Shark Attach

ME 450 W21
April 26, 2021

Team #27
Sarah Armbruster, Connor Boerman, Toby Cormack,
Cameron LaVallee, Leah Paborsky

Section 6
Professor Shorter

Sponsors
Woods Hole Oceanographic Institution (WHOI)
Seth Cones, Aran Mooney

Executive Summary

Smooth dogfish are a near-threatened species of shark that primarily reside in coastal waters off of Central America and the Northeastern United States. As a result of dogfish being a bycaught species, having a late sexual maturity, and having small litter sizes, dogfish populations are now in danger. The species' distinction as "near-threatened," along with the fact that little is known about their fine-scale behavior, has encouraged scientists at the Woods Hole Oceanographic Institution (WHOI) to study dogfish in their natural habitat. To assist in this study, we were asked to design a biologging tag that can securely attach while being minimally-invasive on dogfish.

To guide our design process and conceptualization of potential solutions, we developed a set of specifications that any solution must meet. This list includes securing the sensing electronics to dogfish while minimizing invasiveness, which is measured using metrics such as tail beat frequency and qualitative analysis of behavior by the researchers at WHOI. We further specified that the solution must be sufficiently durable to stay on the animal for 72 hours under typical environmental conditions and activity levels, characterized by depth and movement of the animals. The tag must also detach autonomously and float to the ocean surface for retrieval. Finally, the device must not contribute to ocean pollution and have an affordable cost.

Through research, rapid prototyping, and physical testing, we developed a method to attach the necessary biologging electronics to dogfish. The final solution features a flexible harness around the circumference of the body with hydrodynamically efficient packages housing the electronics on either side of the body in line with the first dorsal fin. The harness closes around the shark by threading a strip of Nichrome wire through a clasp. The wire will break and release the tag when a strong electrical current is triggered at a time programmed by the researchers.

We used a number of analytical and experimental approaches to verify our solution. Early in the design process, we used computational fluid dynamics (CFD) to study the hydrodynamic qualities of a virtual model dogfish. The package designs were hydrodynamically improved using CFD and the final package design adds roughly 5-7% drag to the baseline shark. A physical model of the dogfish was created and taken to the Michigan Hydrodynamics Laboratory to verify our analysis procedure and test a prototype tag in their tow tank. Through tow tank testing we verified the results from the CFD while also observing qualitative information about the attachment method. Finally, we mailed a prototype tag to WHOI for testing on live dogfish that they have on campus. Testing on the live dogfish highlighted potential areas for improvement in the design and confirmed that the attachment method was effective, but too invasive for long-term deployment.

The current final prototype is not ready for deployment on dogfish in the wild. However, our design and analysis procedures have been verified and can be used in future work related to tagging small marine animals.

Table of Contents

Executive Summary 2
Table of Contents 3
Introduction 5
- Project Background 5
- Project Significance 6

Problem Statement 7
Requirements and Specifications 8
- Attaches to Dogfish 9
- Is Non-Invasive 9
- Is Durable 9
- Allows for Sensor Package Retrieval 9
- Does Not Disrupt Sensor Measurements 9
- Limits Ocean Pollution 10
- Has Affordable Cost 10
- Additional Aspects to Consider 10

Concept Exploration 12
- Concept Generation 12
  - Attachment Strategies 13
  - Detachment Strategies 13
  - Electronics Package Designs 14
- Concept Screening 14

Prototyping 15
- Prototype Development 15
  - Attachment Methods 15
    - TheraBand® Shark Belt 15
    - Clasp 16
  - Package Shapes 17
- Prototype Evaluation 18
  - Prototype Evaluation Tools 18
  - Attachment Methods 19
    - Physical Prototyping of Shark Belt 19
    - Virtual and Physical Prototyping of Clasp 19
  - Electronics Package Shapes 19
    - Computational Fluid Dynamics (CFD) 19
      - Background and Purpose 19
      - Methods 20
      - Limitations 24
    - CFD Initial Drag Analysis 24
      - Base Shark Model 25
      - Package Location Test Results 26
    - Hydrodynamic Shape Optimization of Package 27

Risk Assessment 29
Testing and Evaluation of Final Prototype 30
- Final Prototype Design 30
- Tow Tank 30
  - Background and Purpose 30
  - Methods 31
  - Limitations 33
  - Results 34
- Comparison of CFD to Tow Tank Results 35
  - Surface Roughness Correlation 36
- Testing on Live Dogfish 37
- TheraBand® Strap 40
- Electronics Packages 40
- Clasp 41
- Buoyancy Analysis 43

Verification 45
- Attaches to Dogfish and Is Non-Invasive 46
- Is Durable 46
- Allows for Sensor Package Retrieval 46

Does Not Disrupt Sensor Measurements 46
Limits Ocean Pollution 46
Has Affordable Cost 47
Discussion and Recommendations 48
Strengths of Proposed Design 48
Limitations of Proposed Design 48
Comparison of CFD to Tow Tank Conclusions 48
Recommended Design Changes 49
Band Material 49
Electronics Packages 49
Band Closure 49
Ethics Statement 50
Conclusion 51
Key Stakeholders and Project Team 52
Sponsor Background 52
Team Background 52
Acknowledgements 53
Information Sources 54
Appendix 1: Concept Development 57
Hoop Around Body 57
Body Clip 58
Concept Development Tool: Model Fins 59
Appendix 2: Fin Clip 61
Version 1 61
Version 2 64
Appendix 3: Shark Belt Initial Iterations 69

Introduction

Project Background

It is very difficult to study the fine-scale behavior of numerous marine species because many components of their life cycles occur solely or partially outside of the observable realm of researchers. A common method for monitoring marine animals is biologging, which is the process of attaching instruments or sensors to animals to take measurements of their behavior or surroundings [1]. Biologging tags have sensors that can collect a variety of information including GPS location, conditions of the surrounding environment (e.g. oxygen and light levels, and depth), and conditions of the animal's body (e.g. body temperature, traveling speeds) [2]. There are many different types of biologging tags that currently exist; tags may be attached internally or externally, may transmit data via satellite or only when the tag is returned to the lab, and may release from the animal after a predetermined amount of time or naturally [2]. These biologging tags can give researchers a glimpse into otherwise unobservable states. Many biotags in existence are designed for large or mid-sized marine species, while smaller species are largely under-studied [3]. Our sponsors at the Woods Hole Oceanographic Institution (WHOI) have experience using biologging tags to monitor and study squid and other marine species. Currently, they perform research on squid using an internally designed sensor package, shown in Figure 1, called the iTag.

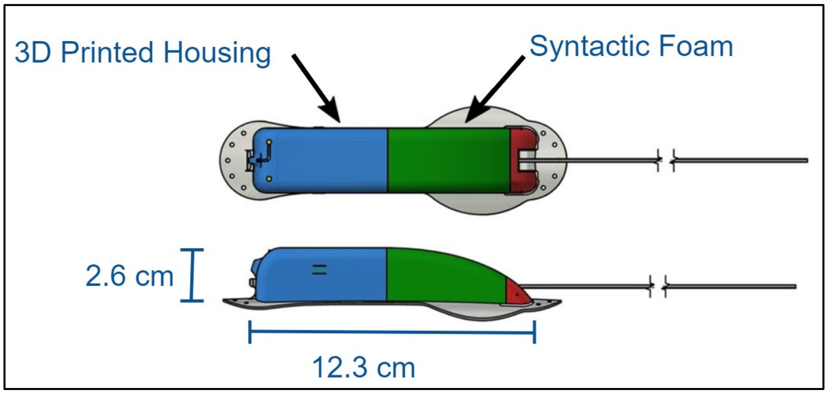


Figure 1: The existing sensor package and 3-D printed housing that is used for biologging squid. [4][5]

Researchers at WHOI would like to expand their research to other small-sized marine species and are interested in an externally attached archival tag that can be used on a small species of shark, the smooth dogfish. The outcomes from this project will likely be applied in future studies with other species, but we are focusing on smooth dogfish for this project. This project aims to design, prototype, and test a non-invasive attachment method for an archival biologging tag for smooth dogfish. Smooth dogfish, also known as dusky smooth-hounds, shown in Figure 2, are a small, slender species of shark that average between 100 and 150 cm in length when fully grown [6]. The dorsal fins of the smooth dogfish are ‘fleshy’, making them extremely flexible. Additionally, the posterior end of the fin detaches from the surface of the body [4]. The smooth dogfish species is largely understudied and threatened by human fishing activity so learning more about them can contribute to public knowledge and conservation efforts.

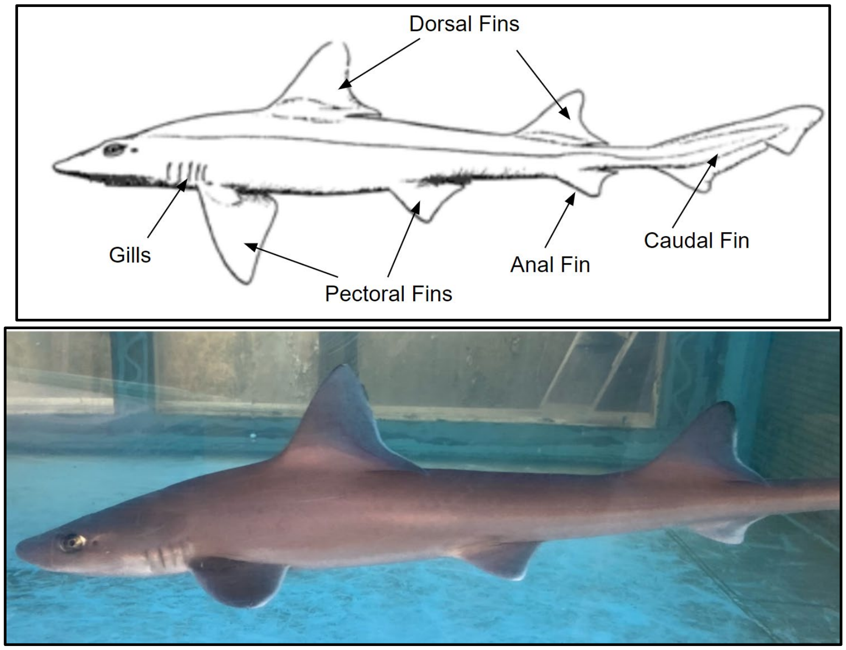


Figure 2: (Top) Diagram of smooth dogfish with relevant features labeled [6]. (Bottom) A smooth dogfish in a tank at WHOI [4].

