a weight of three because it is important that we use material we have access to, but there are ways to get substitutes if needed. The baseline design, the spring-loaded design, and the vent design were all ranked equally well because each design had only one or two materials/components. The parachute and Christmas tree designs required access to more materials, so those scored lower.

Our fourth criterion was modeling accuracy. A design for which a mathematical model would be harder to derive scored lower. This criterion was assigned a weight of three because it is the second objective of our project so it was important that we could do this, but we also assumed that assumptions can be made with each design to make an accurate model. The parachute, vent, and Christmas tree designs all scored badly here because the aerodynamics would be complicated between the multiple different systems of each design. For the parachute and christmas tree design it would be difficult to assume how the pores throughout different parts of the systems would contribute to the aerodynamics, while the vent design would be variable depending on how the air flowed through them.

Our fifth criterion was reusability. We defined reusability as the ability of each design to be used multiple times on many different whale tagging trips that would not be time consuming to set up again. This criterion was assigned a weight of four because it is critical that each design can be run for many trials as a stakeholder requirement. The christmas tree and parachute designs were given a negative score because they both may have issues with being fished out of the water and reassembled to be dropped again.

Our sixth criterion was performance. We associated performance with how well they will function theoretically depending on analysis of the physics of the concepts. We gave a five for the weight of performance because our project is heavily focused on figuring out the best concept for getting the best stability out of the design as quickly as possible. The vent was given the only negative values because the response of the aerodynamics on the vents would be dependent upon the angles at which the vents are placed inside of the design. This is a problem because it would be more complicated and difficult to control the design by the way air moves through the internal vents to reach a stable vertical orientation.

Our seventh criterion was ease of use. Each design was ranked based on how easy it would be for somebody to use the design. If a design had any special instructions, special features, or special dangers/hazards that the user would have to be briefed about, then the design scored a lower score. This criterion was assigned a weight of three because we want the researchers to have no issue operating the concepts, but if there is difficulty, some tutorial videos could be created to teach the best methods of use. The parachute and the Christmas tree designs ranked lowest in this category because the parachute would have to be repacked every attempt and the christmas tree would be very difficult to attach to the drone given its multi-layered design.

## ENGINEERING ANALYSIS

We used theoretical and computational to conduct the Engineering Analysis used to guide our design. The theoretical methods were used to create a dynamic model for our DTAG and fin attachment flight system. Computational methods were used to plot the dynamic responses of the flight system during freefall.

### Theoretical Methods

We created a dynamic mathematical model to approximate the motion of the DTAG during its descent using kinematics and dynamics fundamentals. After making several critical assumptions about our system, we derived an equation of motion for the DTAG. The equation of motion and the dynamic model were used as tools to help us make informed design decisions.

The creation of the dynamic model necessitated a firm grasp of the physics that influence our flight system. This section will explain the concepts behind the derivation of the governing equations of our system.

We started the derivation process with a heavily simplified visual of our fin attachment (Figure 17 below).

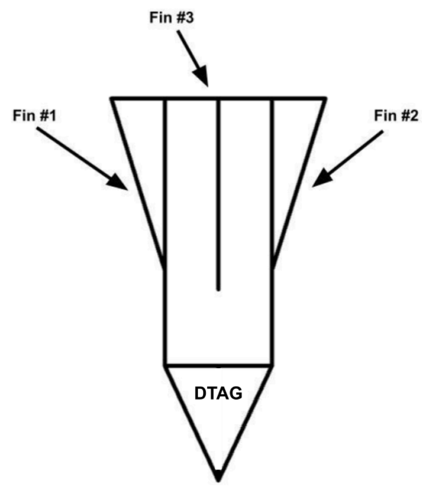



**Figure 17:** Simplified fin attachment visual with four fins (three of which are labeled and one on the back side of the system (not visible)) and the location of the DTAG.

We considered the vertical orientation of the system depicted in Figure 17 a stable orientation. Any angular deviation away from this orientation was considered unstable. Our intention was to use the fins shown above to re-stabilize the system when it moves to an unstable orientation. Given that the system is inevitably going to reach an unstable orientation, we based our analysis on the forces that act on our system when the system is tilted or perturbed away from its vertical orientation. Figure 18 below is a free-body diagram that shows the forces acting on our perturbed system assuming a non-zero vertical velocity.

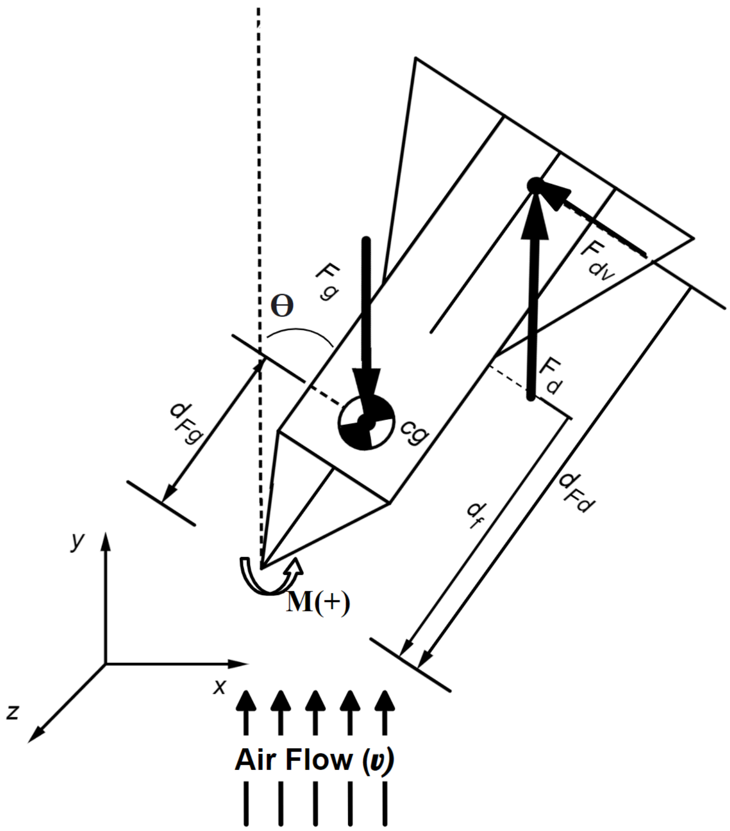



**Figure 18:** Simplified flight system (assuming DTAG and fin attachment are both included in total mass of the figure displayed), where the DTAG would be located at the tip (triangle) at the bottom of the shape. All relevant forces related to the angular stability of the flight system are represented by arrows and are labeled as $F_d$,$F_{dv}$, and $F_g$ which represent the force of drag on the fins due to vertical linear velocity, the force of drag on the fins due to angular velocity of the flight system about the point of rotation (located at *M(+)*), and the force of gravity acting at the center of mass, respectively.

In the free-body diagram of the flight system above, we included the force of gravity ($F_g$ ), the drag force induced by the downward linear velocity of the flight system ($F_d$ ), and the drag force induced by the angular velocity of the system about the bottom-most point of the system ($F_{dv}$ ).

The general equation for the force of gravity is defined below in Equation 1.

$$F_g = m * g \quad (1)[19]$$

The equation contains variables for the mass, $m$ [kg], of the flight mechanism and the acceleration due to gravity acting on the system, $g$ [m/s$^2$]. This force acts at the center of gravity of the flight system, which is labeled as $cg$ in Figure 18 above.

Equation 2 below is the equation for $F_{dv}$ , the drag force induced by the linear velocity of the system.

$$F_d = \frac{1}{2} A_{proj} \rho_{air} C_d (v)^2 \qquad (2)[17]$$

In Equation 2 above, the force of drag acting on a body or surface can be represented using the projected area ($A_{proj}$ [m$^2$] where projected area is the two-dimensional area that an object occupies when viewed from a particular direction - in this case, the "viewing direction" will take the form of the vectorial direction of the air flow), the density of the air through which the flight system is traveling ($\rho_{air}$ [g/cm$^3$]), the coefficient of drag reflecting the aerodynamic resistance of an object ($c_d$ [-]), and the velocity of fluid flow around the object ($v$ [m/sec], in this case the instantaneous velocity of the flight mechanism at any time throughout its trajectory).

The equation for $F_{dv}$ , the drag induced by angular velocity, is shown below in Equation 3.

$$F_{d,v} = \frac{1}{2} A_{proj,max} \rho_{air} C_d \left(\frac{d\theta}{dt} * d_{fd}\right)^2 \qquad (3)[18]$$

In Equation 3, $A_{proj,\, max}$ represents the projected area on which the drag force induced by the rotational velocity of the system acts. This projected area remains constant during the descent because the drag force acts perpendicularly to the surface of the fin, which is why the maximum projected area (the standard geometric area of the fin) is used. The velocity of the system can be rewritten in terms of the angular velocity multiplied by the distance between the center of rotation of the system and the centroid of the fins ( $\frac{d\theta}{dt} * d_{fd}$ ).

The primary difference between $F_d$ , the drag induced by linear velocity, and $F_{dv}$ , the drag induced by angular velocity, is the nature of how the air flow around the fin is induced. The $F_d$ term is solely dependent on the linear velocity of the flight system and the angular orientation of the system ($\theta$ in Figure 18 above). Because the linear velocity of the system and the angular orientation of the system both change as the flight system falls, the projected area of the fin that experiences the drag force $F_d$ also changes at different system angles. This differs from the drag force induced by the angular velocity of the system ($F_{dv}$). Based on our free-body diagram in Figure 18, the $F_{dv}$ drag force acts directly over the entire area of the fin. This means that the projected area of the fin over which $F_{dv}$ acts remains constant.

After examining all of the forces acting on the flight mechanism throughout flight, we can generate the equation of motion by taking the sum of all moments acting on the flight mechanism (Equation 4).

$$\sum_{i}^{n} M_p = M_d + M_{d,v} - M_g = I\frac{d^2\theta}{dt^2} \tag{4}[20]$$

This equation represents the dynamic equilibrium of the flight mechanism, where $M_p$ is the net moment acting on the system due to all external forces, $M_d$ and $M_{d,v}$ are the moments due to the drag forces (linear and rotational, respectively), and $M_g$ is the moment due to gravity. The right side of the equation, $I\frac{d^2\theta}{dt^2}$ denotes the moment of inertia of the flight mechanism multiplied by the angular acceleration, which is the rate of change of angular velocity over time.

The moments induced on the fins arise from the dynamic interplay between drag forces and their distance to the fins' center of rotation. This distance is influenced by the shifting center of pressure on the fins, which varies with changes in airflow and fin orientation. The specified distance, which is the separation between the point of drag force application and the moment center (denoted as the distance from $F_d$ to M(+)), is variable and is depicted below in Figure 19.

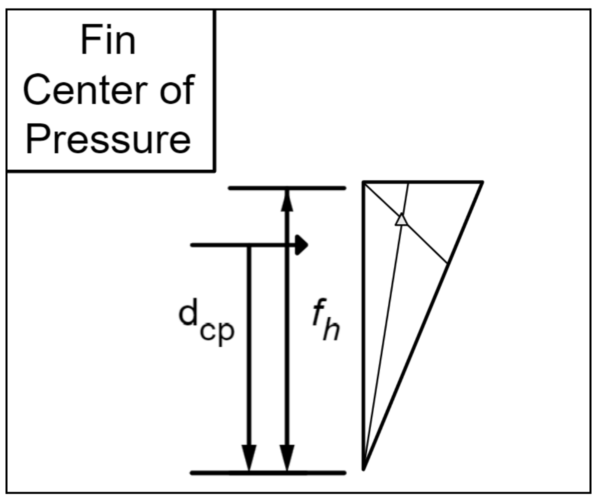



**Figure 19:** Schematic representation of the fin's center of pressure ($d_{cp}$). The diagram illustrates the geometric relationship between the fin height ($d_f$) and the vertical distance to the center of pressure ($d_{cp}$).

The variable center of pressure ($d_{cp}$) is defined in Equation 5 below.

$$d_{cp} = d_f(1 - \frac{1}{3}sin\theta) \tag{5}$$

In this equation, $d_{cp}$ is dependent on the fin's height and the angle of deflection (θ, which is the same angle found in Figure 18 above), capturing the effect of area projection on the location of the center of pressure in the y-direction along the fin's height. The summation of the fixed distance from the center of rotation to the bottom of the fin ($d_f$) and the distance from the bottom of the fin to the center of pressure of the fin ($d_{cp}$) can be used to describe the lever arm (related to $M_p$) for pressure drag ($F_d$) acting on the fin.

In this context, the equation serves to balance the moments generated by aerodynamic drag and gravity against the inertia of the flight mechanism, providing a comprehensive understanding of how these forces and moments interact to influence the angular motion of the system. The equation emphasizes the significance of considering both linear and rotational dynamics for a complete analysis of the flight mechanism's behavior, particularly in understanding how these forces contribute to the stability and control of the flight response by inducing moment onto the free body.

Finally, we can expand on each of the moment terms included in the summation of the moments in Equation 4. The expanded and final form of the equation of motion can be found in Equation 6 below.

$$I\frac{d^2\theta}{dt^2} = (\frac{1}{2}A_{proj,max}\rho_{air}C_d(\frac{d\theta}{dt} * d_{Fd})^2) * d_{Fd} + (\frac{1}{2}A_{proj,var}\rho_{air}C_d(\nu)^2)sin\theta(d_f + (d_f(1 - \frac{1}{3}sin\theta))) - F_g sin\theta \cdot d_{Fg} \qquad (6)$$

$F_d$ acts at the fins' center of pressure, located at the projected area's geometric center, with its lever arm extending from the center of rotation *M(+)* to the center of pressure. The rotational drag force $F_{dv}$ is perpetually perpendicular to the fin surface and acts at the fin's geometric center (given that the airflow is constantly perpendicular causing $A_{proj}$ to be constant contrary to $F_d$), with its lever arm measured from *M(+)* to $F_{dv}$'s point of action. The last term in the equation is the torque on the system caused by the force of gravity, which is solely reliant on the angle from the vertical of the flight system at any given moment. This force does not generate a moment on the system if the system is aligned with the vertical axis.

<u>Model Assumptions</u>

Throughout this dynamic analysis, assumptions were made to simplify the aerodynamic force analysis of the flight system. One assumption was the focus on pressure drag to the exclusion of skin drag and lift in the equation of motion. This is justified on the grounds that pressure drag is often the dominant force, particularly in objects with bluff shapes or high angles of attack where it far exceeds skin friction.

Furthermore, given that the objective is to assess the oscillatory response of the system rather than its translational motion, pressure drag is more relevant as it significantly influences moments and angular motion. Skin drag is assumed to act tangentially to the surfaces of the fins. This tangential nature means that skin drag has a much shorter lever arm when compared to pressure drag, because the lever arm for skin drag is limited to the fin's width, which is considerably smaller than the fin's length. Since the lever arm in moment calculations is the distance from the axis of rotation to the line of action of the force, the moment generated by skin drag is significantly less than that generated by pressure drag.  The pressure drag acts perpendicular to the airflow and has a lever arm equivalent to the length of the fin attachment. This distinction is pivotal in focusing the analysis on pressure drag, which has a more substantial influence on the system's rotational dynamics and stability.

These assumptions enable a more manageable computational analysis while still capturing the essential dynamics for understanding the system's stability and control. However, it is acknowledged that these simplifications may limit the model's applicability in scenarios where skin friction and lift forces become non-negligible, and these factors may need to be incorporated in a more detailed analysis.

**Computational Method**

With the EOM derived, the MATLAB's ODE45 function, which is a built-in  MATLAB ODE solver,  can be used to obtain the system response. We first rearrange the EOM (Equation 6 above) by expressing $\frac{d^2\theta}{dt^2}$ in terms of $\frac{d\theta}{dt}$ and θ, which will be (Equation 7):

$$\frac{d^2\theta}{dt^2} = (-\ C(\frac{d\theta}{dt})^2 - D)\ /\ I, \tag{7}$$

where the C is $\frac{1}{2}A_{proj}\rho_{air}C_d d_{Fd}^{\ 3}$, and D is $(\frac{1}{2}A_{proj}\rho_{air}C_d v^2)sin\theta(d_f + (d_f(1 - \frac{1}{3}sin\theta)) - F_g sin\theta \cdot d_{Fg})$.

As shown in the Figure 20 below, the ODE function expressed in the code will be:

```
function dydt = odefun(t, y, rho_air, Cd, Fg, d_Fd, d_Fg, d_f, g)
    % Unpack the state vector
    theta = y(1);
    dtheta = y(2);

    % ... A_proj calulation ...

    % Define two constant C and D just to make d2theta equation simpler
    D = (A_proj * rho_air * (d_Fd) ^3) / I;
    C =  (A_proj *rho_air * Cd * (g * t)^2 * sin(y(1)) * ...
        (d_f + (d_f * (1 - 1/3*sin(y(1))) - Fg * sin(y(1)) * d_Fg)) / I;
    d2theta = -D * y(2)^2 - C;% The second derivative of theta, derived from the given equation

    % Return the derivatives as a column vector
    dydt = [dtheta; d2theta];
end
```

**Figure 20:** Screenshot of MATLAB code used to create a function that can solve an ordinary differential equation. Line 52 express the $\frac{d^2\theta}{dt^2}$ as shown in Equation 7, which is needed for the ODE45 input.

Then, as shown in Figure 21 below, the odefun is plugged into the ode45 function with initial conditions and other parameters set up for the tagging system. The theta vs time is then plotted using the calculated result.

```
18    %... set up the parmeter for the simulation, for example, air density rho ...
19    % Initial conditions
20    theta0 = .2; % Initial angular offset
21    dtheta0 = 0; % Initial angular velocity (assuming it starts from rest)
22
23    % Define the time span for the simulation
24    tspan = [0, 20]; % for example, from 0 to 10 seconds
25
26    % Initial state vector
27    init_conditions = [theta0, dtheta0];
28
29    % Solve the ODE using ode45
30    [t, y] = ode45(@(t, y) odefun(t, y, rho, Cd, Fg, d_Fd, d_Fg, d_f, g), tspan, init_conditions);
31
32    % Plot the results
33    plot(t, y(:,1)); % Plot theta over time
34    xlabel('Time (s)');
35    ylabel('Angular Offset (radians)');
36    title('System Response to Initial Angular Offset');
37
```

**Figure 21:** MATLAB code chunk of plugging in the function into ode45 and plotting the result. Line 30 which is key line is in form [t,y] = ode45(odefun,tspan,y0), where tspan is time span we will simulated, integrates the system of differential equations y''=f(t,y,y') from t0 to tf with initial conditions y0. Each row in the solution array y corresponds to a value returned in column vector t. In our case, the y here refers to theta which is the deviation angle.

The plot is shown in Figure 22 below. Right now, the settling time is longer than the specification suggests (0.6 seconds).

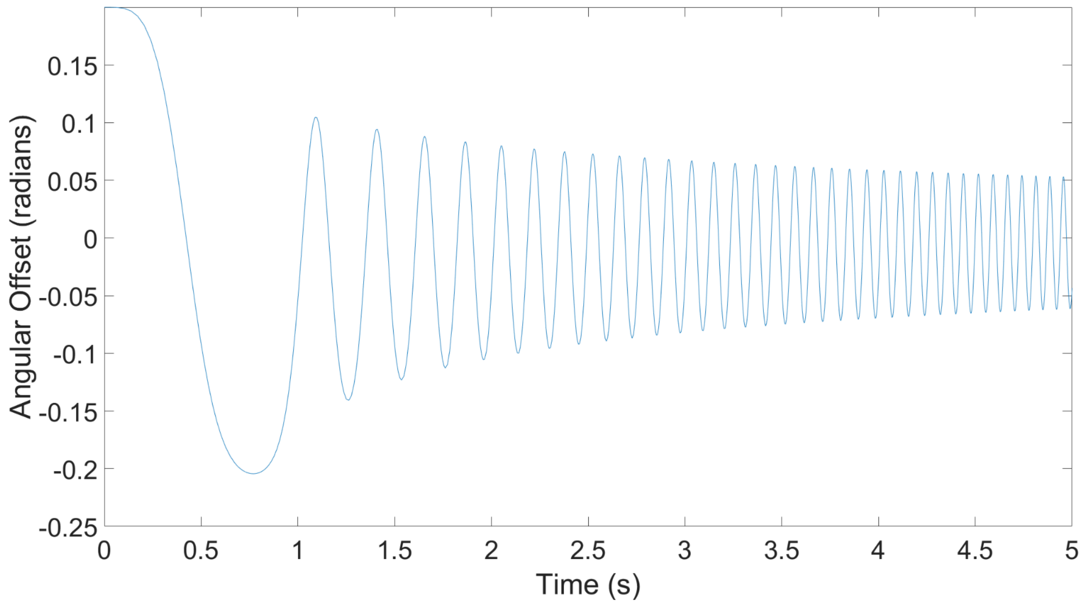



**Figure 22:** Plot of simulation result given an initial 0.2 radian perturbation using untuned fin parameters, which assumes a isosceles right triangle fin with 50mm side length. The $d_{Fg}$, $d_f$ , and $d_{Fd}$ (arm length defined in Figure 18) is set to be 50mm, 100mm, and 150mm correspondingly.

A preferable response example from the shuttlecock model [21] is shown in Figure 23, which reaches a 0.6 seconds settling time specification. Our future goal will be tuning the parameters like the dimensions of the fin to finally reach this state.

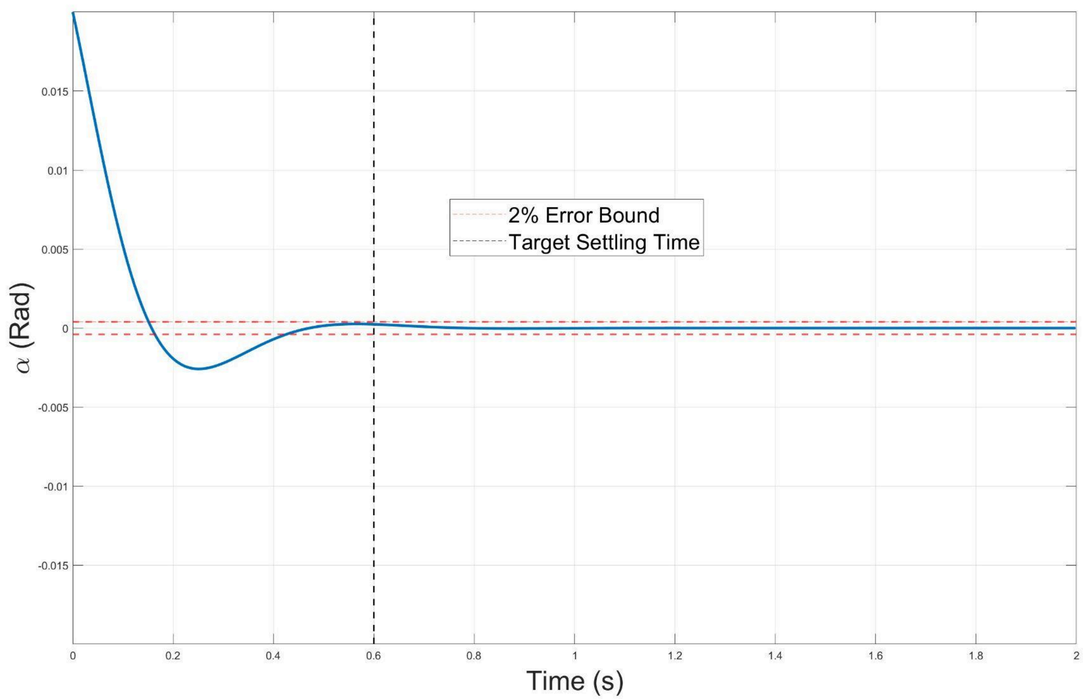



**Figure 23:** Plot of preferred response, which is an underdamped system response with satisfying settling time.

<u>Rod Modelling</u>

A simplified model of dropping a rod is developed using a 2rd order ODE. First, given the free body diagram:

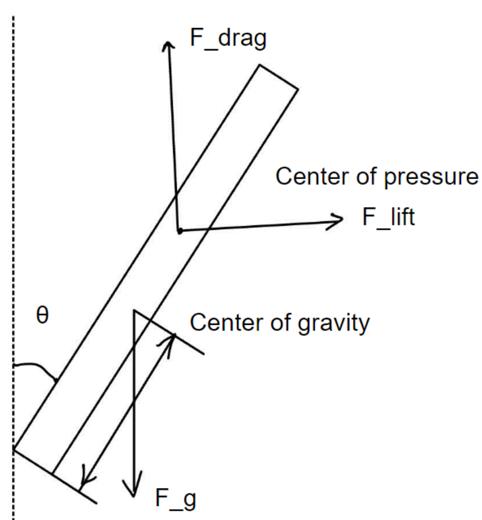



**Figure 24:** FBD of rod, the gravitational force is acting on the center of gravity, and the drag force and lift force is acting on the rod center of pressure

Using Conservation of Momentum and Newton's Second Law, We end up with the 2nd order ODE:

$$I\frac{d^2\theta}{dt^2} = -\, mg\,L_g sin(\theta)\ -\ c_d\frac{d\ \theta}{dt}\ Lcos(\theta)\ -\ c_l\frac{d\ \theta}{dt}\ Lsin(\theta) \tag{8}$$

Where $c_d$ is the coefficient of air drag. $c_l$ is the coefficient of air lift. $v(t)$is the velocity of the rod's center of mass. $I$ is the moment of inertia of the rod. After putting the equation into the ODE45 function in the similar process stated previously we obtain the following result of the angle of attack vs time below:

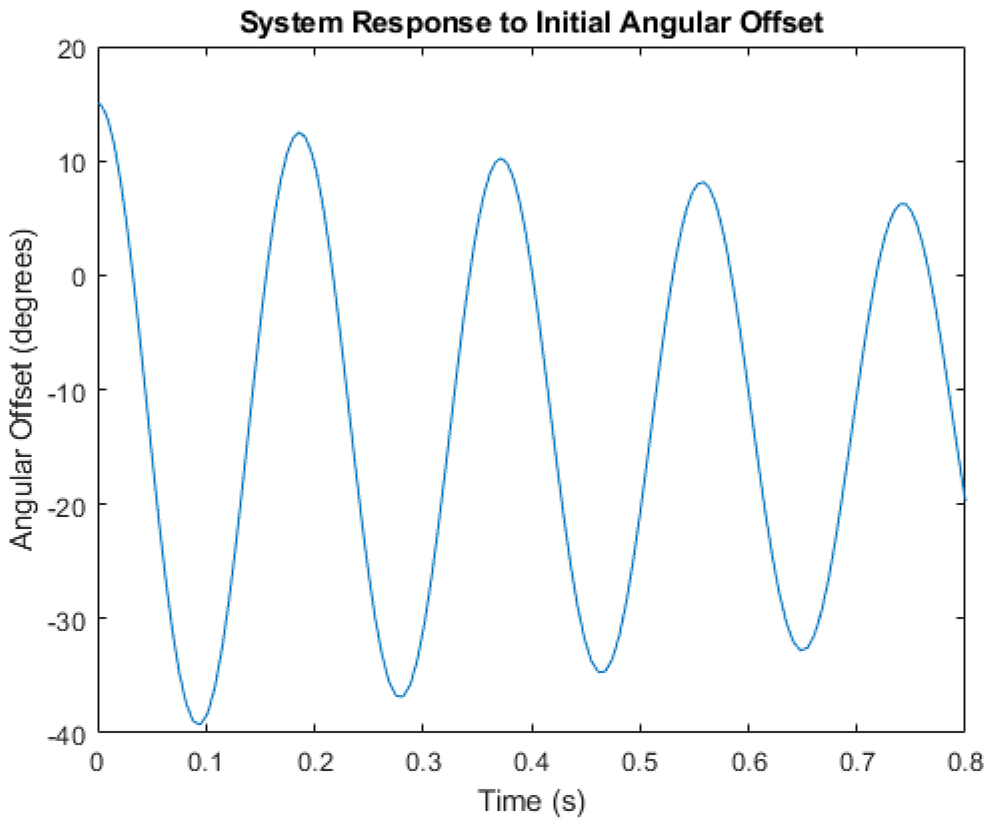



**Figure 25:** The plot of the system response of angle of attack. The rod is considered an unstable system which pivots back and forth since there do not exist fins to provide corrective drag and lift forces.

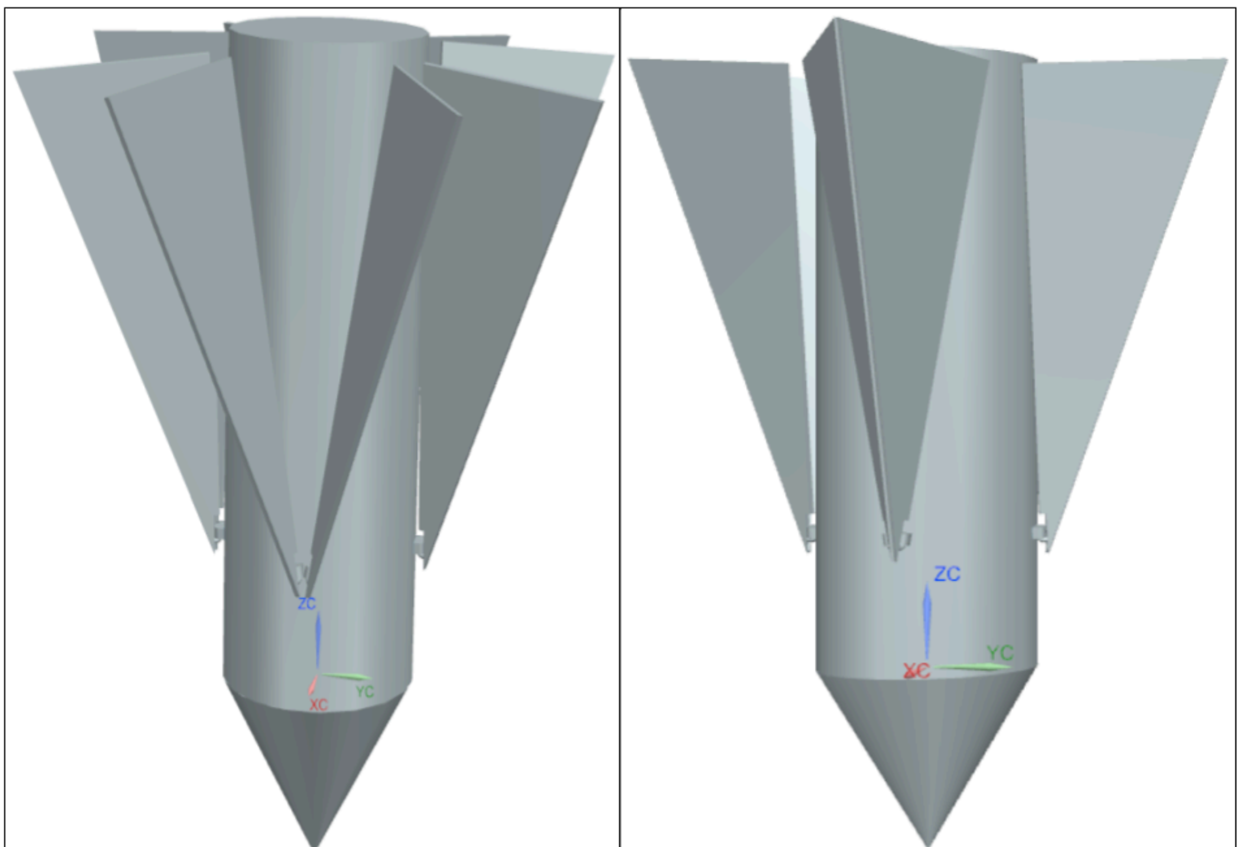
**ALPHA DESIGN**

The selection of an "Alpha Design" was our last step in the concept selection process. This section will explain how the information from our Engineering Analysis was used to make critical design decisions as we fleshed out our final alpha design concept. Our final concept is a fin attachment meant to be fixed onto the DTAG to help stabilize the DTAG's descent.

**Fin Attachment**

The prototype alpha design was chosen after undergoing the concept generation and filtration and being compared thoroughly to all other concepts that were introduced to address the design prompt.

This design embraced a semi-active design type by incorporating a dynamic fin design giving each fin one independent degree of freedom relative to its attachment to the body of the flight mechanism. The primary purpose of incorporating an additional degree of freedom is to enable the fins to interact dynamically with varying airflow, adopting configurations that modify the aerodynamic characteristics of the flight mechanism. These fins will be connected to the main body through a rotary hinge, allowing each fin to pivot along a specific axis, as displayed in Figures 26 below. To control the fin's pivot range, "stoppers" — protrusions on the fin's attachment shaft — will be strategically placed to constrain the range of motion. This arrangement ensures that each fin can adjust within a predetermined arc, enhancing the flight mechanism's maneuverability and stability by optimizing its aerodynamic profile.




| Fin Position Limit #1 (a) | Fin Position Limit #2 (b) |
| --- | --- |

**Figure 26:** Illustration of the fin's range of motion in a flight mechanism. a) The fin at its initial position limit. b) the fin at its second position limit.

Figure 26 above allows for the visualization of the fin limits as well as how the fin pairs merge into one another to create a closed surface that serves as a new fin profile. Below is a bottom view visualization (Figure 27) to understand how the projected areas of the fins are altered relative to the vectorial direction of airflow opposing the linear velocity of the system (vertical) in freefall.

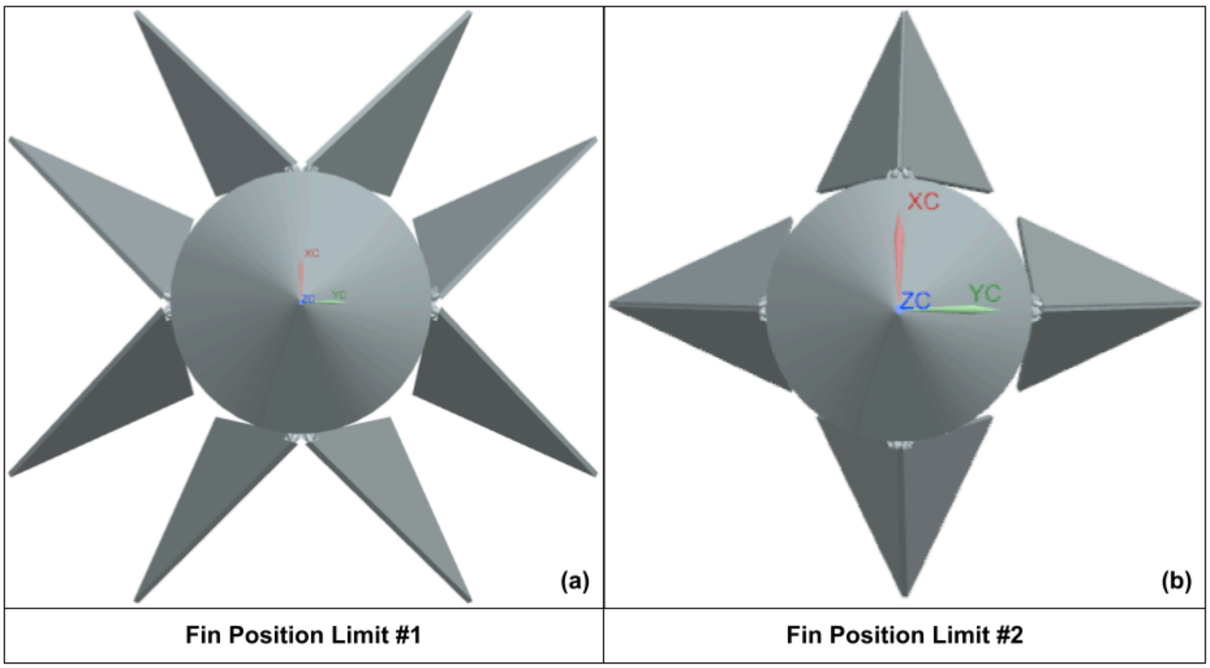



**Figure 27:** Bottom view illustration of the fin limits on the flight mechanism, depicting the two extreme positions. a) 'Fin Position Limit #1' shows the fins fully extended. b) 'Fin Position Limit #2' presents the fins in a retracted position.