Project Significance

Biologging tags successfully deployed in the wild can offer insight into animal behavior and habits that are otherwise obscured by the challenges associated with observing animals in their natural state. Dogfish are interesting to study because they are classified as a “near-threatened” species [7] and have multiple vulnerabilities that make it challenging to recoup from population loss. Smooth dogfish have small litters and take longer to reach sexual maturity which make them extremely susceptible to overfishing [8]. Dogfish are also a known bycaught species, meaning they are accidentally caught by fishermen and may be injured when they are returned to the ocean.

Improving the available data about dogfish behavior will also improve the understanding about the survival rate of bycaught species, the typical regions that dogfish inhabit and their behaviors in those regions. This information can be used to improve marine management tactics and potentially set fishing limits or policies to protect the species. More public information about dogfish can also benefit research about their impact on the rest of their ecosystem [9]. Furthermore, the final tagging method may be applicable for other species of small marine animals.

Problem Statement

Our project goal was to design, fabricate, and test a non-invasive attachment method to secure a biologging tag to dogfish, and design electronics packages to suit the new attachment method. This will allow Sensory Ecology and Bioacoustics Lab at WHOI to better understand dogfish behavior, while minimizing the effects on the tagged animal. Our sponsors have already designed a sensor package for small aquatic animals from a prior study about squid behavior. However, dogfish biology creates additional challenges which require a different tag design.

Dogfish are slender and flexible, leaving few areas available for feasible non-invasive tagging. The top image in Figure 3 shows the iTag relative to a 1:1 scale dogfish model, and highlights the need for a shorter, more compact tag design that would not interfere with any fins or flexibility of the dogfish. The bottom image in Figure 3 shows the electronics, oriented as they are in the iTag, which were used in the dogfish tag design. The sensor board includes a pressure sensor, light sensor, and inertial measurement units. These components remained largely fixed throughout the design process.

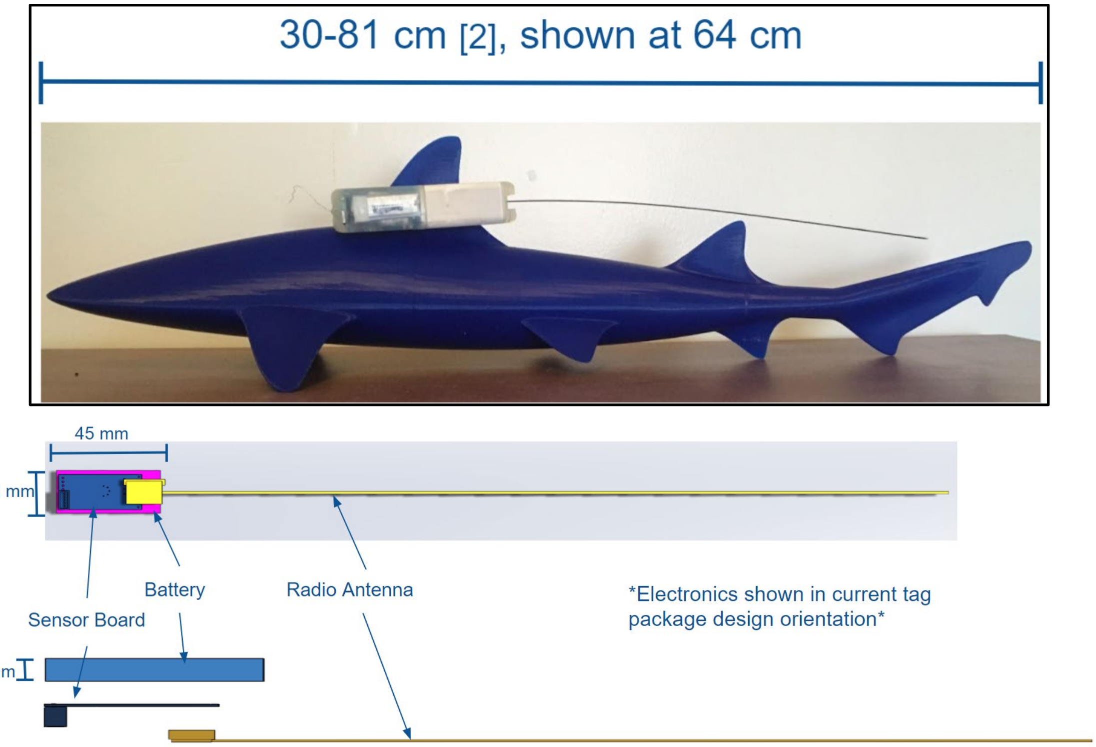


Figure 3: (Top) Current squid biologging tag relative to a to-scale model of a smooth dogfish. (Bottom) Current squid biologging tag electronics top and side exploded view.

This project made progress toward enabling our sponsors to collect meaningful, accurate data about fine-scale dogfish behavior in their natural habitat, including feeding, escape response, and energy expenditure. This project also included methods and procedures developed for successful computational fluid dynamics and water tunnel analysis which can be applied to similar studies in other contexts.

Requirements and Specifications

A robust set of requirements and corresponding specifications were created to ensure a high-quality solution. The source for the majority of requirements was a stakeholder interview with project sponsors Dr. Aran Mooney and Mr. Seth Cones [4]. The criteria that they described were used as the basis for our requirements. Table 1 lists stakeholder requirements and their corresponding engineering specifications in descending priority. Requirements explicitly stated by the sponsors were deemed top priority. These stakeholder requirements are: "attaches existing sensor board to dogfish", "non-invasive", "durable", and "allows for sensor package retrieval". In addition to these requirements, we identified other criteria to ensure high quality data collection, minimal environmental impact, and low cost. All requirements have been translated into engineering specifications to ensure they can be verified during the design process and implemented in the final solution. The engineering specifications were written based on published literature for similar animals, projects, or, in the case of the ocean pollution requirement, based on the design of the iTag.

Table 1: Stakeholder requirements and their corresponding engineering specifications for the shark attachment device listed from highest to lowest priority.

Requirement	**Specification**
Attaches existing sensor board, battery, and radio antenna to dogfish	Secure 4.70 x 2.21 x 1.60 cm box, with 0.127 cm diameter rod of length 34.01 cm attached to smallest face, centered along 2.21 cm dimension, located at a height of 0.08 cm [4] to dogfish of length ≤ 1.5 m [8]
Is non-invasive	No significant change (≤ 5%) in behavior quantified by: - Tailbeat frequency [10] - Roll of animal [11] Ensure that animals interacting with the tagged dogfish have no behavior change, i.e. do not perceive tagged dogfish as weakened or injured [11]
Is durable	Withstand depth > 200 meters; Withstand pressure > 2120 kPa [8] [12]; Withstand > 10 deployments Secures to shark ≥ 72 hours at speeds ≤ 1.9 m/s & accelerations ≤ 31 m/s^2 [13]
Allows for sensor package retrieval; Antenna must protrude out of package and point out of the surface of the water [10]	Has density of combined sensor and package upon release < 1.020 g/cm^3 [14] Antenna oriented at least 20 degrees above the horizon when tag is on the surface
Does not disrupt sensor measurements	Has total error ≤ 5% [11]
Does not add to ocean pollution	Releases < 4.5 g of long-term material per use [4]
Has affordable cost	Costs < $100 / tag [11]

The justifications of the requirements and their specifications are described below.

Attaches to Dogfish

The primary task for this project was to secure the sensor board, battery, radio, and antenna to dogfish. The engineering specification for this requirement was derived from the dimensions of the existing lab equipment and translated to a bounding box and a rod-shaped antenna. The dogfish size was based on existing literature that states dogfish can be up to 1.5 m long [8]. This value was left as an inequality to ensure that our design can be attached to a range of dogfish.

Is Non-Invasive

Another high priority stakeholder requirement was that the design be non-invasive to the dogfish. This requirement exists to ensure the welfare of the animals being studied and to ensure the integrity of collected data. Our sponsors are interested in measurements that are representative of behavior in a natural setting meaning that our design must not disrupt typical behavior. If the forces caused by the tag are too large, they could, for example, affect the metrics of tailbeat frequency [10] and roll [11], which would signify that the animal's behavior has changed due to the tag. Tailbeat frequency is a metric derived both from conversations with our sponsors and from a study that tagged sharks and manta rays and quantitatively studied their behavioral characteristics [10]. We also specified that other animals' behavior should not change after the tag has been attached. If the tagged dogfish is viewed as weak by other dogfish, the other dogfish may exhibit aggressive behavior or group interactions may change.

Is Durable

The requirement that the tag and clip design should be durable ensures that the solution can withstand the conditions of the dogfish swimming (e.g. pressure, speed, and acceleration), be re-deployed many times, and secure to the dogfish for at least 72 hours, as required by our sponsors. The current pressure specification was a function of natural habitats that dogfish are typically found in during summer in the North Atlantic [8,11], when and where the study with our product will be conducted. The current speed and acceleration specifications were set based on literature about evasive dogfish maneuvers [13], so we expect them to be higher than nominal swimming behavior.

Allows for Sensor Package Retrieval

A key stakeholder requirement for this project was that our design must allow for sensor package retrieval. Our sponsors use archival tags, which means that the data measurements are stored locally, and the tag must be recovered for analysis. Furthermore, the researchers do not plan to recapture the dogfish to remove the tag, so the tag must autonomously detach from the animal and float to the surface for retrieval. As such, we set our specification to ensure that the electronics package combined with any permanently attached parts is positively buoyant in ocean water.

Does Not Disrupt Sensor Measurements

The stakeholder requirement to avoid disrupting sensor measurements was set to ensure that our design does not interfere with sensor measurements so that the data match the actual movement of the dogfish and their environment. We set the engineering specification to include a measurement error less than or equal to 5% of the expected value which was determined based on discussions with our sponsor [4]. This requirement also applies to the oxygen and light sensors which must be facing the dogfish's surrounding environment to record proper data [11].

Limits Ocean Pollution

The dogfish themselves are also an important stakeholder in this project so we set an upper bound of mass left in the ocean to help protect their habitat. The mass limit used in the engineering specification is based upon the iTag which leaves approximately 4.5 g of plastic in the ocean for each deployment. Meeting or improving this ocean waste will keep the dogfish's environment from further pollution.

Has Affordable Cost

The final requirement is that the design should be of relatively low cost to produce. This was to ensure that the tag is a feasible cost for the Sensory Ecology and Bioacoustics Lab. The specification was set at $100 / tag, which corresponds to less than $10 per deployment.

Additional Aspects to Consider

Though not explicit stakeholder requirements or specifications, the stakeholders expressed preference for the sensors on the sensor board to face the animal's surrounding environment and for the biologging tag to be secured to the top of the front ⅔ of the animal's body. The sensor package includes pressure and light sensors which measure the environment they are in and thus should not be directed toward the skin of the animal. The sensors in the iTag orientation are shown in Figure 4 on the left, this is the bottom view of the tag so the sensors are facing the animal's body. The right image of Figure 4 shows the sensor board in the same orientation with the key components labeled.

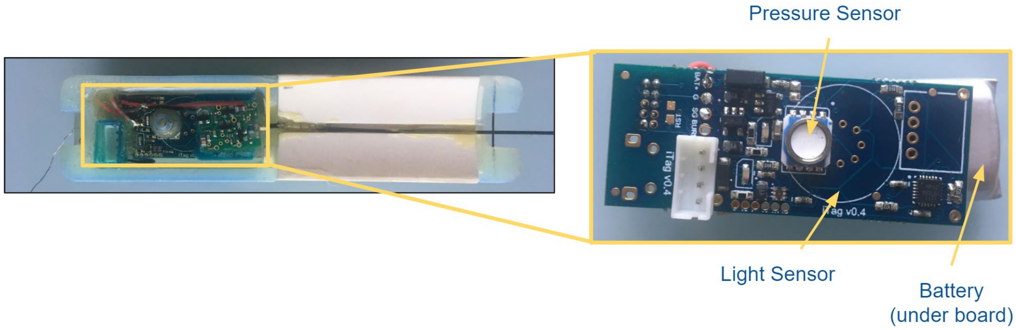


Figure 4: (Left) Bottom view of the iTag design. (Right) Top view of the sensor board with sensors indicated and battery underneath the board.

The sensors shown in the image on the right in Figure 4 must face away from the dogfish body for best data collection. Furthermore, the pressure sensor must be covered in a compliant material so that it can still measure changes in environmental pressure without influence from swimming speed of the individual.

Additionally, the biologging tag should be located toward the front of the dogfish because it measures acceleration and taking these measurements from the caudal fin may introduce unwanted noise. The identified feasible tag locations are shown on a virtual dogfish in Figure 5.

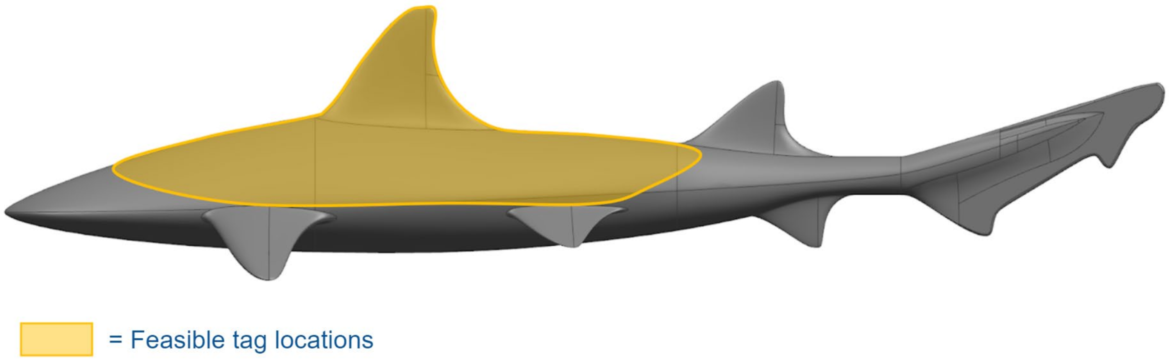


Figure 5: Feasible tag locations highlighted in yellow on the virtual shark.

The dogfish at WHOI also spend a lot of time at the bottom of their tank, a behavior that researchers believe may also be present in their wild habitat. Therefore attaching the sensors to the top or sides of the body will not disrupt that habit and will minimize the risk of damaging the package due to collisions with the bottom surface. Thus, we accommodate the sensor orientation in package design and considered attachment mechanisms that were located toward the front and top or sides of the dogfish body.

Concept Exploration

Once the problem was well understood and the requirements and specifications were defined, we began ideating and developing potential solutions. Figure 6 depicts our process of exploring concepts for our design problem. We began our process with concept generation, aiming to generate the most concepts possible before moving on so that we could ensure that our solution space was thoroughly explored. Moving onto concept selection, we reduced our list of concepts into a manageable number to further develop. Concept development involved expanding upon and refining these initial ideas. After developing our concepts, we determined how to prototype each and evaluate the designs prior to selection. After the evaluation data was gathered, we chose a final concept to continue refining.

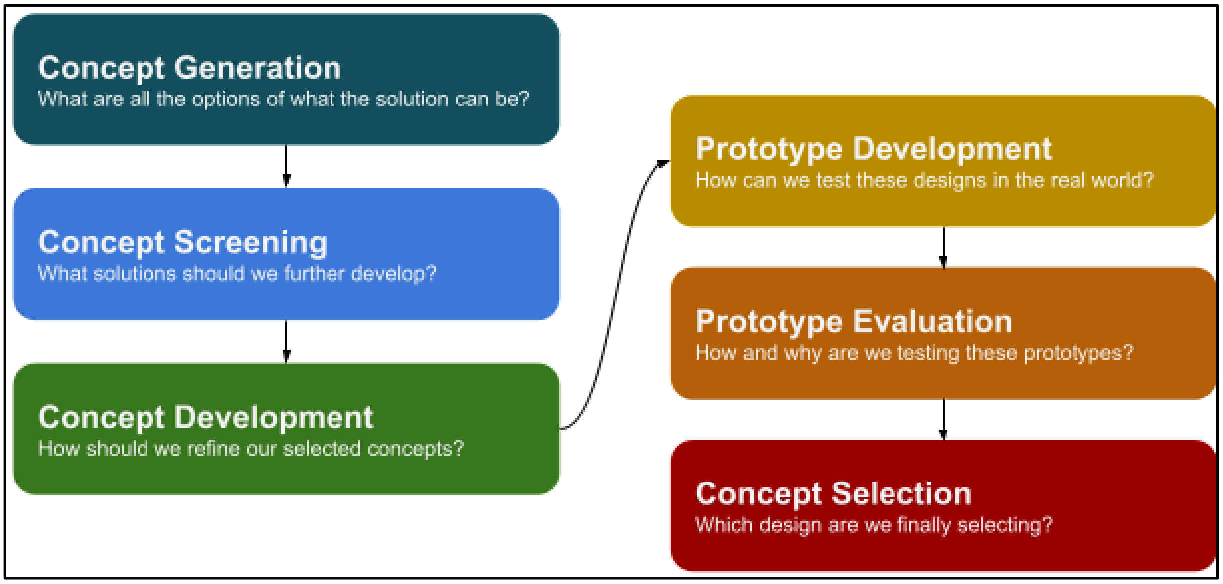


Figure 6: Depiction of our concept exploration process, including the underlying questions at each stage.

Concept Generation

We had multiple internal discussions to spark potential ideas and build off of previous solutions. We mainly used mind-maps to facilitate these discussions, sketch ideas, and represent relationships among concepts. To avoid limiting our designs based on individual features and to provide structure in our discussions, we split the project into functional elements which included: attachment, detachment (release), and electronics package design. Within attachment, we considered different parts of the dogfish body to attach the tag to, as well as general attachment strategies. The mind map created during our first idea generation session is shown in Figure 7 and was used to continue generating additional ideas and also to iterate upon previous ideas in the subsequent ideation sessions.

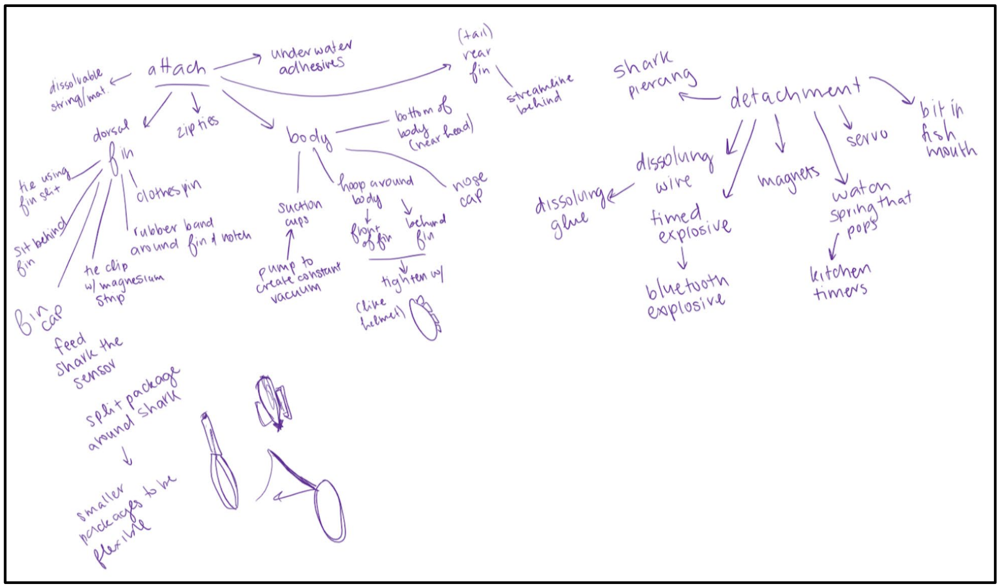


Figure 7: Mind-map created from the first team concept generation session.

Following our internal team discussions, we shared the results of the ideation session with our stakeholders to gain additional insights and include their perspectives in the process. Including our stakeholders' voices in this discussion was valuable to gain a more refined understanding of their needs and uncover some misunderstandings or biases that we had developed from the initial stakeholder conversations. With feedback from stakeholders, we continued developing potential ideas and refining existing ideas.

Attachment Strategies

The tag attachment methods discussed as a team included a wide variety of potential approaches that were based on benchmarked biologging tags as well as synthesizing concepts from outside sources and experiences. The attachment strategies were split into considering attaching to the fin, the body, and general attachment.