The aerodynamic positioning of the fins is governed by a delicate balance between the restoring force of a spring and the opposing force of aerodynamic drag. Each fin is maintained in its initial position, referred to as Position #1, by the tension of a spring that is anchored to both the body of the vehicle and a specific attachment point on the fin's surface (Figure 28, below). As the system enters freefall, aerodynamic drag becomes the predominant force, overcoming the spring's tension and causing the fins to pivot towards Position #2. This mechanical interplay allows for an automatic adjustment of the fins' orientation in response to the drag experienced during descent, ensuring optimal stability and control of the flight mechanism throughout its trajectory.

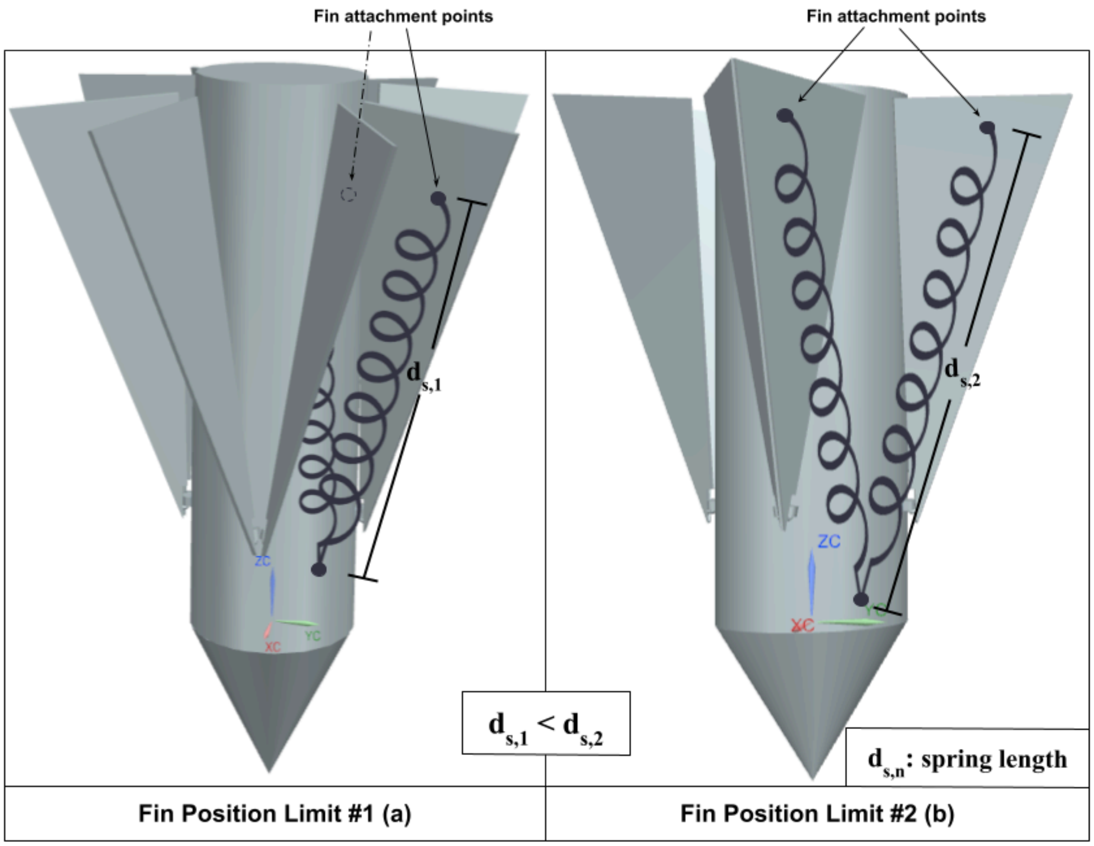



**Figure 28:** This image presents a side-by-side comparison of the fin-spring interface at two distinct fin positions. The spring length is labeled as $d_{s,1}$ **(a)** on the left and $d_{s,2}$ **(b)** on the right.

In the Figure 28a (above left), 'Fin Position Limit #1' shows the spring in a less extended state (length $d_{s,1}$), corresponding to the fin's position under lower aerodynamic drag (the state of the system immediately after being released). The right side, 'Fin Position Limit #2,' illustrates the spring in a more extended state (length $d_{s,2}$), where the increased aerodynamic drag during high-speed conditions has overcome the spring's restoring force, resulting in the fin being drawn to a position closer to the body. This visual representation highlights the physical relationship between spring tension and fin positioning within the mechanism's operational range. This relationship is important for the understanding of the flight mechanism due to the interaction between the spring forces and the force of drag acting on the fins, displayed in Figure 29 below.

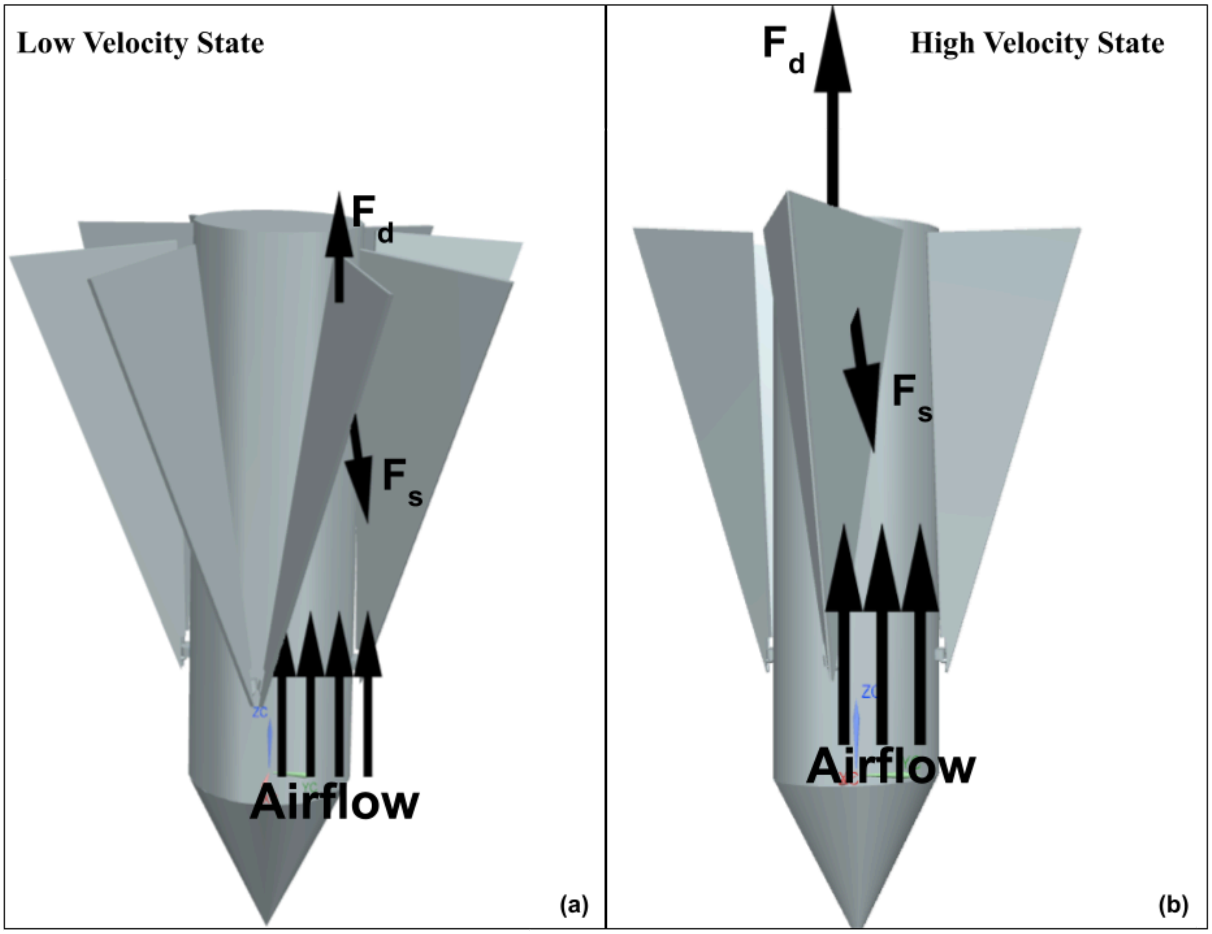



**Figure 29:** Comparative free body diagrams illustrating the forces acting on the fin mechanism at different airflow velocities. a) The condition at low speeds. b) depicts the scenario at higher speeds. The forces denoted as $F_d$ and $F_S$ describe the force of drag on one fin as a result of the airflow and the spring force acting on the fin as a result of a spring in tension, respectively.

The detailed mechanics of the fin's operation are explained through the comparative free body diagrams seen above in Figure 29. These diagrams graphically delineate the forces at play on the fin at varying speeds. The Figure 29a visualizes the low-speed condition wherein the fin is predominantly influenced by the spring force ($F_S$). This force generates a significant moment about the hinge, ensuring the fin maintains its position at the first position limit. At this instant, the force of drag ($F_d$) is minor due to the reduced velocity of airflow (a state that would be expected shortly after the flight mechanism is released from the drone).

Conversely, Figure 29b showcases the high-speed state where the drag force ($F_d$) increases in response to increased airflow velocity, overpowering the spring force ($F_S$) and causing a more substantial moment. This moment shifts the fin towards the second positional limit, a transition indicative of the fin's dynamic response to the changing aerodynamic environment. This comparison displays the fin's ability to alter its projected area onto the airflow which, given this current setup, allows the force of drag to increase at lower speeds (relative to the alternate position 2 of the fins) by increasing the magnitude of the $A_{proj}$ as seen in Equation 3.

The capability to adjust the projected area of the flight system's fins serves two crucial objectives. Initially, drag force is a primary stabilizing factor within the system, yet it remains negligible during the initial moments post-deployment due to minimal airflow interaction (Figure 30 below). Given that the drag equations (1,2) include the square of airflow velocity, its impact is especially limited at the outset of flight. By leveraging the ability to manipulate the projected area, we can amplify the drag force exerted on the fins, thereby enhancing stability of the early system—a vital component of the system's design.

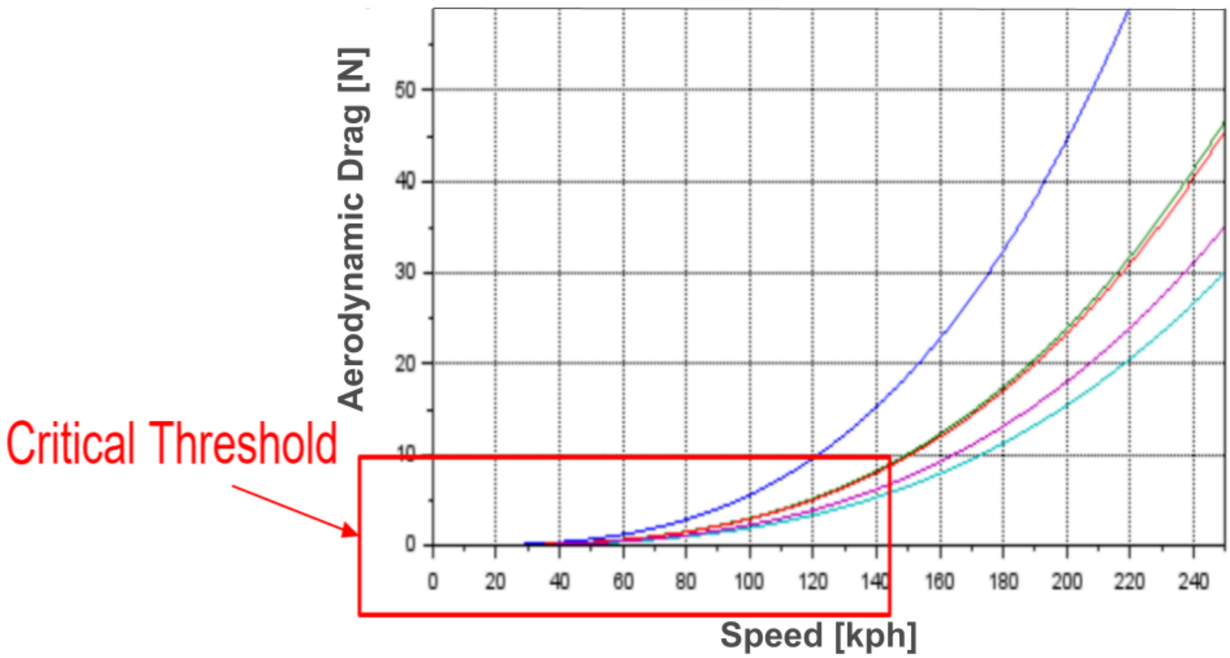



**Figure 30:** Graph relating Speed [kph] to Aerodynamic Drag [N]. The red box represents the critical threshold of speeds at which the aerodynamic drag is small.

Furthermore, managing the impact velocity of the flight system when it makes contact with the whale is essential to ensure an impact force sufficient enough to create proper suction. This too can be manipulated through the semi-active aerobody of the system. Adjustments in fin positioning, alterations in fin shape, the orientation of the hinge, and the spring constant are all variables that can be fine-tuned to influence both the drag force at any point throughout the flight. This level of control is indispensable for ensuring the system's performance meets the operational requirements.

## BUILD DESIGN

We had two primary build designs that we will use to assist us in creating a fully fleshed-out design. The first of these is a mockup of our design made of basic craft materials. The purpose of the mockup is to help us understand the limitations of our design when realized as a physical concept instead of as a CAD model. The second build design was a full prototype of our alpha design which implemented some changes based on what we learned from creating the mockup. The prototype has not been completed yet, but various iterations of the prototype will be made until we find one that satisfies all of our requirements. The motivation for the concepts that will compose the build design were expanded upon above and included the variable position and the springs attached to the fins which work hand in hand to generate a model that is able to alter its aerobody throughout its descent in order to optimize the oscillatory response of our system.

### Engineering Mockup

A physical mockup was made to illustrate the semi-active fin design which has two fin shapes at different drop speeds. The base, representing the D-TAG, was crafted from construction paper. The fin and cylinder were made from a toilet paper ring and paper towel paper. The fin's spring mechanism was created using pipe cleaners. The whole mockup was then assembled using tape, glue, and paper clips. Three views of the mockup are shown in Figure 31 below:


a) b) c)

**Figure 31:** An engineering mockup of our alpha design made using basic crafting materials. a) The position of the fins at the start of the DTAG's descent. b) The position of the fins when the DTAG is towards the end of the descent. The increased drag forces acting on the body towards the end of the descent cause the fins to change to this position. c) The side view of the fins when they are in their closed final

position.  that represents the release system activating when speed increases, causing the fin to close due to increased drag that pulls the springs.

The mockup was created to provide us with a physical model that could show the motion of the fin behavior.  One primary difference between our mockup and our final design is that, since creating the mockup, we have decided to switch from using linear springs to using torsional springs.

**Engineering Prototype**

We will vary the position of the fins using hinges at the interface between each fin and the central body of the flight mechanism. This mechanical hinge will allow the fins to rotate freely about their axis of rotation, and thus will also have pegs on the body of the assembly that will aid in limiting the range of rotation of each of the fins.  A Bill of Materials has been provided in the Appendix.

The mechanism uses torsion springs and hinges to allow the fins to move between two positions based on the speed of the system (Figure 32 below, more views in Appendix)).

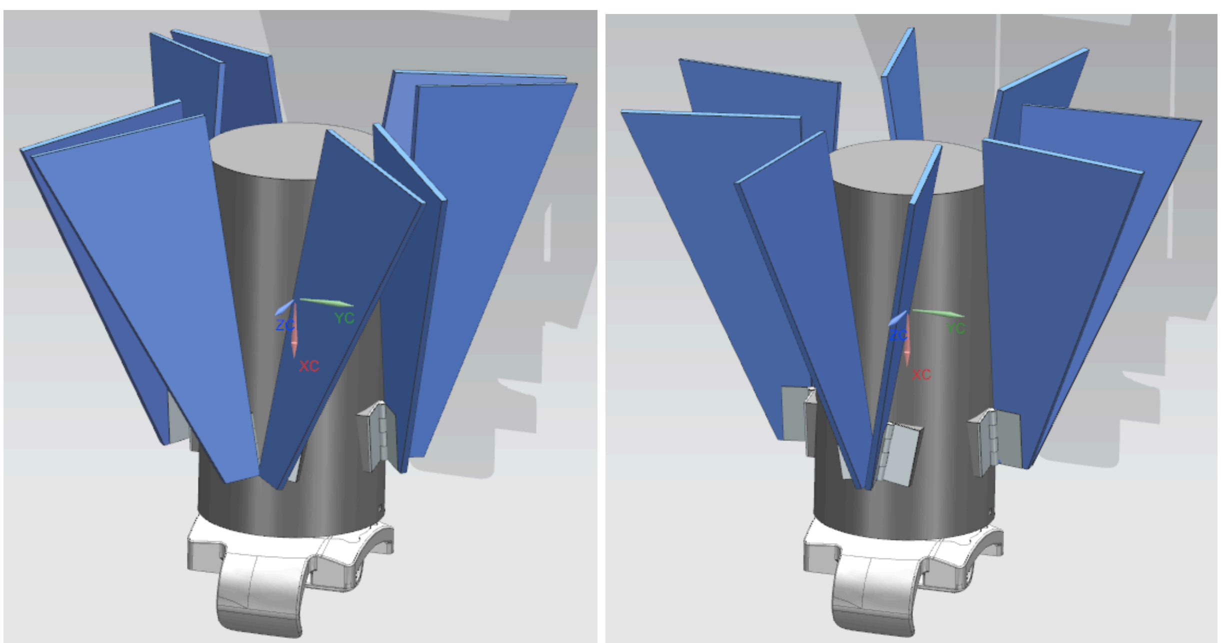



**Figure 32**:  Side-by-side comparison of the final CAD model of our prototype.  The picture on the left shows the position of the fins at the start of the descent.  The picture on the right shows the position of the fins at the end of the descent.

At lower speeds, where drag forces are minimal, the torsion springs push the fins into a starting position, referred to as "position 1" (defined by the positioning of the pegs) as shown previously in Figure 26. As the system speeds up, the drag force on the fins increases, overcoming the resistance of the torsion springs. This causes the fins to rotate towards "position 2", also shown in Figure 26, where the pegs placed on the body of the mechanism stop the fins from rotating beyond this second position. This ensures that the fins can only move within a predetermined range, adjusting automatically to the speed of the system to optimize stability. The components of our prototype are explained in detail below.

Hinges

The selection process for the hinges was guided by a comprehensive evaluation of factors including cost-effectiveness, dimensional requirements, material characteristics, and frictional properties. Initially, we aimed to utilize spring-loaded bearings to function as hinges for the fins, an approach that was quickly deemed impractical due to the absence of commercially available options meeting our specific force and scale parameters. This challenge necessitated a pivot towards a more bespoke solution, culminating in the adoption of a hinge/torsion spring sub-assembly.

This tailored approach proved to be exceptionally advantageous for our application. It significantly enhances cost efficiency and introduces greater adaptability in terms of the individual customization of the spring and hinge materials. Moreover, it affords us the capability to precisely adjust the spring constant, a critical parameter meticulously calculated to align with our application's unique demands. This will allow us to experiment with multiple different spring constants and compare their effects on the system response.

The material for the hinge we chose to be stainless steel 304 or 316 (whichever one we can source will work for our application). Our reason behind this decision was driven by the fact that our flight mechanism will directly interact with an aqueous environment, and thus must be corrosion resistant and oxidation resistant. Stainless steel 304 and 316 both have abundant amounts of Chromium, which make them great materials for aqueous environments as they create a passive layer of chromium oxide that acts as a shield against oxidation and corrosion. A drawing of the hinges we intend on using is included below in Figure 33.

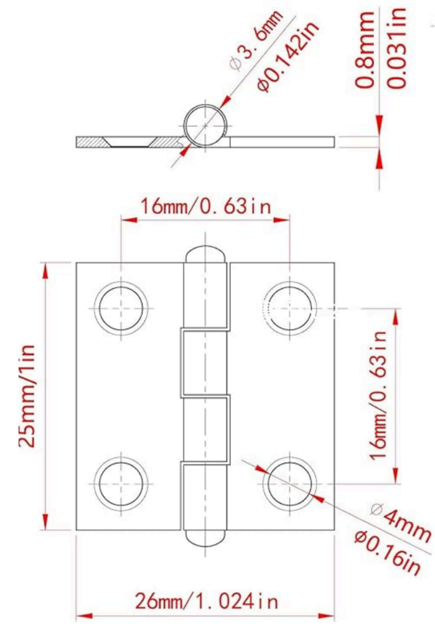



**Figure 33:** Engineering drawing of hinge with denoted dimensions.

Addressing the unique challenges of the hinge design for the flight mechanism necessitates a thoughtful approach to optimizing physical dimensions and adhesive selection. A key concern is the interface between the flat surface of the hinge and the rounded surface of the mechanism's body, which poses a risk for suboptimal adhesion. To mitigate this, a driving requirement has been established to minimize the hinge's width. This strategy is aimed at reducing the "free hanging surface" area that does not make direct contact with the body, thereby minimizing the potential for detachment or failure at the interface. A narrower hinge not only ensures an improved adhesion area relative to the size of the hinge but also integrates more seamlessly into the mechanism's aerodynamic profile and reduces overall weight—an essential factor listed in our performance requirements.

<u>Springs</u>

We initially considered incorporating a traditional linear spring into our design, linking the surface of the fin to the cylindrical body of the flight mechanism. However, we've opted to move away from this idea due to practical concerns. A linear spring's external placement could potentially interfere with the aerodynamics of the flight mechanism and expose it to environmental hazards, such as snagging on objects or detachment.

To overcome these challenges, we've shifted our focus towards integrating a torsion spring directly with the hinge of each fin. This decision is rooted not only in the aim to enhance the aerodynamic profile and reliability of our design but also in simplifying the engineering analysis. Torsion springs offer a more streamlined implementation, as they exert a direct rotational force on the fin, eliminating the need for complex calculations associated with variable geometry and the resultant moments from a linear spring setup. This straightforward mechanical action allows us to use catalog specifications to accurately determine the required spring force, simplifying the design process and ensuring a more predictable performance of the flight mechanism.

To incorporate the torsion spring into our design effectively, we've strategically decided to leverage the functionality of a hinge, integrating both the spring and hinge into a cohesive sub-system, shown below in Figure 34.

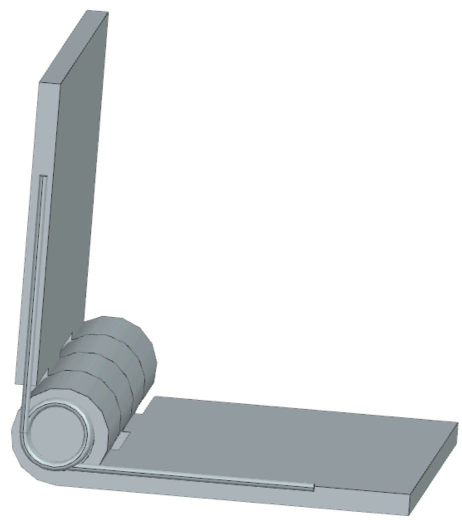


**Figure 34:** Hinge-Spring subassembly. The spring will be adhered onto the side of the hinge using some kind of an epoxy.

This integration results in each fin being equipped with its own spring-loaded hinge mechanism, thereby governing its rotational movement around its own axis. This approach not only enhances the robustness of the fin attachment but also significantly reduces its susceptibility to external interference, ensuring a more secure and reliable operation.

<u>Fin and Body</u>

The fins and the body of the flight mechanism will be constructed using PETG, chosen for its exceptional qualities that align well with our project's requirements. Our decision to employ 3D printing technology for creating this mechanism is driven by the need for a manufacturing process that ensures high repeatability. This characteristic is crucial for the research team working on the project, as it enables easy replication of the mechanism for various purposes, whether for performance optimization, informed by our computational MATLAB model, or for repairs.

The selection of PETG as the material of choice is justified by its superior corrosion resistance, outperforming many other 3D printing filaments in terms of durability under high-impact conditions. However, the most compelling attribute of PETG for our application is its exceptional resistance to UV degradation. This quality is particularly vital for outdoor use, especially in maritime environments where UV ray reflection off the water's surface (particularly off of “sea foam”) can significantly accelerate material degradation. The use of PETG thus ensures the long-term durability and reliability of the flight mechanism, even under the challenging conditions it is designed to withstand.

Adhesive

Epoxy has been selected as the adhesive material of choice, driven by its suitability for the project's specific needs. Epoxy adhesives stand out for their bond strength and resistance to aqueous environments, making them ideal for securing the hinge in conditions where moisture presence is a concern. Their robustness against cycling and impacts further contributes to the durability and reliability of the hinge attachment. Moreover, epoxy's compatibility with the design requirements, including its precision application and gap-filling capabilities, effectively addresses the challenges presented by the flat-to-round surface bonding. This comprehensive approach, combining strategic hinge dimensioning with the selection of epoxy adhesive, is designed to enhance the mechanical integrity and functional performance of the flight mechanism, ensuring a secure and lasting attachment.

## VERIFICATION PLANS

Many of the verification plans presented below involve using a video kinematic analysis method to analyze data collected. We conducted experiments with a falling shuttlecock and compared the system responses to those of an existing dynamic mathematical model of a shuttlecock’s descent [8] to verify that this video kinematic analysis method can be used when we drop our flight system. We then further compared our shuttlecock experimental results with the computational dynamic MATLAB model to ensure that we were able to use it to further inform our design. A detailed explanation of the experimental procedure and results for the shuttlecock experiments can be found in the Experimental Shuttlecock Verification Test Procedure section of the Appendix. The shuttlecock verification tests were successful, so we then conducted verification tests on our final prototype using an almost identical procedure.

Our first engineering requirement was Aerodynamic Stability. The specification associated with this requirement is that our system should attain a steady-state vertical orientation given any initial angular condition (0-180 degrees) in free-fall conditions. We tested this by video-taping ourselves dropping our flight system and analyzing the descent using the Tracker video software package. If the system attained a vertical orientation, then the specification was met.

Our second engineering requirement was Controllable System Response. This requirement had two specifications. The first specification was that the system had to settle about vertical equilibrium given a 15 degree perturbation with a settling time of less than 0.6 seconds with error margins of 5%. The second specification was that the maximum overshoot of the system when it attempts to restabilize itself should be less than 15% of the initial angular perturbation. Both of these specifications will be tested for concurrently using the same empirical test. We will use the video analysis data from the first engineering requirement and compare that data with the computer simulations provided by our derived dynamic model. If the experimental data closely resembles the computational data, then we know that our experimental data was collected accurately. We can then see if our system does indeed have a settling time less than 0.6 seconds and a maximum overshoot less than 15% of the initial angular perturbation.

The previous two requirements were verified experimentally using the same experimental procedure as the shuttlecock verification testing outlined in the Appendix. The empirical data obtained from our test setup was analyzed and compared to our theoretical model predictions. As mentioned earlier, our fin system was made up of a central cylindrical body onto which we attached eight fins using hinges, springs, and screws. We conducted testing on two different body types: a hollow body and a filled body. The purpose of this set of trials was to understand how lowering the vertical position of the center of mass affected the stability of the system. We also tested the filled-body system with and without springs. The system responses were very similar because the resistance of the hinges on the system was enough to hold them in place given the drag forces that were not substantial enough to move the hinges at those speeds. In the future, we would like to source higher quality hinges and conduct our tests with those instead.

Our setup includes: hollow fin system with no spring attached; hollow fin system with hybrid fins setup; filled fin system with no spring attached; filled tag with hybrid fins setup. The main difference of the filled and hollow fin system is mainly the center of gravity, since according to the model lower center of gravity creates a better settling time. All trials were dropped with an angular perturbation of 45 degrees. In addition, the hybrid fins according to the model provides a better settling time with less overshoot. The four plots are analyzed as follows:

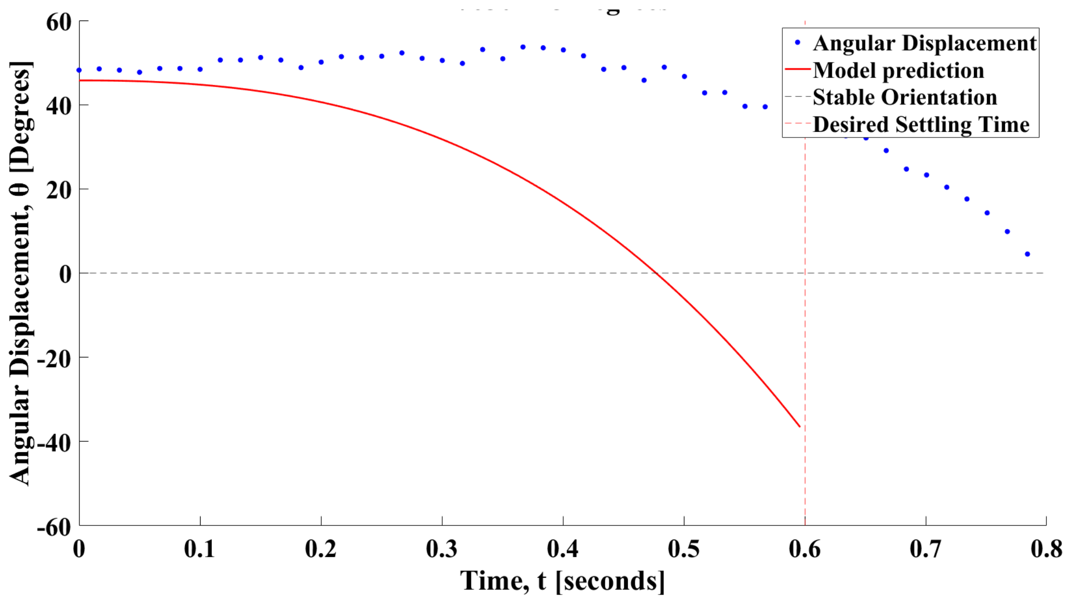



**Figure 35:** Captures the response of the filled fin system without a spring. The experimental data exhibits a notable deviation from the model's predictions, suggesting a need for further investigation. The mismatch may be attributed to extra force applied by the human hand to cause the fin to rotate a little bit > 45 degrees.

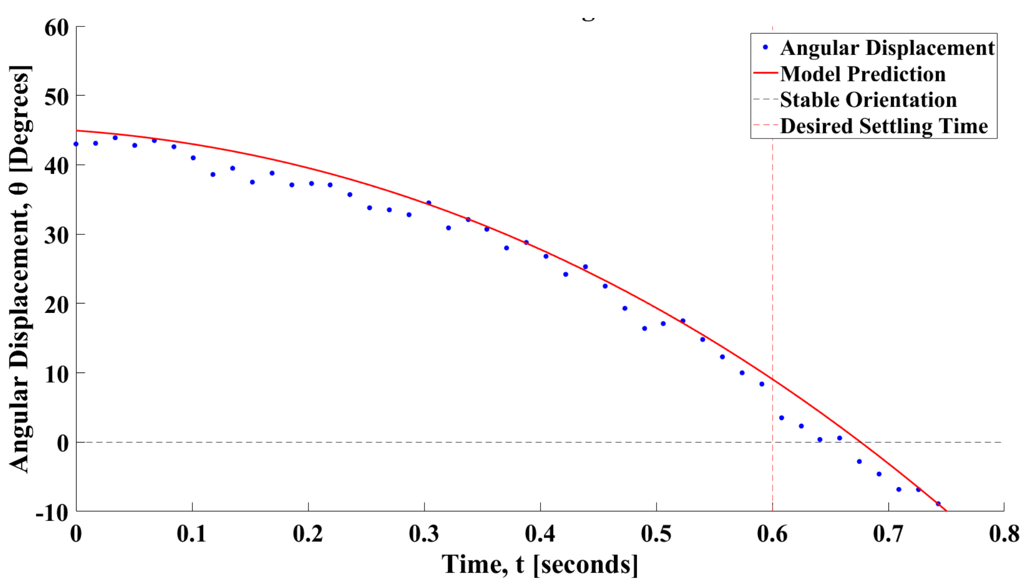



**Figure 36:** Reflects the performance of the hollow fin system without a spring. The anticipated benefits of hybrid fins in terms of settling time and overshoot will be evaluated against the experimental outcomes.

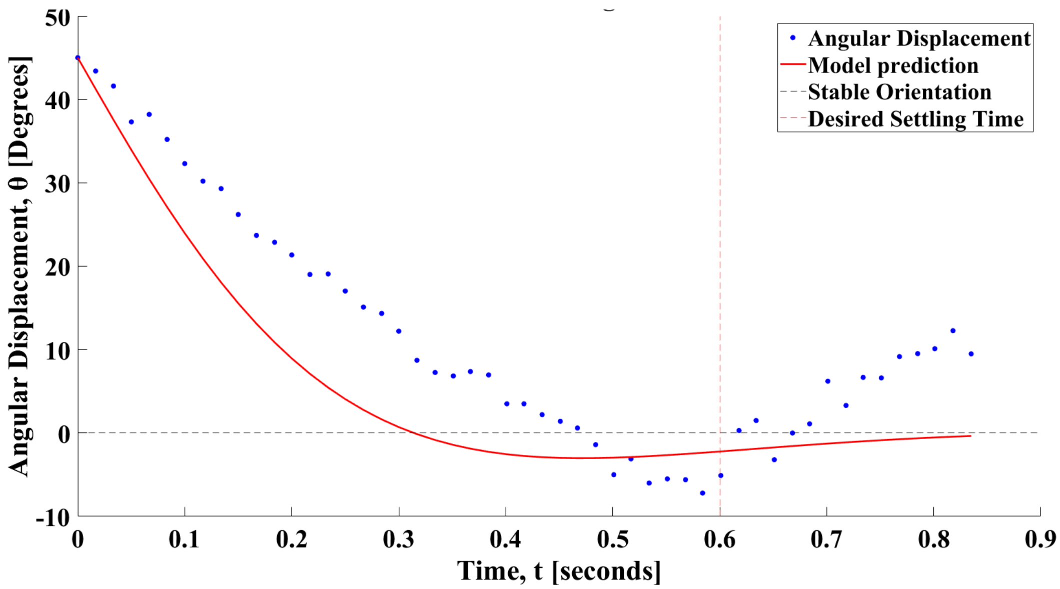



**Figure 37:** Illustrates the behavior of the filled fin system hybrid fin. Which has overall a good match in prediction and empirical data. The overshoot and oscillation is bigger than expected.