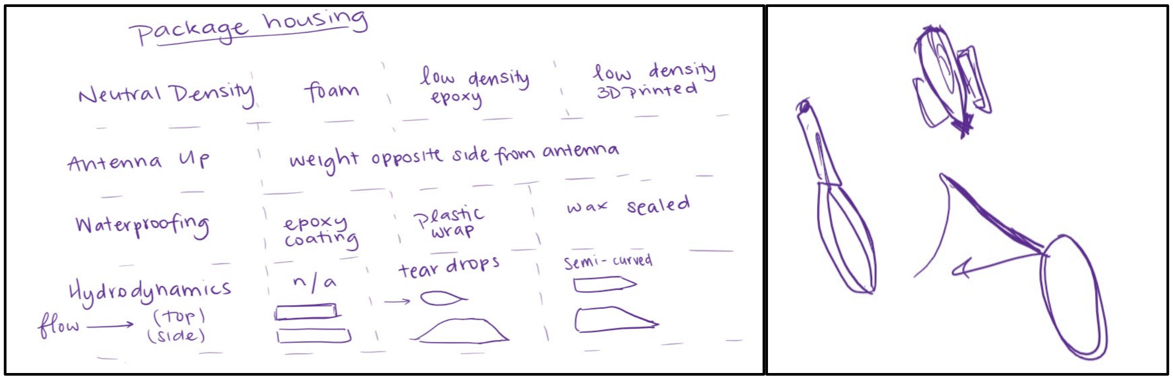
The two main concepts discussed and investigated were a hoop-around-body, and a clothespin design. The hoop method involved creating a fabric piece that stretched around the entire body of the shark onto which the package could be attached. The clothespin concept was based largely upon benchmarking and would attach by compressing against the first dorsal fin on the dogfish. This design required contact with much less of the shark than many designs that we discussed as the entire contact area was a small portion of the dorsal fin. The hoop-around-body design, while in contact with more of the shark than a clip design, we believed would be more stable and secure than the fin clip. Both designs were investigated and prototyped; they are discussed in more detail in the Prototype Development and Appendix 2 sections respectively.

Detachment Strategies

The team initially ideated general detachment methods but understood that the release is heavily dependent on attachment design and that it is generally more difficult to ensure that a package stays secured for a fixed period than to release. Thus, the team focused on attachment and electronics package designs and will leave detachment to future iterations of the project.

Electronics Package Designs

In addition to the attachment and detachment strategies discussed above, we considered how to redesign the electronics housings for dogfish. The functions of achieving positive buoyancy, ensuring the antenna points upward upon surfacing, waterproofing the electronics, and achieving desired hydrodynamic effects were considered. Figure 8 shows a morphological chart used to explore the design space for these functions.



Package housing

Neutral Density	foam	low density epoxy	low density 3D printed
Antenna Up	weight opposite side from antenna		
Waterproofing	epoxy coating	plastic wrap	wax sealed
Hydrodynamics flow → (top) (side)	n/a	tear drops	semi-curved

Figure 8: (Left) Morphological chart based on functions related to packaging. (Right) Initial package location sketches.

Electronics package shape is largely determined by the attachment strategy selected, so the package redesign was started later in the design process. Once the attachment mechanism was selected, the hydrodynamic shape and attributes of the package were refined and optimized.

Concept Screening

Following our initial ideation sessions, it was necessary to filter through our concepts to determine which should be further developed and which should not. Our goal was to narrow down our large number of concepts into a manageable set for research, evaluation, and, eventually, selection. We first sorted through our ideas and eliminated those that were not feasible for obvious reasons. This included ideas such as a timed explosive for the detachment method and feeding the shark the sensor as a way to attach it. After filtering out ideas that were not feasible, we turned to determining which concepts would best address our problem and meet the requirements and specifications that are tabulated in Table 1 on page 8**.** During this step, we made sure to apply our requirements and specifications as we originally defined them. Our requirement for the attachment method to be non-invasive proved to be very limiting towards our concepts, as well as the requirement specifying the need for retrieval of the sensor package. After completing these evaluations, the “hoop around body” and “clothes pin” concepts were identified as viable themes to continue iterating upon. We chose these concepts because they offered a wide range of possible mechanical designs and represented distinct regions of the design space. We also decided to move forward with foil-shaped package designs due to the favorable hydrodynamics and compact nature of the design.

Prototyping

Prototype Development

To gain a better understanding of the concepts we screened, we developed proof of concept prototypes for the "hoop around body" and "clothes pin" concepts. The design corresponding to the initial "hoop around body" concept is called the "Shark Belt" and the "clothes pin" concept is the "Fin Clip." After prototyping, the team moved forward with the Shark Belt concept, so the Fin Clip discussion is included in Appendix 2 and Shark Belt is discussed below.

Attachment Methods

The team prototyped many iterations of the Shark Belt concept, using different materials, structural concepts, and sizes. The initial iterations of designs are discussed in Appendix 3, but the most promising prototype included a TheraBand® resistance band material as the strap.

TheraBand® Shark Belt

The first iteration with the TheraBand® material replicated the one strap design from the initial prototypes made out of elastic. The TheraBand® material is thinner than the elastic, and we anticipated that the rubbery texture may be more secure on the dogfish skin. This strap is 1.5 in wide and attaches underneath the body with Velcro®, shown in Figure 9. There was significant interference with the dorsal and pectoral fins at this width. The adhesive Velcro® also did not attach to the resistance band material as securely as it attached to the elastic band.

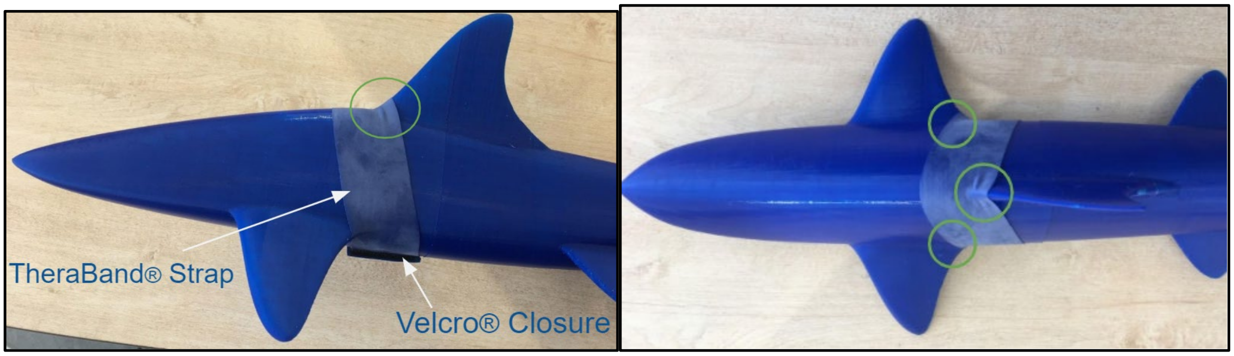


Figure 9: Single strap belt located forward of the first dorsal fin. (Left) Side view highlights interference with the dorsal fin and the Velcro® closure. (Right) Top view highlights interference with pectoral fins and dorsal fin.

We also created a wider belt, or vest, using the TheraBand® material with a slot for the first dorsal fin to protrude through, shown in Figure 10.

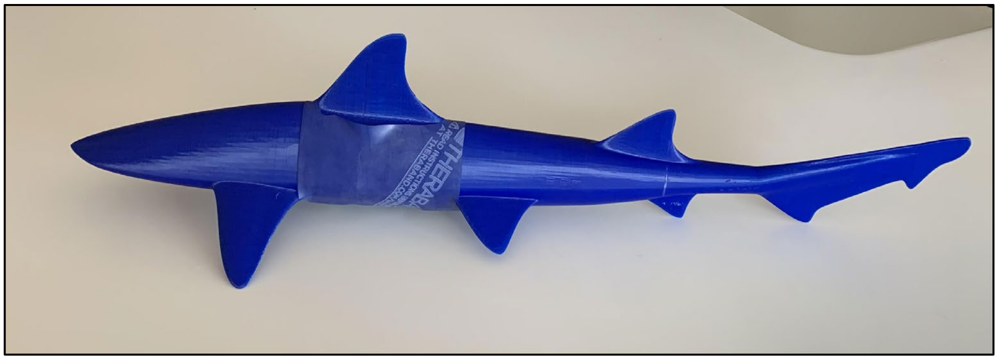


Figure 10: Image of shark "vest" surrounding the first dorsal fin. Vest is secured under the dogfish with Velcro®.

This method was chosen because it is relatively simple to create and sewing or modifying with the elastic material can be very difficult. This design also has ample area to secure packages to the strap which is beneficial for package design and data quality.

Clasp

This part was designed in response to the need to close the Shark Belt without using Velcro®. The Velcro® used during prototyping was presumed to induce a significant amount of drag, so a smaller method of attaching the belt around the shark was designed. The first prototype, shown on the left in Figure 11, was 3-D printed, fit quite well, and had sufficient clearance to sew the pieces into the strap and connect the two halves with Nichrome wire.

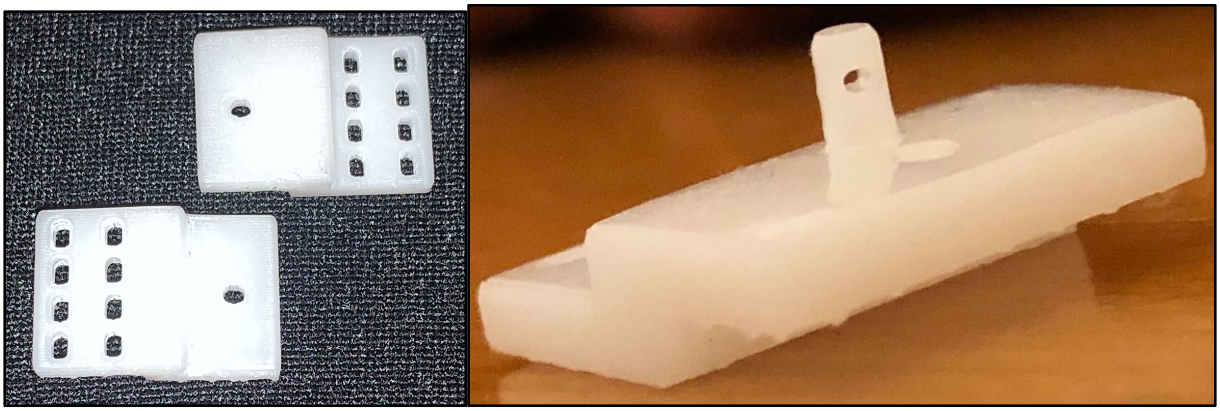


Figure 11: (Left) First prototype of the clasp. The singular holes stack together for Nichrome wire to be threaded through during attachment. (Right) The second prototype was slightly wider (1.5 mm) but more significantly featured a way for the wire to be looped off and secured upon deployment.

After prototyping the first model, we recognized the need for a way to hold down the Nichrome wire once it threaded through both pieces of the clasp. The second model, shown on the right in Figure 11, solves that problem by including a strut to secure the wire. The small cylinder allows the wire to be threaded through the hole and wrapped around the cylinder to stop it from becoming undone during deployment.

Package Shapes

The initial tag concepts were designed with the intent of using the iTag, however, after further research on the size and flexibility of dogfish it was evident that a more compact package design would benefit our project. The iTag is shown on a 1:1 model of a dogfish in Figure 12.