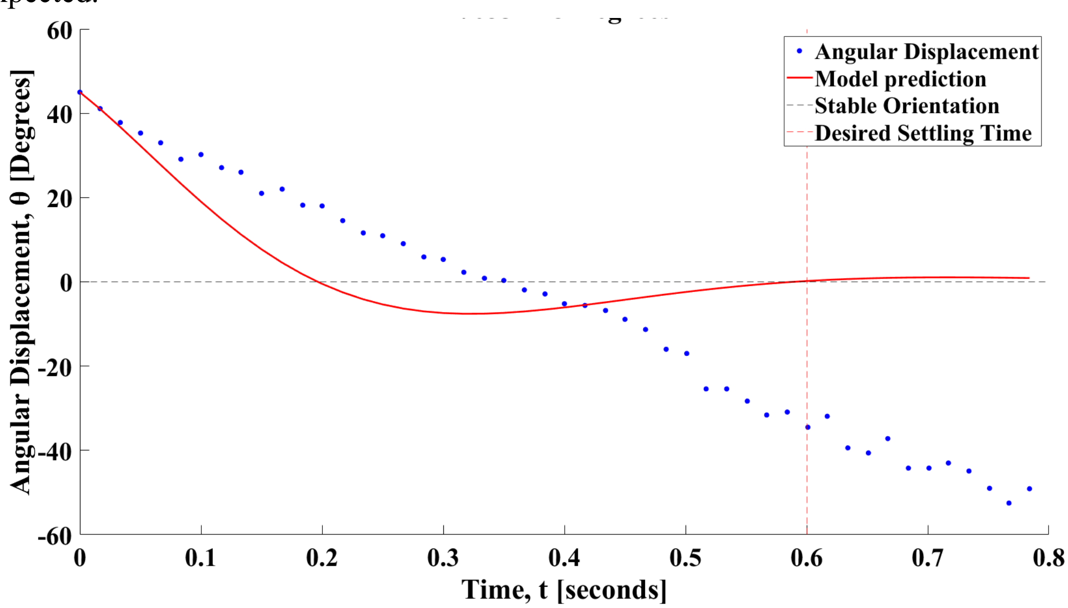



**Figure 38:** Illustrates the behavior of the hollow fin system hybrid fin. This configuration is expected to display a shorter settling time due to a lower center of gravity, but not observed. The possible reason could be an extra force from the human hand during the movement of the drop and cause the tag to even rotate further to negative 50 degrees.

Our third engineering requirement was proper suction. The associated specification was that the impact force of the suction cup onto the whale should be between 2.8 N and 5 N. This ensures that the suction cup will fall with enough force to maintain a proper tag attachment without hurting or otherwise disturbing the whale. We assessed this by developing a way to test the quality of the attachment between the suction cups and the whale mimicry surface. We dropped a hollow DTAG (it was hollow to prevent unnecessary damage to the electronics that would have usually been housed inside the DTAG) from a height of 225 cm. To simulate the final weight of the flight system, we attached lead weights and fasteners of various sizes to the DTAG. This meant that we could see whether our flight system, when dropped from a height lower than the height the researchers use, could guarantee a final velocity and impact force great enough to achieve the proper pressure differential necessary for proper depression of the suction cups. Proper suction was defined as having three of the four suction cups mostly attached to the acrylic such that when we lifted the acrylic and rotated it from a flat orientation to a vertical orientation, none of the suction cups undid themselves. We observed the quality of the suction by visually inspecting the underside of the suction cup through the clear acrylic after the system was dropped. Figure 39 below shows an example of a successful drop test with proper suction achieved.

**Figure 39:** A picture of the suction quality for a successful drop. All four suction cups were fully depressed for this particular trial.

We could not gather images of unsuccessful attempts because the attempts were so unsuccessful that by the time we flipped the acrylic plate to observe the attachment, the suction cups all fell off and there was no suction. However, there were some trials that were close to being unsuccessful. Figure 40 below shows an example of a system that was slightly tilted when it landed.

**Figure 40:** A picture of a trial that was considered successful but not ideal. The suction cups are folded over themselves which indicate that the DTAG might have been tilted upon impact with the acrylic.

This was one of the primary difficulties of conducting this test. It took many tries to obtain a successful trial because dropping the weighted DTAG on its own created an unstable system. There was such a strong oscillatory response, so the DTAG did not usually land in a stable vertical orientation. However, this difficulty helped us realize the importance of developing a successful flight stabilizer because the system was highly unreliable.

Our fourth engineering requirement was Easy Drone Fit. The associated specification was that the flight system (DTAG and fin attachment) had to fit within the drone with a clearance of 1 cm between the grips of the drone and the edges of the flight system. We tested this by constructing a cardboard box to the required dimensions for the flight system to fit within. We then placed the design inside the box. The box closed properly, so the design dimensions were verified as successful.

Our fifth engineering requirement was Impact Resistance. The specification associated with this requirement was that the material we choose for the fin attachment must withstand the maximum loading conditions with a safety factor of 2.5. The simplest way to assess this is by doing a literature review to see if the material we choose has published/established material properties. We would look at the yield stress, fatigue strength, toughness, and hardness to evaluate whether the fin attachment can withstand the maximum loading conditions. If the material we choose does not have reliable published material properties, then we will conduct material stress tests by applying forces up to the maximum anticipated load, multiplied by the safety factor of 2.5. These forces can be applied using calibrated weights or a hydraulic press in a controlled environment. If the material sustains the applied load without structural failure while adhering to the specified safety factor, then we can conclude that the selected material meets our specifications. We can conclude that PETG does satisfy this requirement.

Our sixth requirement was Reusability.  It was split into three specifications.  The first specification was that the material had to resist degradation for more than 5 years.  We can evaluate the material we choose by examining prior testing procedures and results, the material manufacturer's longevity claims, and the established material properties published in the literature. If all of the sources claim that the material will not suffer damage in a salt-water (highly corrosive) environment, then we can confirm that the material we chose meets our specification.  The second specification was that the force of buoyancy acting on the fins has to be at least 2.5 times greater than the weight of the fins.  We can test this by temporarily integrating a fishing line into the existing design and obtaining a water tank.  We can use fishing weights to apply force incrementally to the fishing line.  This will help us determine the maximum weight the design can support without failure.  The third specification was that the design had to last more than 30 cycles of loading and unloading before failure.  This will be judged by reviewing existing empirical data and fatigue analysis simulations for the selected material to find its predicted performance under cyclic loading.  We would conduct our analysis using the expected impact conditions over the material's lifetime.  If the material's historical data and simulated fatigue analysis indicate that it can withstand more than 30 cycles of impact at 5 N of load, then this specification has been met.  PETG does meet these specifications as well.  The system is buoyant.

Our seventh and final requirement was that the financial burden of the product had to be low. The specification associated with this requirement was that the cost of manufacturing the prototype had to be less than $5.  This would be evaluated by using the Granta EduPack software to conduct a cost analysis of our design.  If the estimate they provide is less than $5, then we know that this specification was met.  The cost was quite a bit more than $5 just for the materials, which means that our design did not meet this specification.

## VALIDATION PLANS

We also created plans for how we would ensure that our design addresses the problem we set out to solve.  The problem, unchanged from the original statement provided to us by our sponsor, was that the aerodynamic instability of the remote drone tag-deployment system currently in use by Ocean Alliance to tag whales caused unreliable tag attachments.  Our goal was to find a way to stabilize the tag's descent to the whale.  Table 4 below summarizes our validation plan.

**Table 4:** Validation Plan

| Question/Assumption | Validation Method | Testing Plan | Testing Metric |
|---|---|---|---|
| Field Performance - How well does the design work in the real world? | Field Testing in Natural Environment | Test the fin attachment in wind tunnel and computational simulations to evaluate stability at varying angles and speeds. | Deviation from vertical orientation during free-fall and settling time. |
| Ethical Interaction with Wildlife - Is our design disturbing the whale's natural behaviors? | Ethical Impact Assessment | Use material simulating whale skin to assess impact force and suction cup adherence at different angles and speeds. | Range of impact forces required to achieve proper suction without harm. |
| Long-term Data Collection Efficiency - How well does our design assist the researchers in collecting accurate data compared to previous products? | Longitudinal Study | Have potential users interact with the prototype in a controlled environment to assess ease of deployment. | Stakeholders feedback |

Our first measure of how well our design addresses the original problem is the field performance of the design. Our chosen validation method for this is a field test. We plan on simulating the natural environment that the researchers using our design are likely to see. This could mean dropping our flight system at varying angles and speeds in a controlled wind tunnel or outdoors to see whether the flight system behaved as we expected it to according to our computer simulations. If the flight system's deviation from a vertical orientation and its settling time meet those specified by our engineering requirements and specifications, then we know that the field performance has been validated.

Our second consideration is the ethicality of our level of interaction with the whales. We will assess this by dropping our flight system onto a surface that mimics the texture of a whale's skin to determine the impact force and the quality of suction cup attachment at various angles and speeds. If the experimental impact force lies within the range of forces required to achieve proper suction without harming the whale that we specified in our engineering requirements and specifications (state numbers here), then we know that our design is following the ethical standards in our treatment of the whales.

Our third consideration is the efficiency and ease of use of our proposed flight system. The simplest way to assess whether what we designed is easy to use is by having the intended operator use it and provide us feedback about the usability of the flight system (ease of use, handling, transporting, retrieving, learning curves, packaging, etc.). If our stakeholder feedback is positive, then we know that our proposed design resulted in more reliable tag attachments.

These validation plans will help us understand how well our design addresses the needs and concerns of our sponsors and stakeholders.

**PROBLEM DOMAIN ANALYSIS**

The problem must be thoroughly evaluated using our engineering principles. For this project, our team is going to use our prior core engineering classes to guide our decision-making process. The different engineering fundamentals that we will look at can be seen in Figure 41 below.

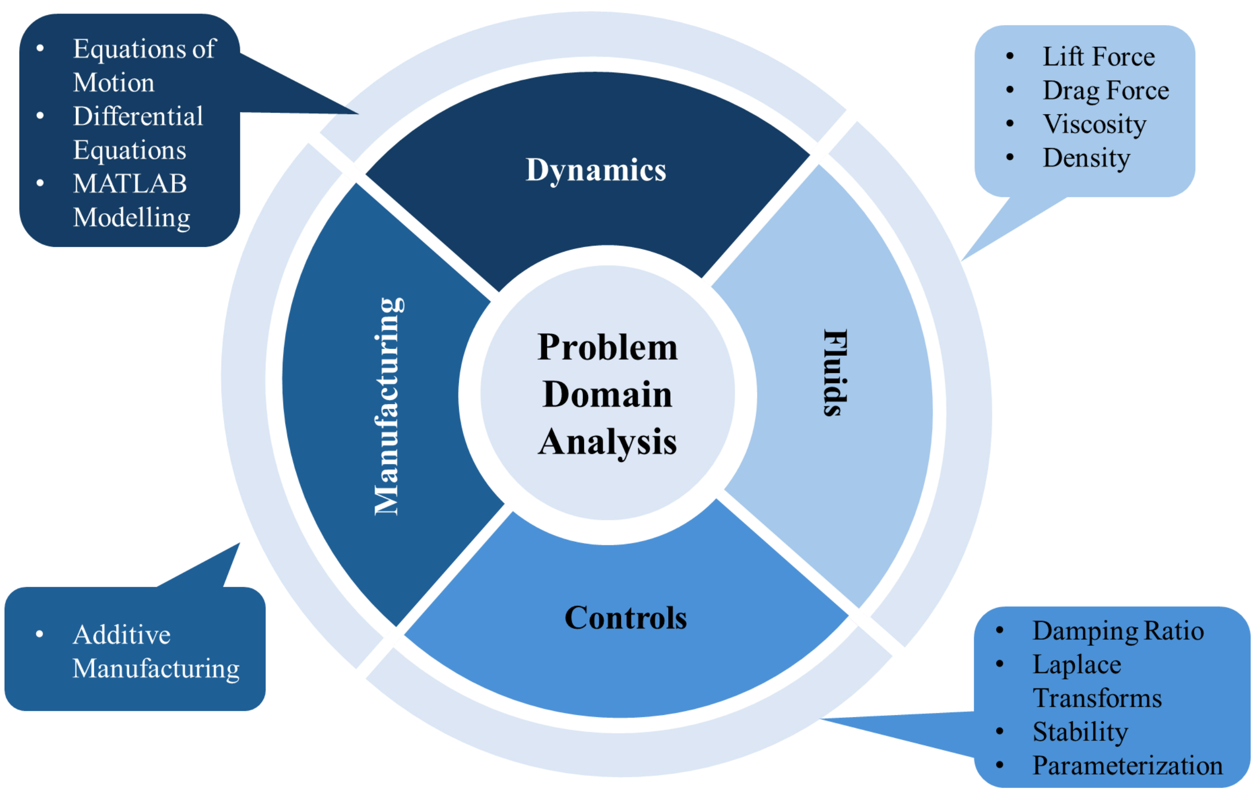



**Figure 41:** Engineering fundamentals with their associated knowledge blocks that will be used.

**DISCUSSION**

This section will discuss what questions we would explore further given more time and resources to collect data and better define the problem, what methods we would use to explore those questions, the strengths and weaknesses of our design, what can be improved and how (future modifications), what we would have done differently, the challenges we encountered in the design process, how we addressed those challenges, and the associated risks for the end-user of our design.

**Problem Definition**

In our project, we aimed to enhance the reliability of biologging tag attachment on whales using a drone-based deployment system. Given more resources and time, further exploration into several key areas could significantly refine our understanding and increase design efficacy. Firstly, the dynamic interactions between the drone, environment, and tag upon deployment could benefit from high-fidelity computational fluid dynamics (CFD) simulations to predict and optimize aerodynamic performance under various environmental conditions. Additionally, engaging in a broader data collection with real-time tracking will be beneficial. For example, repeating the same experiment will allow for the verification of results and improve the reliability of the data by identifying any anomalies or inconsistencies across trials.

**Design Critique**

Our design's innovative approach in utilizing a unique hinge mechanism for deploying biologging tags represents a significant strength, enabling precise control and orientation during descent. The system's ability to stabilize the tag effectively under calm conditions was proven, demonstrating the core functionality and potential efficacy of our deployment strategy. However, the CAD model did not initially include springs, leading to a hard decision regarding the selection of the specific type of spring (linear vs torsional). The chosen hinges were also of substandard quality, with misalignment issues in the shafts causing operational difficulties. These challenges were mitigated somewhat by the application of lubricants to improve motion, but this was a temporary solution that underscores the need for more rigorous component testing and selection during the design phase.

For future enhancements, it would be beneficial for subsequent teams to undertake extensive testing with a variety of springs and hinges to determine the most effective combinations, ensuring smoother operation and greater reliability. Additionally, our aerodynamic testing was limited by the size of the wind tunnel, which did not permit rotation of our fin system to fully assess its aerodynamic properties. Conducting tests in a larger wind tunnel that allows the system to be rotated relative to the airstream would enable more accurate measurements of lift and drag coefficients, providing valuable data to optimize the design. The current system's susceptibility to disturbances from sudden wind gusts also presents a critical area for improvement. Addressing this by enhancing the system's robustness against environmental perturbations would significantly improve its reliability and performance in field conditions.

**Risks**

Throughout the design process, one major challenge was ensuring the ethical considerations associated with wildlife interaction, specifically minimizing the disturbance to whales during tag deployment. To mitigate these risks, our team employed a combination of theoretical, computational, and empirical methods to refine the tag's impact dynamics and attachment reliability without increasing whale disturbance.

For end-users, the primary risks involve operational complexity and potential harm to wildlife if the tag fails to attach correctly or detaches prematurely. Future designs would benefit from simplifying user interaction with the deployment system, possibly through automated flight and deployment controls, and ensuring all materials and components are biocompatible and minimize environmental impact.

## REFLECTION

Now that we have reached the conclusion of our project, it is important for us to reflect on the social and economic impacts, inclusivity and equity issues, and the ethics of our project. Public health was not relevant to our final product as most of the public will never come in contact with our product. Our product is meant to be used by a select group of people - those few who are qualified to tag whales in the US. The safety and welfare of both the whales and the researchers using our product were significant factors to consider in the design and implementation of our product. Our design will not benefit a global marketplace. The social and environmental impacts of our fin attachment include the negative (environmental) effects of sourcing the stainless steel and PETG. The process used to source stainless steel and PETG pollutes the air which will hurt the communities living near those production facilities. This air pollution will also lead to global warming which will negatively affect all of the stakeholders identified in our stakeholder map (Figure 9).

**Inclusion and Equity**

The members of our team had a mix of cultural backgrounds which carried inherent privilege structures within it. However, these cultural, privilege, and identity differences did not play a role in the approaches our team took throughout the project. As stated earlier in the report, our sponsor naturally had more power over us because he could choose the direction of our project. We also have power over the whales because we are designing something for them without their input.  We made sure to consider the health and wellbeing of the whale when designing our product.

**Ethics**

The biggest ethical dilemma we faced was in the decision to have sharp wire endings from the spring exposed.  If the spring attachment procedure is not redesigned, then we run the risk of potentially hurting the whale.  As of now, we plan on working in industry,where intellectual property ethics are far more important than they were for us in this project.

**ANTICIPATED CHALLENGES**

One of the difficulties we anticipate having when assessing the engineering specifications of our project is that many of the specification parameters must be experimentally derived, so it will take longer to assess whether we met the specification. Also, we will have to come up with some way to physically (and eventually mathematically) model any natural disturbances that could affect the flight stability of the tag-drop.

The biggest problem we anticipate having is trusting our dynamic model that approximates the motion of the tag as it falls. There is a chance that our model fits the experimental data very well, but deviations between the two data sets are more likely. We will address this challenge by adopting an iterative strategy to adjust certain parameters of our model after each of our experimental tests.

The most obvious piece of special equipment that we will need is some surface that mimics the texture of the surface of a whale. This would be used to assess the angular displacement from vertical at which the suction cups will no longer adhere to the whale surface and to test the efficacy of various fin designs.

The information that is currently missing is the best way to model the trajectory of falling objects. The knowledge we have about video kinematic analysis is elementary at best. We will have to learn more about the most up-to-date video modeling analysis by consulting other members of the University of Michigan faculty.

One significant challenge identified in the project involves the simplification of the model through strong assumptions to make the initial modeling more manageable. Specifically, the model assumes that pressure drag significantly outweighs both skin drag and lift forces in the equation of motion. This assumption is predicated on the understanding that for objects with bluff shapes or those encountering high angles of attack, pressure drag predominantly governs the aerodynamic forces, rendering it far more impactful than skin friction. The solution to this challenge lies in the gradual incorporation of additional, more complex factors into the model, for example, incorporating skin drag and lift forces into the analysis.

Another specific challenge relates to the limitations imposed by the current manufacturing method, notably 3D printing, in producing the tagging device. The inherent constraints of 3D printing, such as potential inconsistencies in material density and the risk of structural weaknesses, could compromise the device's quality and performance. To tackle this issue, conducting Finite Element Analysis (FEA) within the context of 3D printing constraints is proposed as a solution. FEA would enable the identification and mitigation of potential weak points in the design, informed by the limitations and characteristics of 3D printing materials and processes.

## RECOMMENDATIONS

The ongoing development of our flight mechanism design has revealed several areas where refinements are necessary to enhance performance, reliability, and manufacturability. The recommendations outlined below are intended to guide the next phase of the project, ensuring a more aerodynamically stable and robust deployment system.

### Design Improvements

1. Modification of Fin Geometry:

    - Redesign the fins to include dual plane surfaces, which will optimize the projected area effect necessary for stable descent. By changing the geometry to accommodate a more complex surface, we can achieve a larger effective area without increasing the body diameter, thus maintaining a streamlined profile that reduces unnecessary drag. Alternatively, but not advised, utilizing a multi-axis hinge mechanism would allow for the use of more degrees of freedom for the fin to work with in order to configure the projected area even more effectively, though, this might prove to be too complicated and outside the scope of this project.

2. Internal Hinge Attachement:

    - Reengineer the hinge attachment points by integrating hinges directly within the body of the flight mechanism rather than being screwed and epoxied to the surface of the mechanism’s body. This approach will significantly reduce the external surface area (protrusions) required for hinge attachment, leading to a narrower body profile. It will minimize the impact of wind gusts on the system's stability by reducing horizontally projected area and thus reduce the overall drag forces horizontally.

3. Thicker Fins for Enhanced Durability:

    - Increase the thickness of the fins to withstand the stresses induced by the vertical loading conditions during impact. A thicker design will improve the structural integrity and durability of the fins, reducing the risk of the fins fracturing under impact loading conditions.

4. Improved Fin and Hinge Interface:

    - Design a slot within the fins to seamlessly accommodate the hinge flap, thereby enhancing the adhesive contact area. This modification will significantly reduce stress concentrations during impacts encountered in flight mechanism deployments from height, thus bolstering the fin-to-hinge connection for improved structural integrity. Should this adaptation prove to strengthen the structural integrity, it could pave the way for a more user-friendly attachment mechanism without the use of epoxy adhesive. This would enable easy interchangeability of fins, allowing users to adapt the fin types based on varying drop heights or specific flight dynamics required for different mission profiles. Such versatility could greatly enhance operational flexibility and system performance.

5. High-Quality, Low-Friction Hinges:

    - Source hinges of superior quality with lower friction coefficients to ensure that the aerodynamic profile of the fins is primarily dictated by the spring constants and not the hinges themselves. The current hinges introduce excessive friction, which impacts the dynamic response of the fins to aerodynamic forces.

6. Optimization of Spring Mechanics:

    - Utilize shorter springs to improve the responsiveness and control of the fin movements. Current springs chosen out of a limited selection are too long and are not stretched throughout the entire rotational path of the hinges which only allows us to make use of a portion of the rotational freedom of the hinges.

**Assembly and Manufacturing Improvements**

1. Standardization of Screw Lengths:

- Transition to using screws that match the thickness of the fins without modification. This change will streamline the assembly process, eliminate the need for manual screw shortening, and reduce assembly time significantly.

These recommendations aim to address the current limitations observed during the testing and manufacturing phases and are expected to significantly enhance the performance and reliability of the flight mechanism. Continued iterative design and testing are crucial to refining these improvements and achieving the project objectives.

**ACKNOWLEDGEMENTS**

Throughout this project, we had the privilege of collaborating with several esteemed colleagues who created a dynamic and supportive environment that was instrumental to our progress. We extend our special gratitude to Professor K Alex Shorter, whose extensive expertise in biomechanics and marine research has been invaluable. As our mentor and project sponsor, Professor Shorter provided continuous, insightful feedback and guidance, enriching our development process. His role as a dynamics professor at the University of Michigan enabled us to grasp the complex dynamics of our flight mechanism from the outset. Professor Shorter’s proactive and engaging mentorship allowed us to swiftly pivot our design strategies and optimize our use of resources and time whenever we encountered challenges. His contribution has been a cornerstone of our project's success. We also extend our sincere thanks to Ethan McMillan, a dedicated researcher in Professor Shorter’s lab, for his substantial contributions to our project. Ethan provided invaluable assistance with CAD work and generously supplied the materials we needed for our assembly.

We are deeply grateful to the Undergraduate Machine Shop Staff and Anupama Kar for their indispensable assistance during the testing, manufacturing, and assembly stages of our project. Their expertise and willingness to help were vital in bringing our designs to life and ensuring each component was crafted with precision. Their support was crucial in navigating the complexities of our project's practical implementation.

We would also like to extend our heartfelt thanks to the Teaching Assistants, Adi Scharf and Anika Satish, who provided crucial support and guidance throughout our project. Their expertise and dedication significantly contributed to our learning and project success.

## CONCLUSION

The aim of our project was to implement a biologging tag attachment that can stabilize the descent of the tag as it falls onto the whale. This will allow researchers to learn more about the behavior and biomechanics of whales so that they can advise the public about ways to reduce the disturbances caused to the whales. We did this by developing a mathematical model approximating the motion of the tag as it falls to inform the generation of a physical fin prototype. A rudimentary equation of motion approximating the behavior of the DTAG was derived. A primary alpha design of a fin attachment was designed after evaluating many different design ideas. A thorough verification and validation plan has been created to ensure that all aspects of our design can be tested. The verification tests were completed - the design met all of the critical requirements. The interdisciplinary efforts of our team highlight the importance of stakeholder considerations, environmental sustainability, and ethical design practices.

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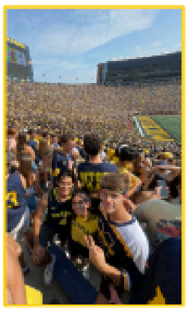
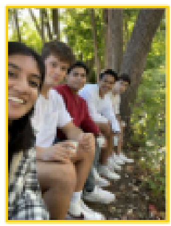
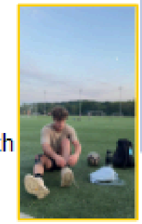
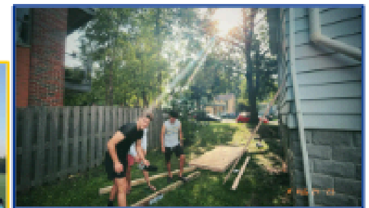
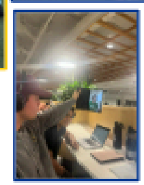
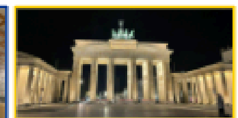
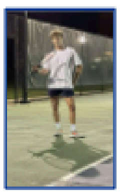
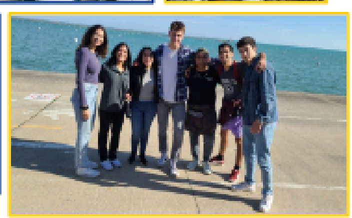
## TEAM MEMBER BIOGRAPHIES

### About Me: Carlos Otterbach

**Born:**
Mexico City, Mexico
**Previously Lived In:**
- Munich, Germany
- Frankfurt, Germany
- Wildeshausen, Germany
- San Antonio, Texas

**Hobbies:**
~ Sports (soccer, tennis, gym, and skiing)
~ Travel (Cidermill fanatic)
~ Cooking (award winning tacos)
~ Literally just sitting and talking with friends



**Project Experience:**
~ University of Michigan Solar Car Team
- Motor Design Team - Founder
- Mechanical Design/FEA

~TESLA
- Passive Electronics and Magnetics System Optimization

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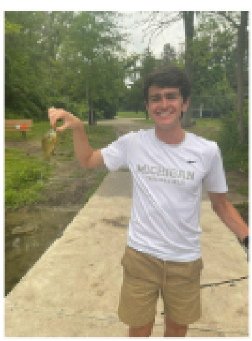
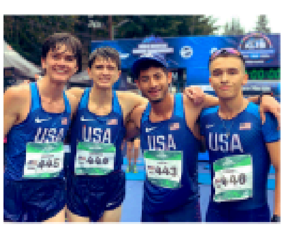


# Anthony Hancock

- From Dearborn, MI
- Runner on the Cross Country and Track Team
- I have a twin brother studying business
- Hobbies: Outdoors, Fishing, Ice Skating, Running, Board Games, Card Game, Sports
- Dual Citizenship between Mexico and USA
- Fun Fact: Competed in Argentina for the USA Junior Mountain Running Championships



## Chong Qian

**Education:**

Sichuan University, Chengdu, China — Sept. 2020 - June 2022

Mechanical Engineering BSE

University of Michigan, Ann Arbor, MI — Sept. 2022 - Present

Mechanical Engineering BSE

**Hobbies:**

Sleeping, Bamboo flute, Animation

**Engineering Experience:**

Working with Jesse Capecelatro and his postdoc Jack on a Finite element solver

# Meghna Krishnan

## Education
- Major: MechE
- Minor: MatScie
- Conc: Manf
- Grad: FA 2024

## Personal
- Twin, elder brother
- Sterling Heights, MI
- September 3rd, 2002

## Hobbies
- Music
- Movies
- Ushering

## Work
- Autocam
  - Precision Manufacturing
- General Motors
  - Stamping
  - Dimensional Performance

## Skills
- Continuous Improvement
- CMM Operations
- Writing/editing

## Five Fast Facts
- Favorite Food: Chocolate
- Favorite Movie: Holiday Inn
- Favorite Sport: Cricket
- Favorite Holiday: Valentine's Day
- Favorite Car: 1911 Brass-Plated Oldsmobile Limited

## Dream Jobs
- Fighter Pilot
- Test Pilot
- Submarine Naval Officer
- Housewife
- Manufacturing Engineer

## Would Love To
- Have 6 dogs, 2 cows, 2 pigs, 4 ducks, 6 bunnies, 3 goats, 2 sheep

**APPENDIX**

**Intellectual Property (IP)**

Intellectual property is not playing a role in our project so far. We were not required to sign any IP agreements, so anything that we design or derive can be claimed as our intellectual property. We do not expect to encounter any issues with IP in future stages of our project. Perhaps if our team gets more involved in other aspects of whale biologging besides the flight mechanism, we will need to communicate with the research team to address IP concerns. As of now, our project team will own both the model and prototype designs after the completion of this project in the event we want to pursue some sort of patenting.

**Concept Generation**

1. Umbrella fin concept:
    a. This concept would encapsulate the use of an umbrella-like fin with the purpose of increasing the drag of the system at the point furthest from the center of gravity.

2. Helical Fin designer:
    a. aiming to induce angular momentum, and increase vertical stability of the system.
    b. Concept similar to a gyroscopic stabilizer.


3. Gyroscopic Fin:
    a. A fin with a built-in gyroscope for stability during descent.
4. Tilted Fin:
    a. A fin with an adjustable angle to control the descent direction.
5. Two-winged fin design:
    a. A design aimed at attaining a parallel planar orientation to any aerodynamic disturbances.

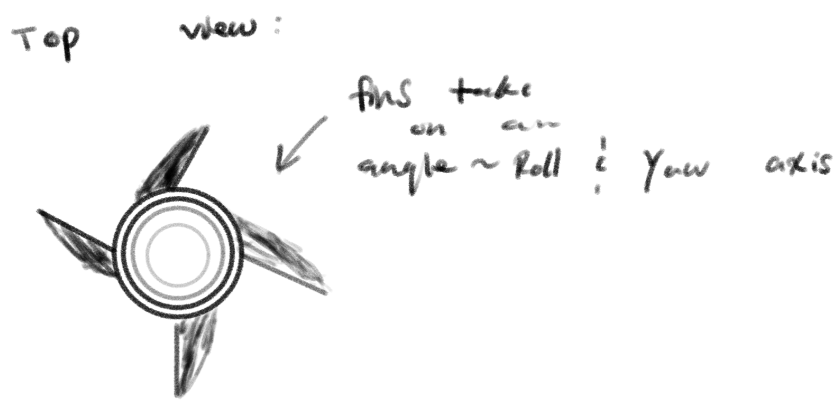
6. Webbed wing design:
    a. aims to increase the drag of the system progressively (vertically increasing tend).

7. Carbon Fiber Fins:

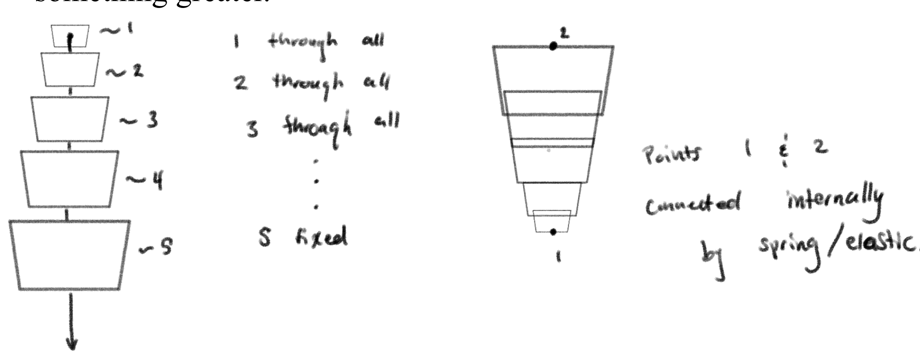
a. Employing carbon fiber fins for reduced weight and enhanced aerodynamics.

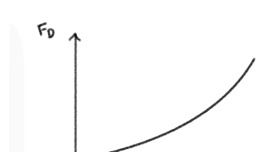
8. Pneumatic Fin:
   a. A fin that uses compressed air for controlled descent and landing.
9. Dual Stage Fin:
   a. A fin with two stages of deployment for precision control and reduced impact.

10. Slanted-Fin Design:
    a. Alternate approach to inducing rotation.



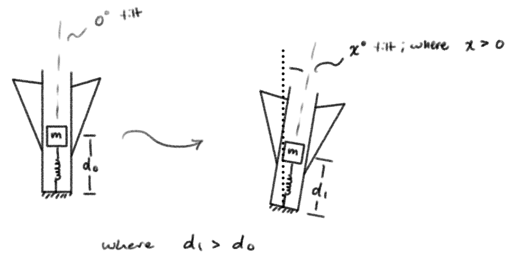

11. Variable Surface Area Fin:
    a. A fin with adjustable surface area to control the rate of descent.
12. Spring-loaded Fins:
    a. Initial positions at slants, springs resisting the fins' movement to align with the body of the shaft, the larger magnitude of an aerodynamic force will cause fins to surpass the force of spring and become vertical.
    b. This would allow the system to spin but would limit the angular velocity of the system to allow for proper suction.
13. Christmas Tree Spring:
    a. This mechanism would serve the function of increasing the surface area of the "fin" or tailing system, given the increase of air speed past the system. This would thus increase the ROC of the drag from a squared relationship to velocity to something greater.



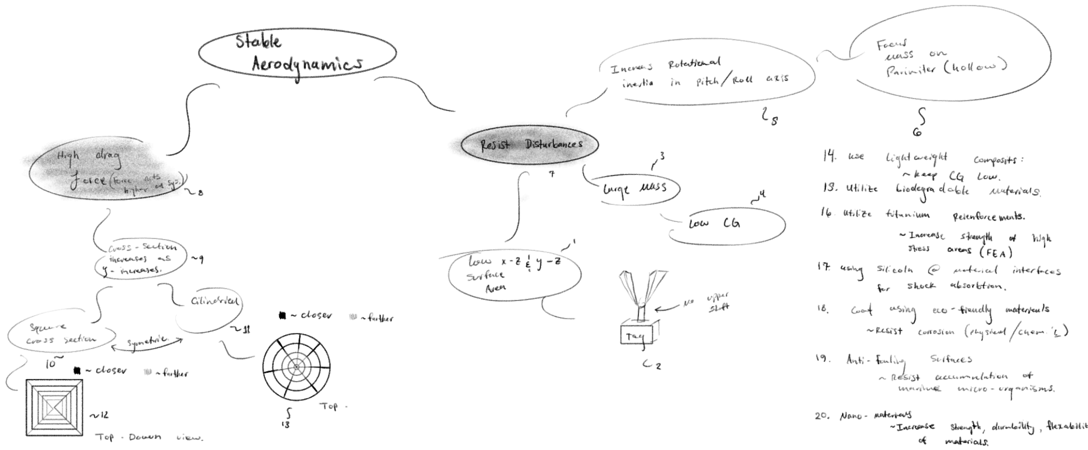



14. Changing the Drag during flight:
    a. Increase in the force of drag given an increase of time. Any relationship that is non-linear and has a d^2F/dt^2 > 0 would be more advantageous than that of d^2F/dt^2 = 0.