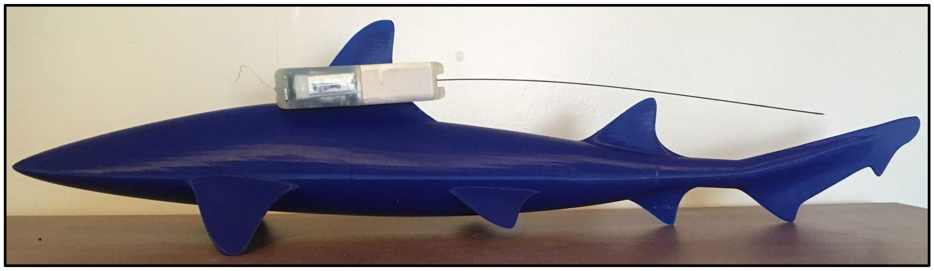


Figure 12: Side view of the dogfish with the existing squid tag package on its first dorsal fin.

The goal of redesigning the package was to contain the same or similar electronics as the iTag in hydrodynamic shapes that are suitable for dogfish. To minimize the invasiveness of the design and reduce frontal area of the package (and therefore, drag), the package was split into multiple parts that could be placed around the dogfish body. Various package shapes and electronics arrangements were investigated. The first package design, shown in Figure 13, houses the battery and sensor board in one airfoil, and the antenna and radio in the other.

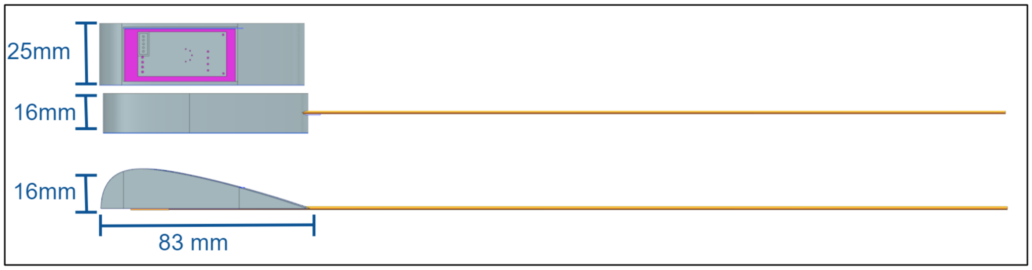


Figure 13: Top view (Top) and side view (Bottom) of the airfoil package design with sensor board shown on top of the battery (pink) and the antenna and radio (gold) in its own housing.

The second package, shown in Figure 14, houses each component individually which allows for a narrower frontal area of each package, but ultimately a wider and longer tag.

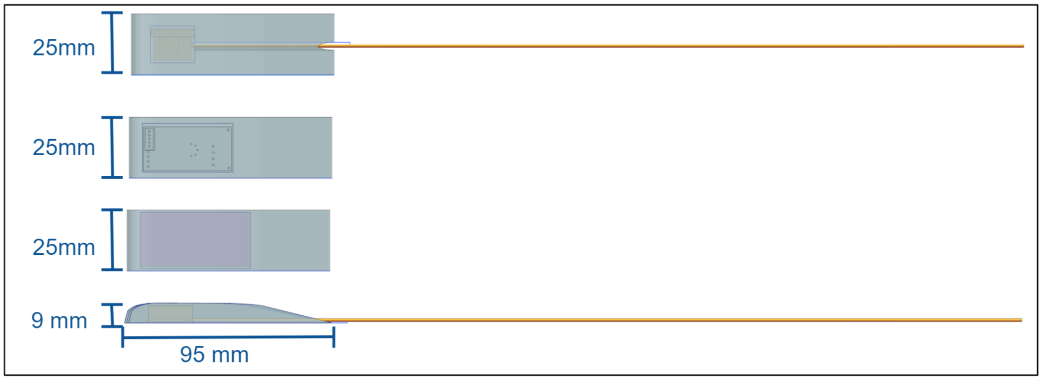


Figure 14: Top view (Top) and side view (Bottom) of airfoil package design with housing for each component.

These packages will be helpful to integrate the electronics with various prototypes and can be easily altered to accommodate any other design changes that arise. After these initial designs, the shape of the package was optimized to minimize drag (discussed on page 28) and meet our engineering specifications (discussed on page 8).

Prototype Evaluation

The prototype attachment methods and package shapes were evaluated at each stage of the design process using both a to-scale virtual and physical dogfish model. This evaluation guided the refinement of designs and was critical to each iteration in the design process.

Prototype Evaluation Tools

Concept development and prototype development and evaluation were aided by using a virtual shark, and 3-D printed models of the shark. These models were used to visualize appropriate dimensions and locations for the tag design.

A virtual shark model was created (Figure 15) based on a 3-D scan and comprehensive measurements of the two dogfish at WHOI, provided by our sponsors. Simplifications on this model compared to an actual dogfish include: no eyes, gills or mouth, and no slots on the rear half of the dorsal and pectoral fins. This model is also fixed and does not simulate the movement or flexibility of live dogfish.

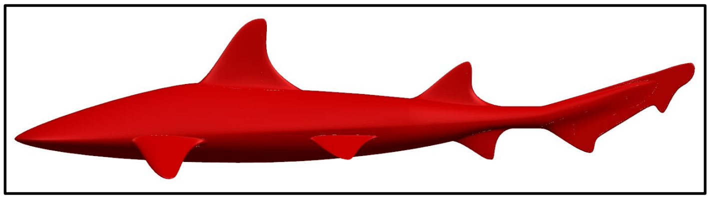


Figure 15: Virtual model of a dogfish used for concept generation and analysis.

The virtual shark was used for initial qualitative design choices such as potential feasible locations or sizes of the tag, and then used heavily for more in-depth quantitative analysis.

A physical model of the shark was 3-D printed using resources available at the University of Michigan Mechanical Engineering Machine Shop. The virtual shark was split into three pieces to create flat printing surfaces and fit within the available printer volume. The three pieces were then glued together to create a to-scale model of the dogfish, shown in Figure 16. The physical model was extremely useful in the physical prototyping and analysis processes.

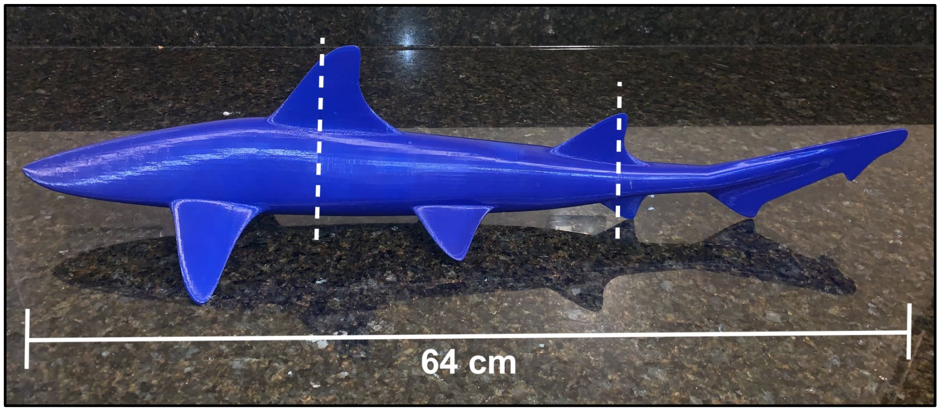


Figure 16: Physical model of a dogfish used for prototyping and analysis. Dashed lines demarcate the three sections used for 3-D printing.

Attachment Methods

Physical Prototyping of Shark Belt

Prototype evaluation was conducted throughout the development process for the shark belt, since each iteration was a physical prototype. The design was qualitatively evaluated for how well it fit the shark shape, how well it stayed in one location, and if it interfered with any significant anatomical features of the shark. Subsequent design decisions were made based on these observations to continue iterating through concepts.

Virtual and Physical Prototyping of Clasp

The clasp was designed and evaluated qualitatively in the virtual environment before 3-D printing. Based on the success of the initial print, discussed above, only functional design changes were implemented in the second iteration. Due to the limited schedule of this project, the clasp mechanism was not deployed with the rest of the tag for testing. However, based on component tests and analysis, we believe it will be successful in future system tests.

Electronics Package Shapes

Computational Fluid Dynamics (CFD)

Background and Purpose

CFD is a numerical tool used to predict the behavior of fluids. To do this, the continuity (mass conservation) and Navier-Stokes (momentum conservation) equations are discretized so that they can be evaluated on finite elements to calculate fluid properties. One of these finite elements is called a cell. The collection of these finite elements is called a mesh, or grid. To further simplify these calculations and make the process computationally feasible, additional models are applied to estimate the turbulence effects in the fluid. Additional simplifications exist for the same purpose, such as neglecting transient effects and the laminar region of the flow. CFD has two uses for this project:

1) Inform our decision on where the biotag should be attached. By running CFD trials each with a representative biotag attached in a different location, we can see how drag reacts to tags in different locations.
2) Predict hydrodynamic forces and moments exerted on the dogfish with our tag design attached. We can use this information to refine our design to reduce drag in an effort to make our tag affect dogfish behavior as little as possible.

Methods

STAR-CCM+ was chosen for CFD due to its ease and widespread use. Settings were chosen based primarily on best practices found for similar studies [15], but with three changes. First, an unstructured mesh was used instead of a structured one as it is much less time consuming to generate. Second, a mesh dependency study was done to determine the number of cells instead of matching what was done in the cited study. Third, no transition model was used. While transition models can be useful as they predict the laminar flow region instead of assuming all flow is turbulent, transition models need further developing to accurately predict the laminar-turbulent transition in flow fields with separation [16].

For convenience, a summary of the CFD cases completed is shown in Table 2 which includes the geometry, velocity/velocities, and water properties. For some runs, water properties were changed to match the water in the tow tank and allow for a more direct comparison of results.

Table 2: Summary of CFD cases.

	Base	**Location Testing**	**Shape Optimization**	**Tow Tank Correlation**	**Final Design**
Geometry	Shark	Shark with package	Shark with package	Shark, Shark with package	Shark with package
Velocities [m/s]	1.9	1.9	1.9	1.4, 1.9, 2.4	1.9
Water Density [kg/m^3]	997.6	997.6	997.6	998.2	997.6
Water Dynamic Viscosity [Pa-s]	8.887e-4	8.887e-4	8.887e-4	1.001e-6	8.887e-4

The domain is the region in which the finite volumes exist for computation. It is important to have a domain large enough to not interfere with the flow field around the body for external fluid dynamics. Per the cited article, a domain five times the length of the model upstream, fifteen times downstream, and five times to the sides, top, and bottom of the model was used. This is illustrated in Figure 17.