15. Vane Fin:
    a. A fin with adjustable vanes to control the tag's orientation during descent.




16. Flutter Fin:
    a. A fin with flexible segments to create a fluttering effect for controlled descent.
17. Quadcopter Fin:
    a. A mini quadcopter-like design with propellers for precise control during descent.
18. Telescopic Fin: A fin that extends upon release to provide a controlled drop and retracts upon landing.




19.

**Preliminary Stability Study With Shuttlecocks**

The purpose of the shuttlecock experiment was to understand how a stable system will look in the real world. Shuttlecocks were dropped (cap side down) from a height of 10 feet many times with three different initial conditions. The first initial condition was an unperturbed condition. The shuttlecock was released from rest and videotaped until it fell to the ground. This process was repeated three times. The second initial condition was an angled condition. The shuttlecock was released such that the cap was 35 degrees away from being pointed vertically down. This drop was recorded six times - three times perturbed 35 degrees to the right and three times perturbed 35 degrees to the left. The third initial condition was a rotational condition. The shuttlecock was flicked in the air so that it made at least one full rotation on its way down to the ground. This was also repeated six times - three times flicked to the right and three times flicked to the left. The videos recorded during the experiment were slowed down for easy video kinematic analysis. We were specifically interested in how the shuttlecock oscillated back and forth during its descent. Our most significant observation was that the shuttlecock had decaying oscillations no matter which perturbation was induced which implied that the system was a self-stabilizing system.

**Concept Selection - From Many Down to Six**

In order to get to a pugh chart at the end of the selection process we first had to filter through all the generated concepts. This process involved multiple stages that would exclude designs from consideration.

The first stage was to eliminate designs based on our requirements and specifications. Although all requirements and specifications were considered, some contributed more heavily to the elimination of designs than others. The low cost requirements eliminated many concepts, specifically the jet- powered descent. The controllable system response also took out some designs due to lacking the possibility to control the oscillations during the flight.

The next stage we looked to for guidance to exclude designs was the stakeholder feedback. Professor K Alex Shorter looked through some of our designs, and noticed a theme of rotation associated with many of these. After he noticed this, he informed us of the importance of keeping a non-rotational design because we would like to drop the DTAG onto the whale oriented from its tail to head. This feedback eliminated many of the designs based on a rotating body to stay stable.

The final stage was to judge the feasibility of the designs. We gauged the design based on how realistically we believed that we could generate a fully fleshed out prototype and model by the end of the semester.

**Experimental Shuttlecock Verification Test Procedure**

We dropped the shuttlecocks from a height of 225 cm and videotaped it falling using a phone camera-tripod setup at 220 frames per second. We did this at four different initial drop angles (0, 15, 30, and 45 degrees) and three different masses (6g, 10g, 14g dropped at 45 degrees). The masses were added by gluing 5/16 locknuts onto the inside of the cap of the shuttlecock.

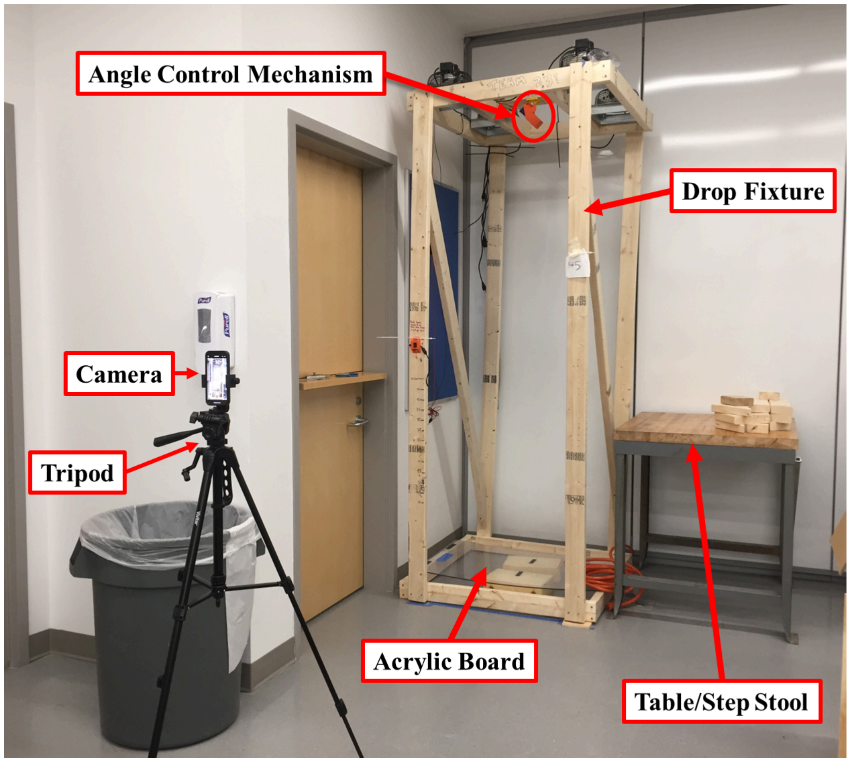



**Figure 35:** Experimental setup for the shuttlecock experiments. One person stood on the table/step stool to drop the shuttlecocks from a height of 225 cm. The angle control mechanism was used to keep the initial drop angle constant within trials and properly set between trials. One person operated the camera-tripod setup to tape the descent of the shuttlecocks.

We also glued a lightweight rod to the inside of the base of the shuttlecock for all trials (Figure 36). The rod was slightly made of a clear polymer. Black tape was added to the top of it to make the top of the rod visible to the camera and easily identifiable by the Tracker software.

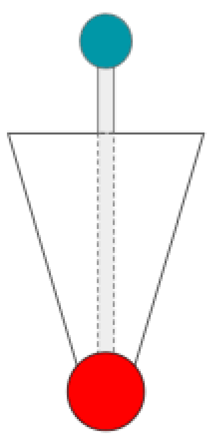
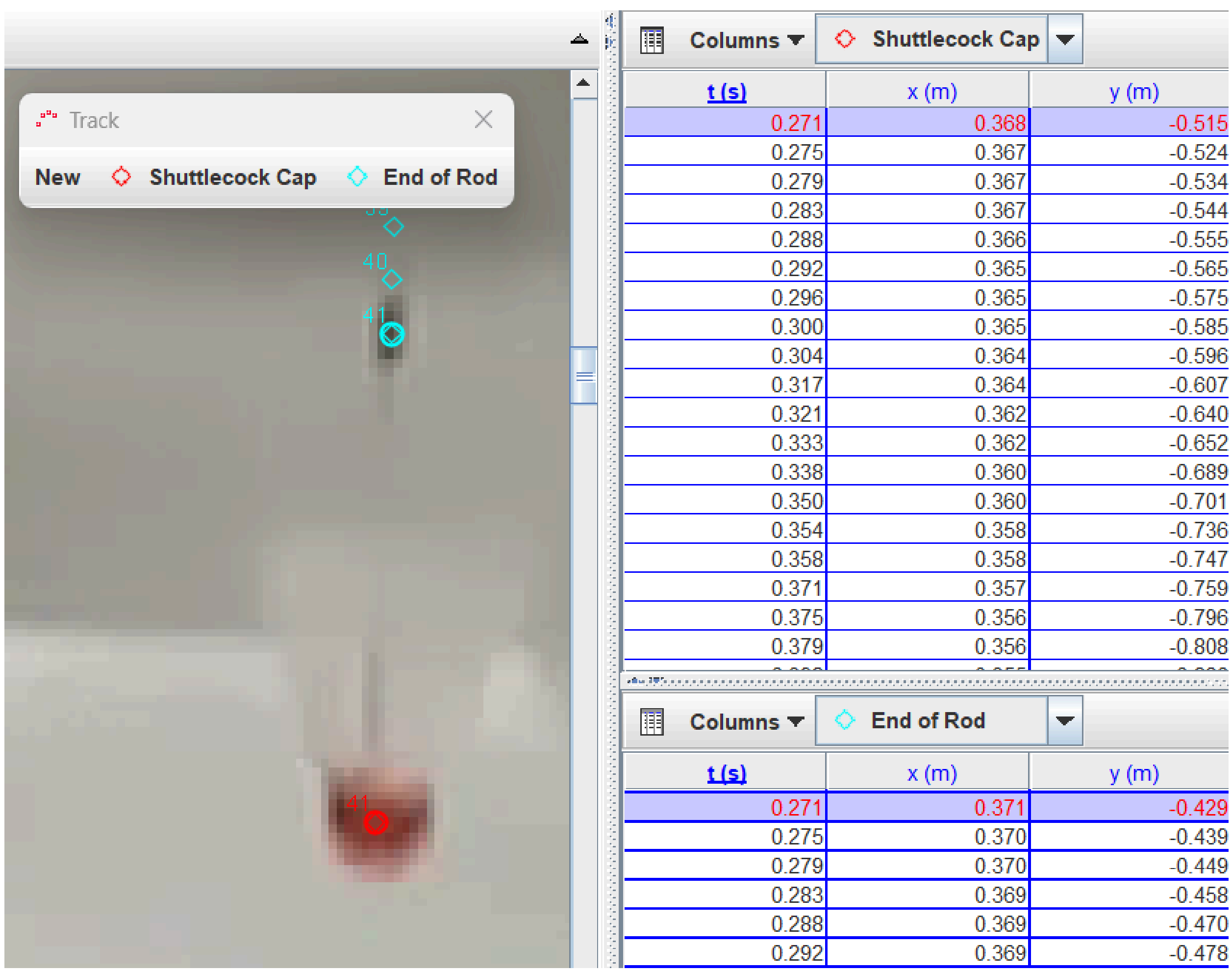


**Figure 36:** The rod glued onto the inside of the base of the shuttlecock. The marker at the top helped prevent the possible y_axis rotation of the shuttlecock from influencing the data analysis process that Tracker uses to produce position data.

The purpose of the rod was to remove the possibility of the rotation of the shuttlecock about the y-axis conflating the topmost position of the shuttlecock. The addition of the rod gave the Tracker software a topmost reference point that would not be influenced by the y-direction rotation of the shuttlecock.

<u>Verification on Shuttlecock Model</u>

The videos taken during these experiments were uploaded to the Tracker software for further analysis. The Tracker software conducted a frame-by-frame analysis of every video. It collected position and velocity data for the bottom most point of the shuttlecock and for the top point of the rod placed in the shuttlecock (Figure 37 below).




Shuttlecock Cap

| t (s) | x (m) | y (m) |
|---|---|---|
| 0.271 | 0.368 | -0.515 |
| 0.275 | 0.367 | -0.524 |
| 0.279 | 0.367 | -0.534 |
| 0.283 | 0.367 | -0.544 |
| 0.288 | 0.366 | -0.555 |
| 0.292 | 0.365 | -0.565 |
| 0.296 | 0.365 | -0.575 |
| 0.300 | 0.365 | -0.585 |
| 0.304 | 0.364 | -0.596 |
| 0.317 | 0.364 | -0.607 |
| 0.321 | 0.362 | -0.640 |
| 0.333 | 0.362 | -0.652 |
| 0.338 | 0.360 | -0.689 |
| 0.350 | 0.360 | -0.701 |
| 0.354 | 0.358 | -0.736 |
| 0.358 | 0.358 | -0.747 |
| 0.371 | 0.357 | -0.759 |
| 0.375 | 0.356 | -0.796 |
| 0.379 | 0.356 | -0.808 |

End of Rod

| t (s) | x (m) | y (m) |
|---|---|---|
| 0.271 | 0.371 | -0.429 |
| 0.275 | 0.370 | -0.439 |
| 0.279 | 0.370 | -0.449 |
| 0.283 | 0.369 | -0.458 |
| 0.288 | 0.369 | -0.470 |
| 0.292 | 0.369 | -0.478 |

**Figure 37**: Tracker software user interface. The software analyzes each frame of each video to determine the position of various objects in each frame. This data was used to calculate the velocity and acceleration of the shuttlecock at various points during its descent.

The position data was used to find the angle of the shuttlecock away from the vertical axis throughout the shuttlecock's descent. This experimental angular displacement was plotted against time and compared with the dynamic mathematical model we know to be true in the shuttlecock research paper (Figure 38 below) [8].

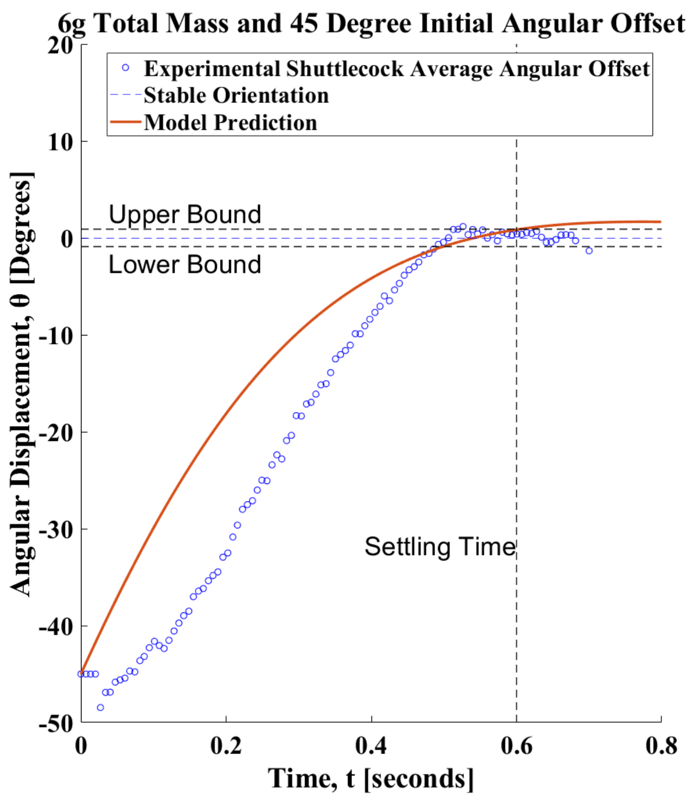
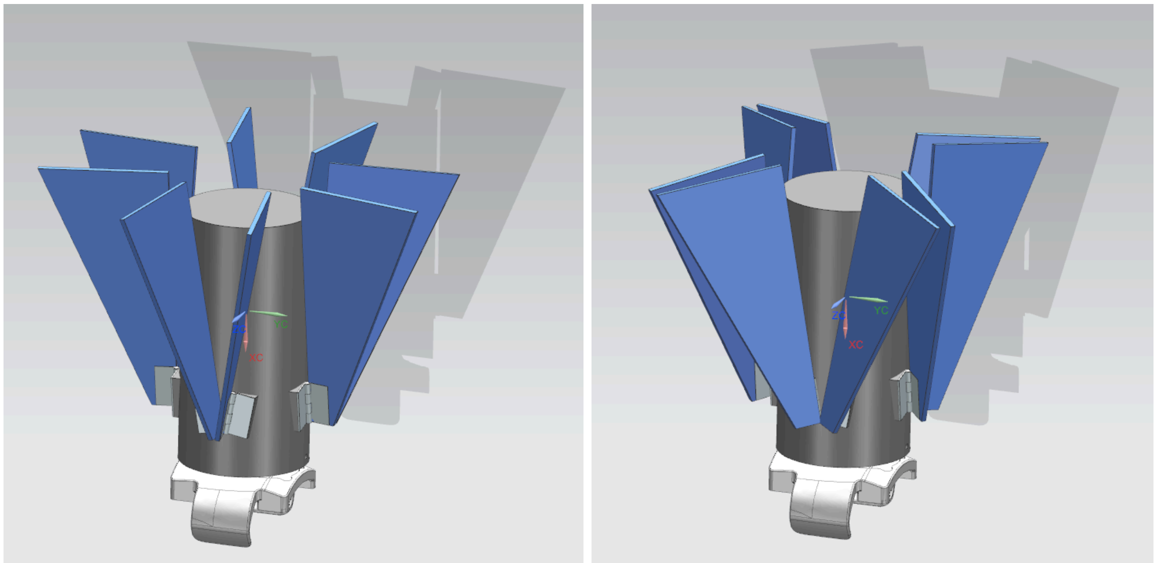



**Figure 38:** Comparison of system response from experimental data with system response derived from mathematical model.

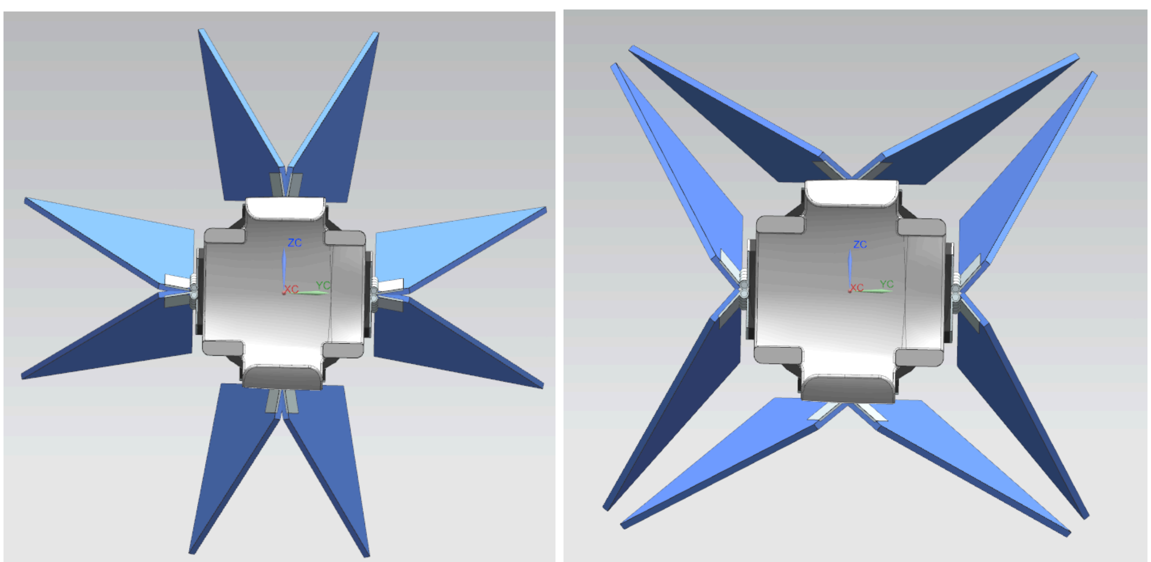
The experimental data and the theoretical data both start at 45 degrees when time is at zero as expected. They both have some overshoot (they cross the vertical orientation point) between 0.3 and 0.4 seconds by around 6-8 degrees and return to a stable vertical orientation at 0.8 seconds. The similarities in the results (the similarities were seen across all angles and masses to varying degrees, but they were there nonetheless) convinced us that using the drop fixture and the Tracker software as an analysis and verification tool was a good and accurate way to analyze our data.