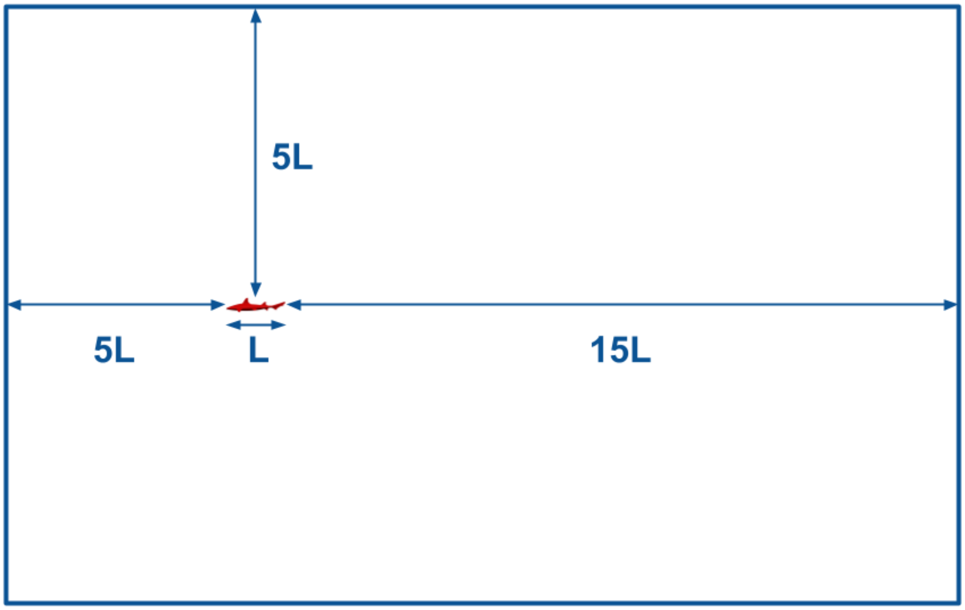


Figure 17: Side view illustration of computational domain used for CFD, with our smooth dogfish model shown in red. Not pictured is the distance between the shark and the side walls, which is five times the shark length on either side.

As previously mentioned, an unstructured mesh was generated using the built-in tools of STAR-CCM+. The mesh on the surface of the body sets the basis for the mesh in the rest of the volume between the shark and walls of the domain. For this, a “base size” is specified for the mesh to target. In addition to this surface mesh, “prism layers" are added. These are very fine cells that extend off the surface and are important for accurately predicting forces on a body for external flow. A key metric for these prism layers is wall y^+, which is defined as follows [17]:

$$y^+ = \frac{y u_\tau}{\nu}$$

$$u_\tau = \sqrt{\frac{\tau_w}{\rho}}$$

where y is the absolute height of the cell from the wall, u_τ is friction velocity, v is kinematic viscosity, τ_w is wall shear stress, and ρ is fluid density. To accurately predict the formation of the boundary layer along the surface, and by extension accurately predict forces on the body, a wall y^+ less than 1 is targeted, with wall y^+ less than 5 still being considered good. Figure 18 shows a distribution of wall y^+ values along the surface of the shark.

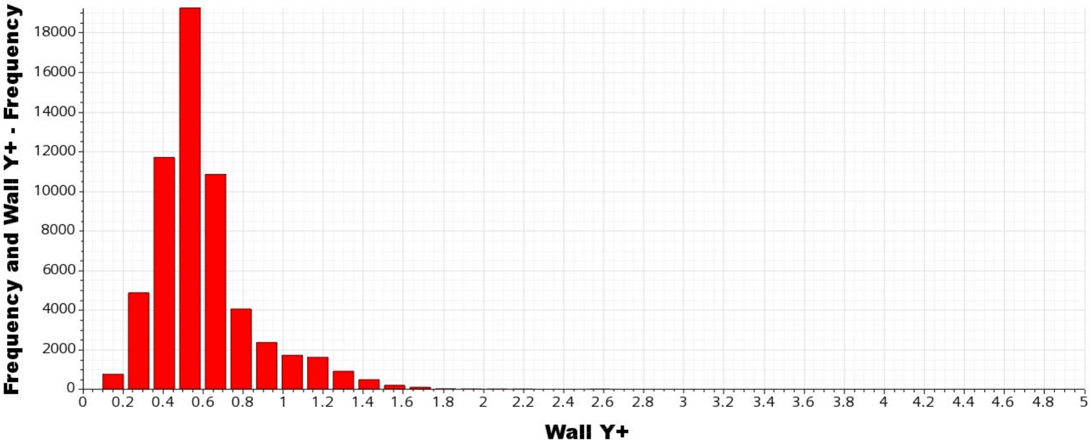


Figure 18: Histogram of wall y^+ values along the surface of the shark. Lower values are ideal for good prediction of forces on the shark, with values < 1 targeted and values < 5 accepted. All cells on the shark had wall y+ < 2.

In addition to the prism layers, a refinement zone is included around the shark to keep the mesh size fine around it. There is additional refinement directly behind the shark where we expect the wake to be. Figure 19 includes several views of the mesh.

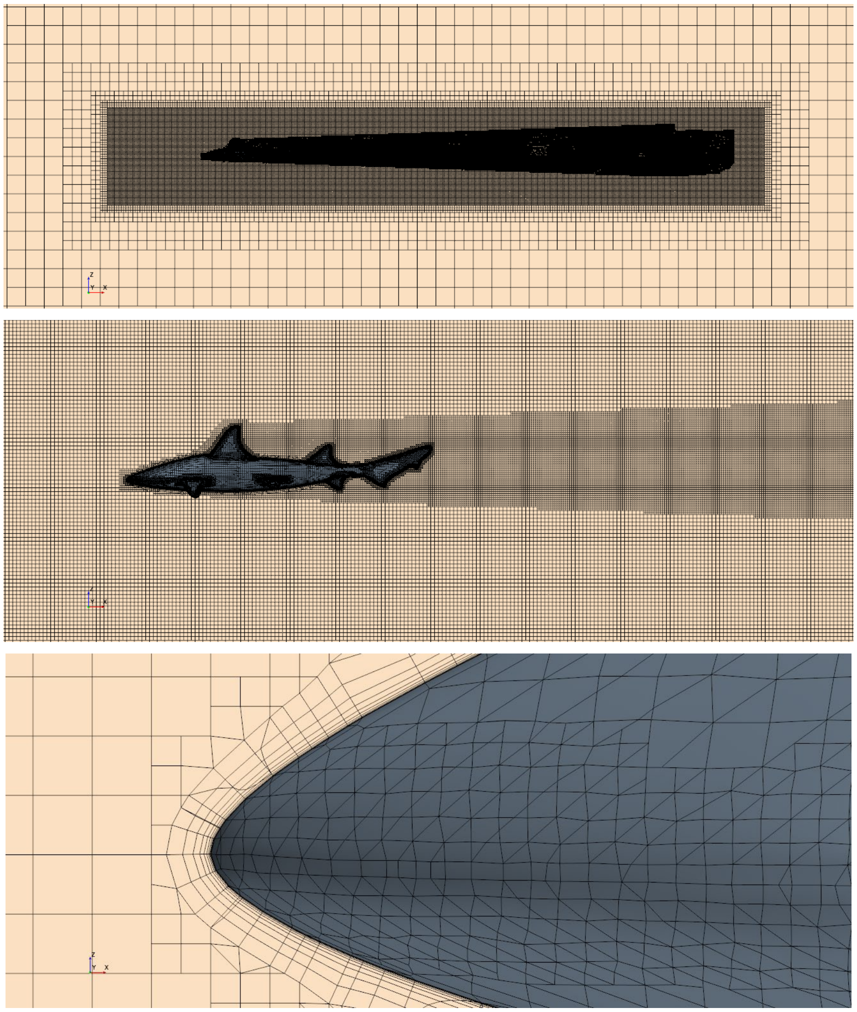


Figure 19: The computational mesh used for CFD, with cross-section shown. Zoomed out view of most of the domain (top). Closer view of the shark, wake refinement, and refinement box (middle). Boundary layer cells on the nose of the shark (bottom).

There are two driving factors for the accuracy for CFD: accuracy of the physics modeling and computational accuracy. Physics modeling is discussed at the bottom of the page. One of the sources of computational inaccuracy comes from the discretization of a continuous flow field that exists in the real world to a computational mesh. To tackle this source of error, a mesh dependency study was done. To complete this, different base sizes were used in the mesh, including 2 mm, 4 mm, 8 mm, and 16 mm. The goal is to find a good balance between accuracy and computational cost. While it is assumed that an increase in the number of cells will lead to a more accurate solution, the computational cost will at some point be prohibitive. Figure 20 shows the results of this study. As a result of this study, about 10 million cells, and a 4 mm base size was used.

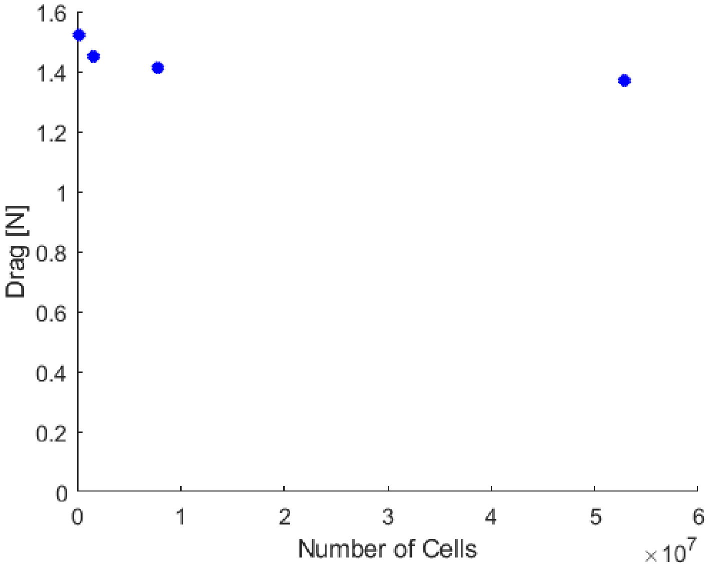


Figure 20: Results of mesh dependency study. The third data point, corresponding to about 10 million cells for a base size of 4 mm was selected to find a solution that is accurate, but does not exceed the available computation resources.

Boundary and initial conditions must be set for the solver. The front wall of the domain (“inlet”) is set as a “velocity inlet” at the velocity associated with each case, as noted in Table 2. The rear wall (“outlet”) is set as a “pressure outlet” with 0 Pa gauge pressure. The top, bottom, and sides are set as symmetry planes. The shark (and tag, if included) is set as a no-slip wall with no velocity.

Physics conditions are set to tell STAR-CCM+ what equations to solve in the analysis. The following settings were used, per the cited article for CFD best practices: steady-state RANS, k-ω SST turbulence, low y^+, constant fluid density.

Many iterations of the computations are done on the grid to ensure that flow quantities converge. It was seen from testing that 700 iterations were sufficient for this setup. Figure 21 shows several quantities of interest as a function of the number of iterations.

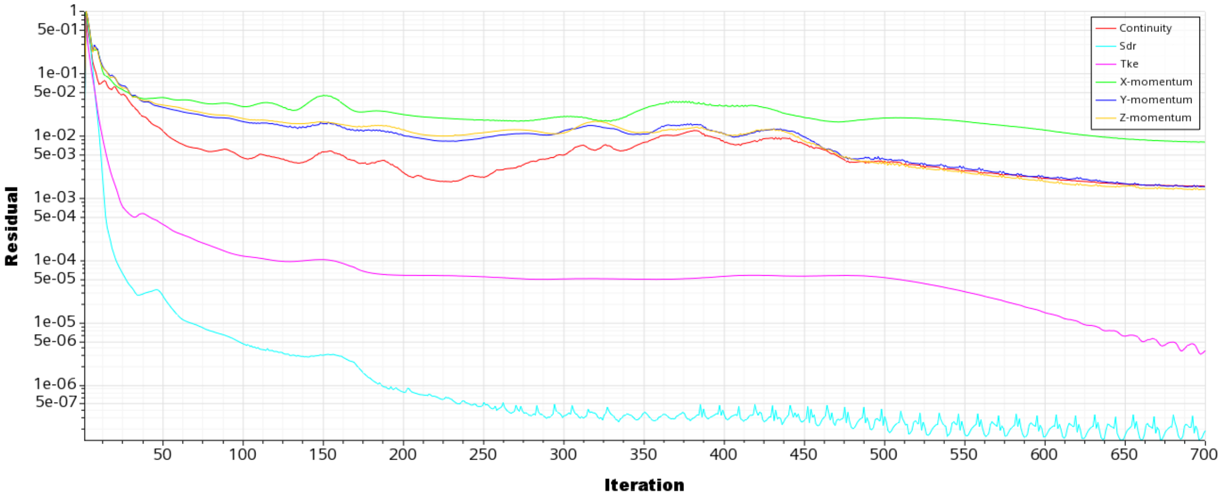


Figure 21: Convergence of the solution for our baseline simulation. Based on this result, it was decided that we would run 700 iterations for future simulations.

Limitations

There are several limitations that will cause errors between the resulting flow field from CFD and the real-world flow field around a dogfish:

(1) The kinematics of the dogfish are not modeled. That is, the shark is modeled as moving perfectly straight as opposed to beating its tail from side-to-side or manipulating its fins to maneuver.
(2) The flow is assumed to be steady-state, and as a result any unsteady effects in the flow field are ignored.
(3) Turbulence is assumed throughout the flow, as opposed to some region on the dogfish experiencing laminar flow as well.
(4) A turbulence model is used instead of a direct numerical simulation due to the prohibitive cost of the latter.
(5) The surface of the dogfish and tags in CFD are assumed to be perfectly smooth. In reality, both have a textured surface.

CFD Initial Drag Analysis

To inform our biotag design from the perspective of minimizing drag, we explored how drag would change from attaching a biotag in different locations. We used the setup described above first on the Base Shark Model (shark model without any tag), and then on the shark model with one biotag in five different locations. The baseline shark test also provided insight to flow behavior around (an idealized) dogfish and highlighted several notable features.

Base Shark Model

With the above setup, a drag of 1.25 N is predicted for the baseline (no biotag) smooth dogfish. Several notable features can be seen in our baseline simulation. Forces that act on the surface of a body come from both normal and shear stress. The normal stress, pressure, changes along the surface. Pressure on faces with normals pointing forward push the body back. Pressure on faces with normals pointing backwards push the body forwards. For any real flow, pressure will not be fully “recovered”, and there will be drag because of this pressure distribution, called pressure drag. Shear stress along the surface results from velocity gradients in the boundary layer. Any real flow has a drag component from this, called skin friction.

The first notable feature is the high pressure that can be seen on leading edges, which in this case is the nose of the shark and the front of fins. Figure 22 shows relative total pressure along the body of the shark, as well as streamlines off the body. Relative total pressure includes both dynamic and static pressure and is normalized to the pressure in the free stream.

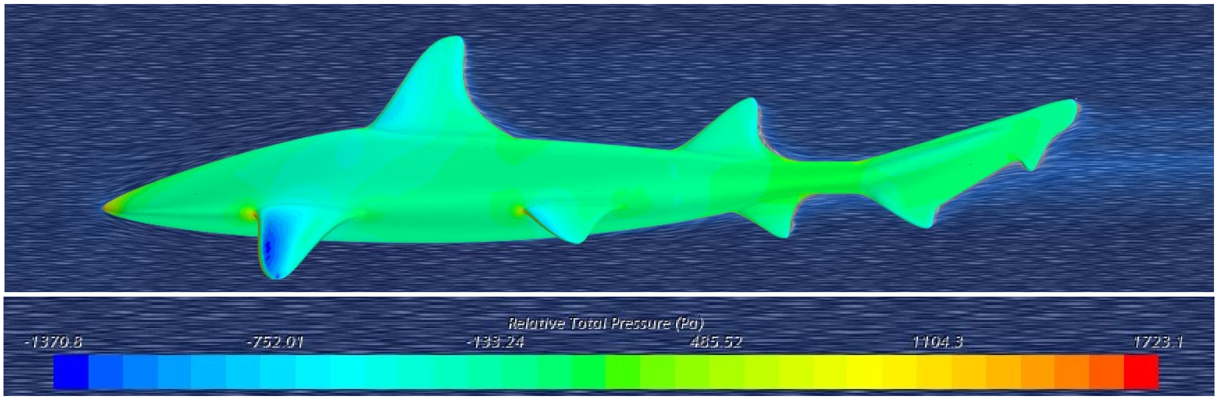


Figure 22: Relative total pressure scaler along the body of the shark. High pressure regions can be seen on leading edges. Streamlines are shown on a cross-section cutting through the middle of the shark. The color of the off-body flow is not meaningful.

The second notable feature is the separation that exists on the back side of fins. Separation occurs in regions where pressure is going from low to high and the geometry of the body is too sharp for the boundary layer to have the necessary velocity to stay attached. In regions of separation, pressure is lower than it otherwise would be. As a result, pressure drag exists. Figure 23 shows a region of separation behind the fin, which can be seen by the non-parallel streamlines.

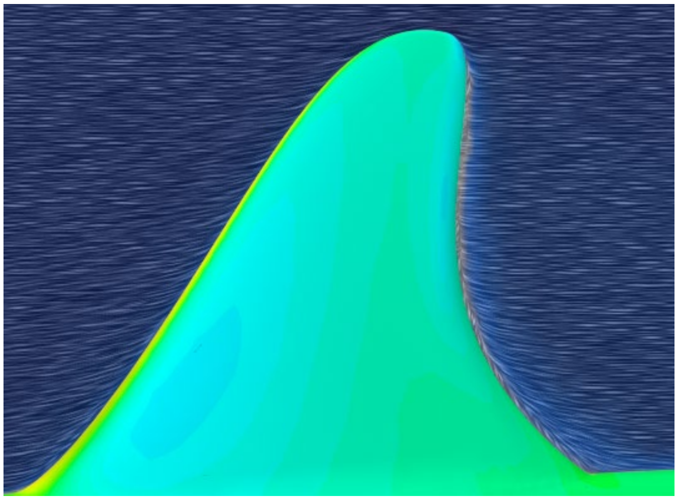


Figure 23: Separation occurring on the trailing edge of the first dorsal fin. This leads to lower pressure than the leading edge, which gives rise to pressure drag.

The third notable flow feature is the high skin friction that occurs near the front of fins, shown in Figure 24. On airfoil-like shapes, velocity is high near the region of maximum thickness. This high velocity gives rise to high shear stress, and as a result skin friction drag.

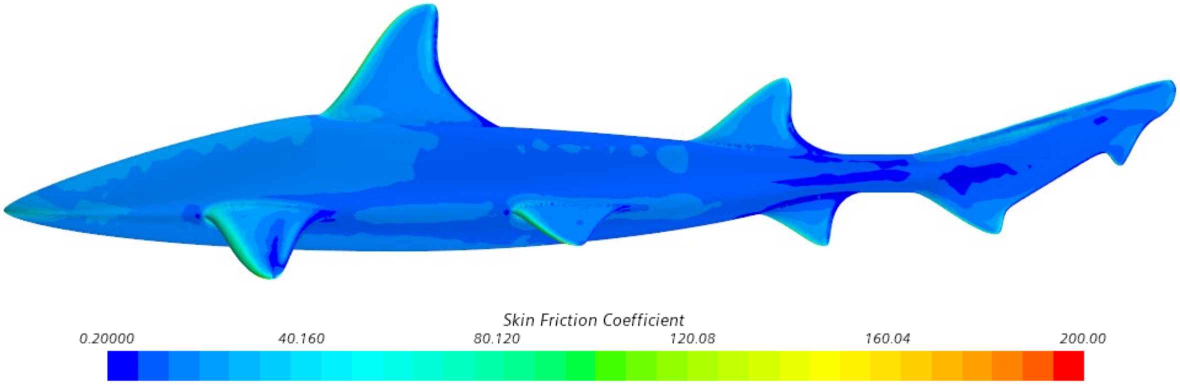


Figure 24: Skin friction coefficient along the shark. High skin friction can be seen by the leading edges of fins.

Package Location Test Results

The simplified package shape used for location testing was the iTag design scaled down to 50% size. This scaling was done to make the tag fit better on the shark, specifically on the first dorsal fin. Figure 25 shows the different locations tested.

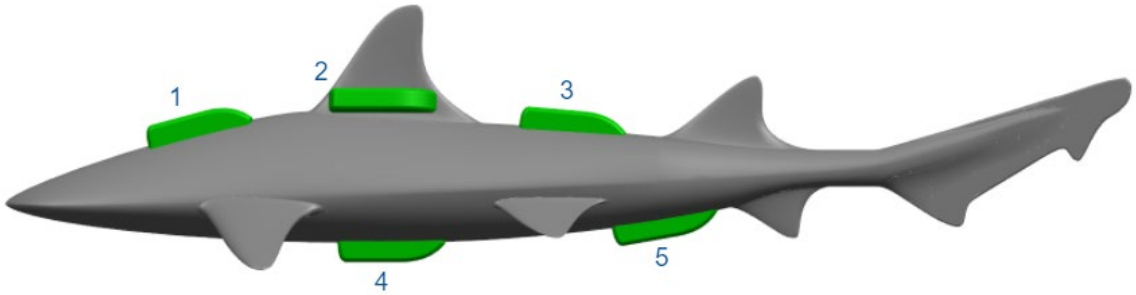


Figure 25: Package locations tested to inform our tag design. In green are the 50% size iTags that were used for this study. Different locations were tested in separate simulations but shown together here.