## CAD Images

### Full Assembly

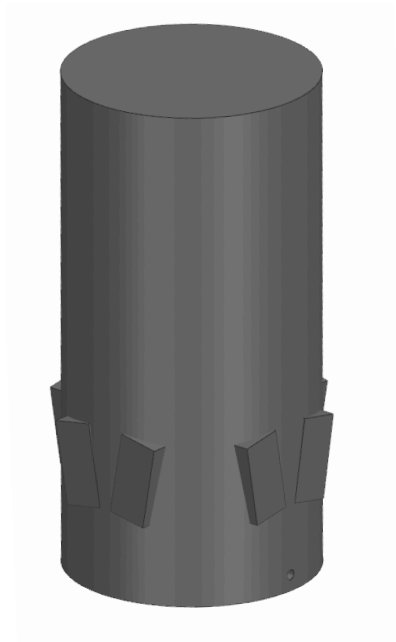


Isometric View: Closed (Left) and Open (Right)

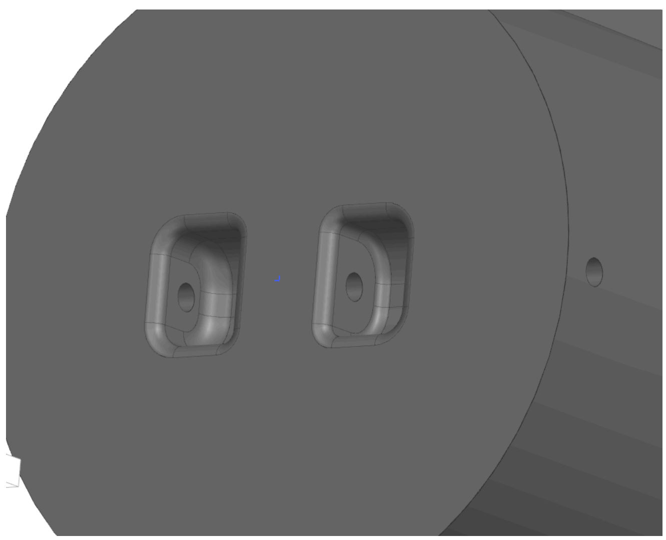


Bottom View: Closed (Left) and Open (Right)

**Flight Mechanism Body (Cylindrical Shaft)**

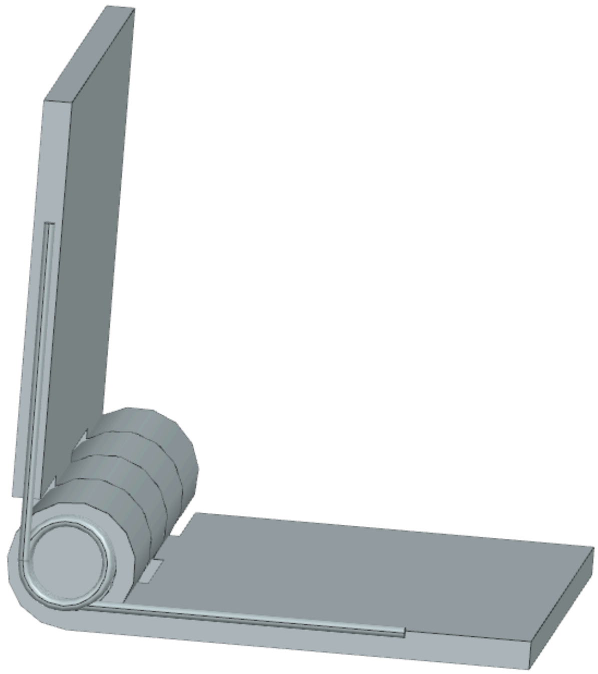


Isometric



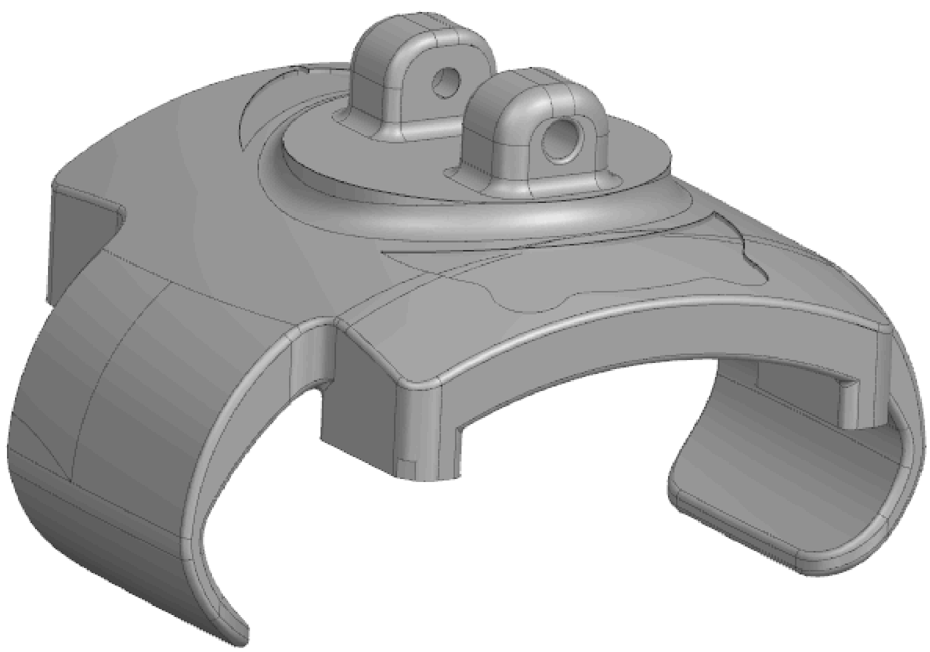
Bottom View (of attachment interface for DTAG Holder)

**Hinge-Torsion Spring Assembly**



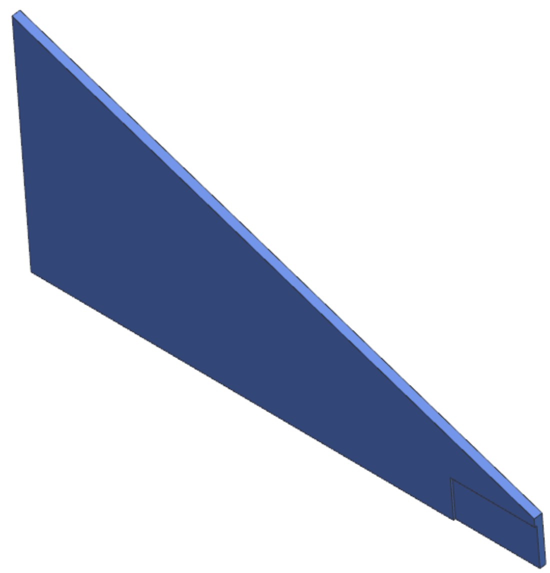
Isometric

**Robot Hand (DTAG Holder)**



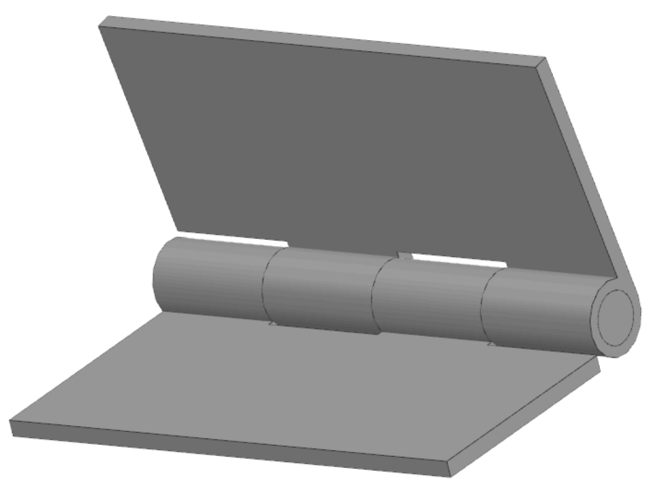
Isometric

**Fin**



Isometric

**Hinge**

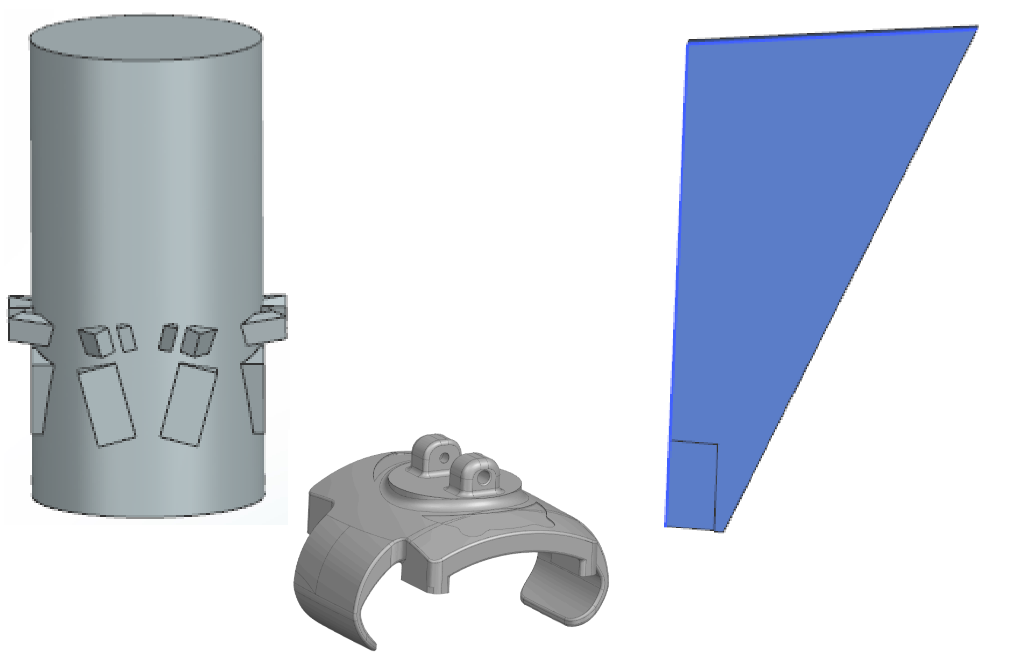


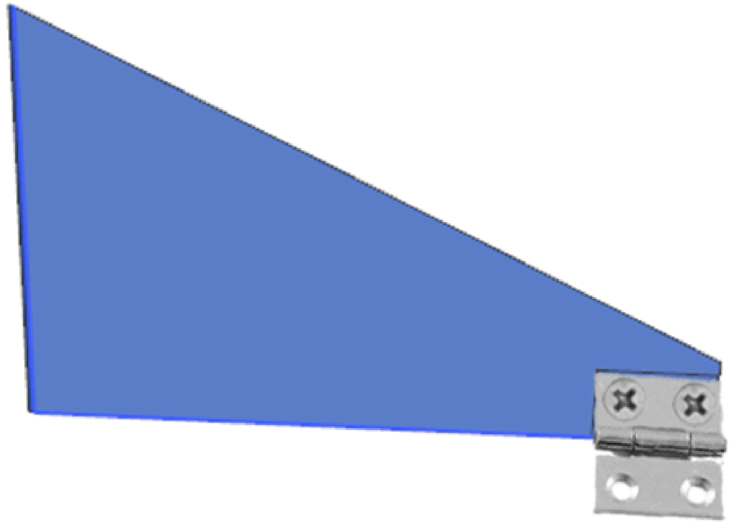
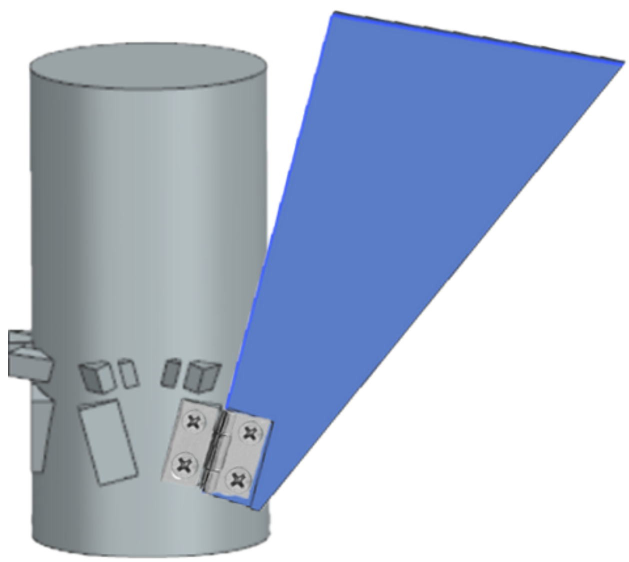
Isometric

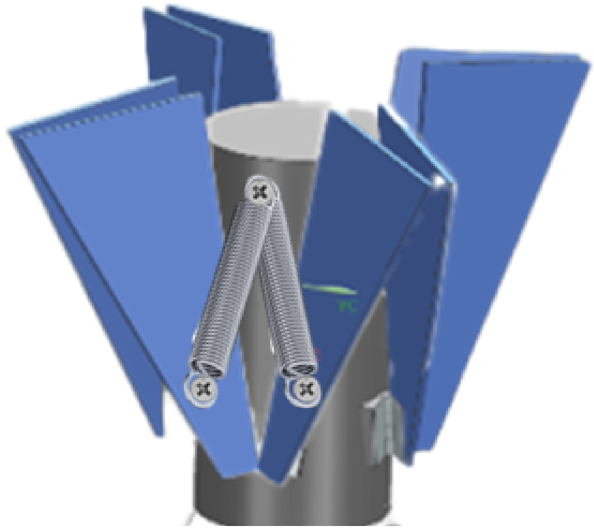
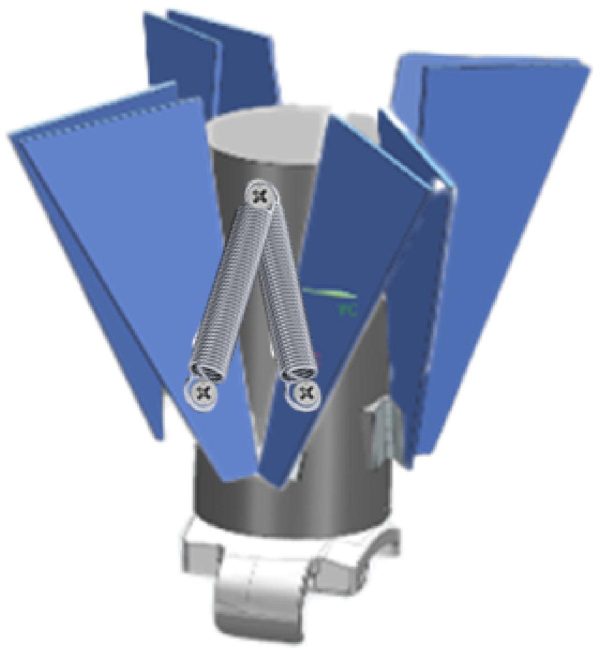
**Bill of Materials**

| Part No. | Item | Quantity | Source | Unit Cost | Contact | Notes |
|---|---|---|---|---|---|---|
| 1 | Flight Mechanism Body | 1 | 3D Printed - PETG Filament | PETG Total cost $22.99 | | |
| 2 | Fin | 8 | 3D Printed - PETG Filament | PETG Total cost $22.99 | | |
| 3 | Robot Hand (DTAG Holder) | 1 | 3D Printed - PETG Filament | PETG Total cost $22.99 | | |
| 4 | 1” Folding Hinge | 8 | Amazon | $0.45 | *amazon.com* | *Stainless Steel* |
| 5 | 1/16” x 3” aluminum rod | 1 | K&S Engineering | $0.67 | *Megahobby.com* | |
| 6 | 1” Extension Spring #100 | 8 | Jack’s Hardware Store | $2.59 | | |

**Manufacturing/ Fabrication Plan (**small parts are enlarged to show clarity)

| | | |
|---|---|---|
| 1. | 3D Print Flight Mechanism Body, 8 fins, and Robot Hand using 3mm PETG filament |  |

| | | |
|---|---|---|
| 2. | Using 29 Drill bit, attach part 4 hinges onto part 2 fins. 1 hinge for each fin in the rectangular indent in the fins. |  |
| 3. | Using the screws that come with Part 4, drill (with 29 drill bit) and attach the fin-hinges from step 2 to part 1 flight mechanism body. |  |

| | | |
|---|---|---|
| 4. | Attach 8 part 6 springs to the fins and the flight mechanism body using screws, and |  |
| 5. | Attach part 3 DTAG Holder into the bottom of the flight mechanism body and lock it into place by feeding the part 5 rod through the flight mechanism body and DTAG Holder supports |  |