The results of the study are shown in Table 3. It was determined that tag locations on top of the shark incur less drag than locations under the shark. While location 1 shows the lowest drag, there are two limitations to this data point. First, the CFD setup does not include a transition model as previously discussed. As a result, it is possible that the flow is laminar in this region without a tag, and that the tag "trips" turbulent flow. If this is the case, the increase in drag will be higher than predicted. Second, the gills of the shark are in this region, and would make attachment very difficult to do while meeting our non-invasive requirement. As a result, we chose to focus on locations 2 and 3.

Table 3: Results of tag location study.

Location	Total Drag [N]	Drag Increase [%]
Baseline	1.250	n/a
1	1.329	6.30
2	1.338	7.01
3	1.356	8.46
4	1.369	9.51
5	1.361	8.90

Hydrodynamic Shape Optimization of Package

In addition to studying optimal tag location, we also completed several iterations of hydrodynamics shape optimization for the tag. Once again, the purpose of this ties back into our requirement of designing a solution that is minimally invasive. We started this process with an initial design that was created from intuition. This design was run through our previously-discussed CFD setup and the flow field was visualized. From these visualizations, we refined the shape of the package. Each step of the optimization process is shown in Figure 26.

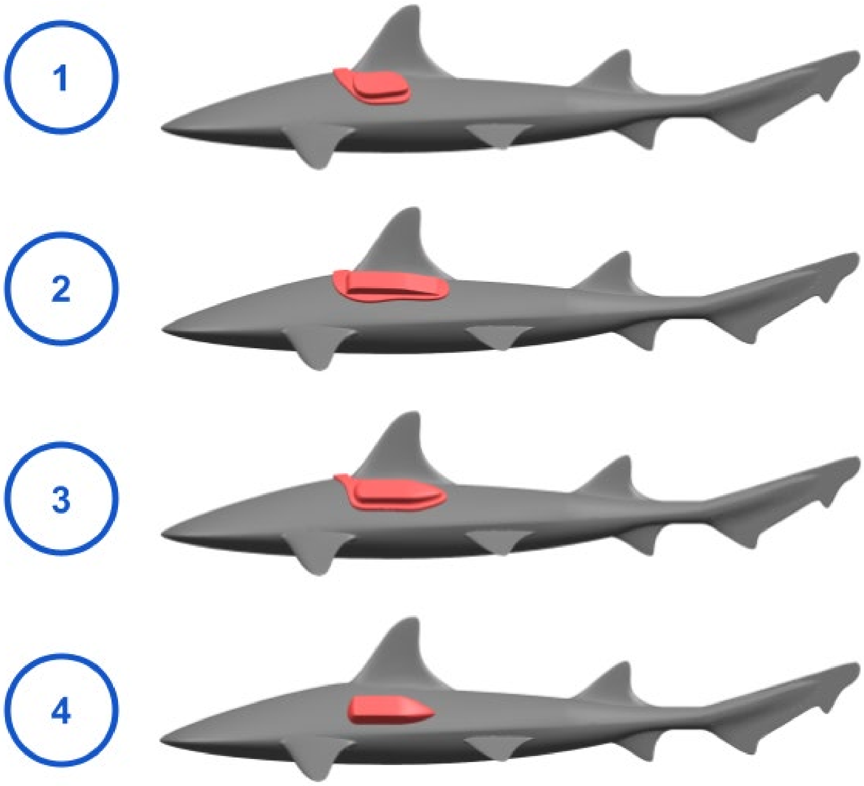


Figure 26: Iterative process of hydrodynamic shape optimization. Between iterations 3 and 4, we transitioned away from the "saddle" design, which helped to decrease drag. At the same time, we had to increase the tag size to incorporate all the necessary electronics, which increased drag.

Drag values for each of these iterations are listed in Table 4. Each iteration of the design improved drag, with the exception of going from iteration 3 to 4. This increase occurred because the tag size had to be corrected to fit in the necessary electronics.

Table 4: Results of hydrodynamics shape optimization. Changes are calculated relative to the first iteration.

Iteration	Total Drag [N]	Drag Change [%]
1	1.655	n/a
2	1.586	- 4.2
3	1.455	- 12.1
4	1.550	- 6.3

Between iterations 1 and 4, we were able to reduce the increase in drag experienced by the dogfish from tag addition by approximately 25%.

Risk Assessment

Many hazards exist during development and deployment of marine biologging tags. An FMEA was conducted to manage these hazards and begin the process of mitigating risk.

Table 5: FMEA Chart

Item	Function	Potential Failure Mode	Potential Effect(s) of Failure	Sev.	Potential Causes/ Mechanisms of Failure	Occurr.	Current Design Controls	Det.	RPN
Band	Hold packages	Package separates from band	Lose electronics/ data	8	Poor attachment	1	Sewn attachment	2	16
	Secure around shark (non-invasive)	Is invasive	Harms the shark	7	Not attached properly	3	Flexible band attachment method	3	63
		Broken band	Early release	5	Material fatigue	2	n/a	4	40
Housing	Secure electronics	Loose wiring	Lose power	8	Poor wire connection	4	n/a	2	64
					Too much movement allowed between the solder and package	2	n/a	1	16
	Waterproof electronics	Leak	Lose electronics	8	Poor epoxy filling	1	n/a	1	8
Nichrome Wire	Close band	Breaking early	Incomplete data	5	Material fatigue	2	n/a	4	40
	Release band (when triggered)	Not burning through	Untimed release	7	Insufficient current	2	n/a	3	42
VHF Radio	Share location with researchers	Unretrievable data	Lose tag	8	Dead battery, failed waterproofing, incorrectly oriented antenna	1	n/a	3	24

Testing and Evaluation of Final Prototype

The success and performance of our design is largely driven by the fluid dynamics around the shark and tag. Pressure and shear forces acting on the surface induce forces and moments on both the body of the shark and the tag. Our selection of engineering analysis tools has been driven by this fact. We chose to pursue both computational fluid dynamics and tow tank testing to design a package that meets our requirement of “is non-invasive” as well as possible. After CFD and tow tank testing were completed, the tag design was tested on one of the live dogfish at WHOI which allowed for qualitative observations to inform potential design changes.

Final Prototype Design

The prototype design used as the “full tag assembly” in tow tank testing and on the WHOI dogfish included the TheraBand® vest with a Velcro® closure and two solid 3-D printed hydrofoils to represent the improved electronics package shape, shown in Figure 27. The two hydrofoils were secured to the TheraBand® strap with Loctite® super glue and the TheraBand® strap was cut using scissors.

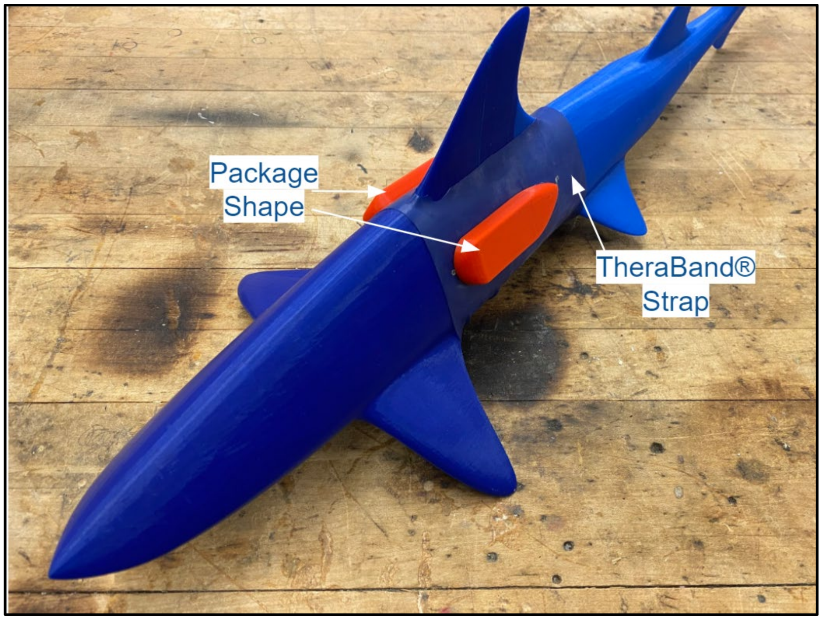


Figure 27: Final prototype design on the model dogfish. Design includes two solid package shapes and a Velcro® closure

Tow Tank

Background and Purpose

A tow tank is a laboratory tool analogous to a wind tunnel, but with the working fluid being water instead of air. Rather than relying on computation, a tow tank is a form of experimental fluid dynamics. A towing carriage pulls a model of the body being analyzed through the water. A load cell is attached to the model to measure forces and moments. Figure 28 shows a picture of the tow tank at the University of Michigan Marine Hydrodynamics Lab that we used.

Figure 28: Marine Hydrodynamics Laboratory tow tank [18].

There are two purposes of using a tow tank for this project:

1) Validate CFD results. Finding agreement between computational and experimental results is an important step in effectively using CFD. If these results align well, we can have high confidence in our package optimization.
2) Complete low fidelity testing on the attachment of our design to smooth dogfish. While the 3-D printed model does not match the surface properties or compliance of a real shark, or the lateral motion of the tail, this still will provide us with good insight. If the tag does not stay attached during these short tests, we can infer that it will not stay attached during the more complex movement that real dogfish exhibit.

Methods

Tow tank testing requires selecting a series of tests to run and designing an attachment setup. For this sweep of tests, we ran the model at velocities of 1.4 m/s, 1.9 m/s, and 2.4 m/s. From our research, we found 1.9 m/s to be a nominal velocity for smooth dogfish swimming. To see trends in data as a function of velocity, we expanded this by 0.5 m/s each direction. We tested this velocity sweep with only the dogfish, with the dogfish and package shapes, and with the full tag system.

The MHL has fresh water and the tank is 6.7 m wide and 3.75 m deep. The bottom of the towing foil was 62 cm below the surface of the water. In each test, the towing carriage was accelerated for 10s at each end of the steady-state speed period. Between runs, a 10 minute waiting period was observed to minimize any effects of turbulence remaining in the water from the previous run.

As previously mentioned, the dogfish must be attached to a load cell to measure forces and moments. The load cell has four M4 bolts that must screw into the shark. The load cell attaches to a coupon that attaches to the carriage that actually moves through the tank. Additionally, a fairing should be shrouded around the load cell to minimize the effects of the load cell on the flow field. Figure 29 shows this setup. The shark will be upside-down in the water as a result of this setup.

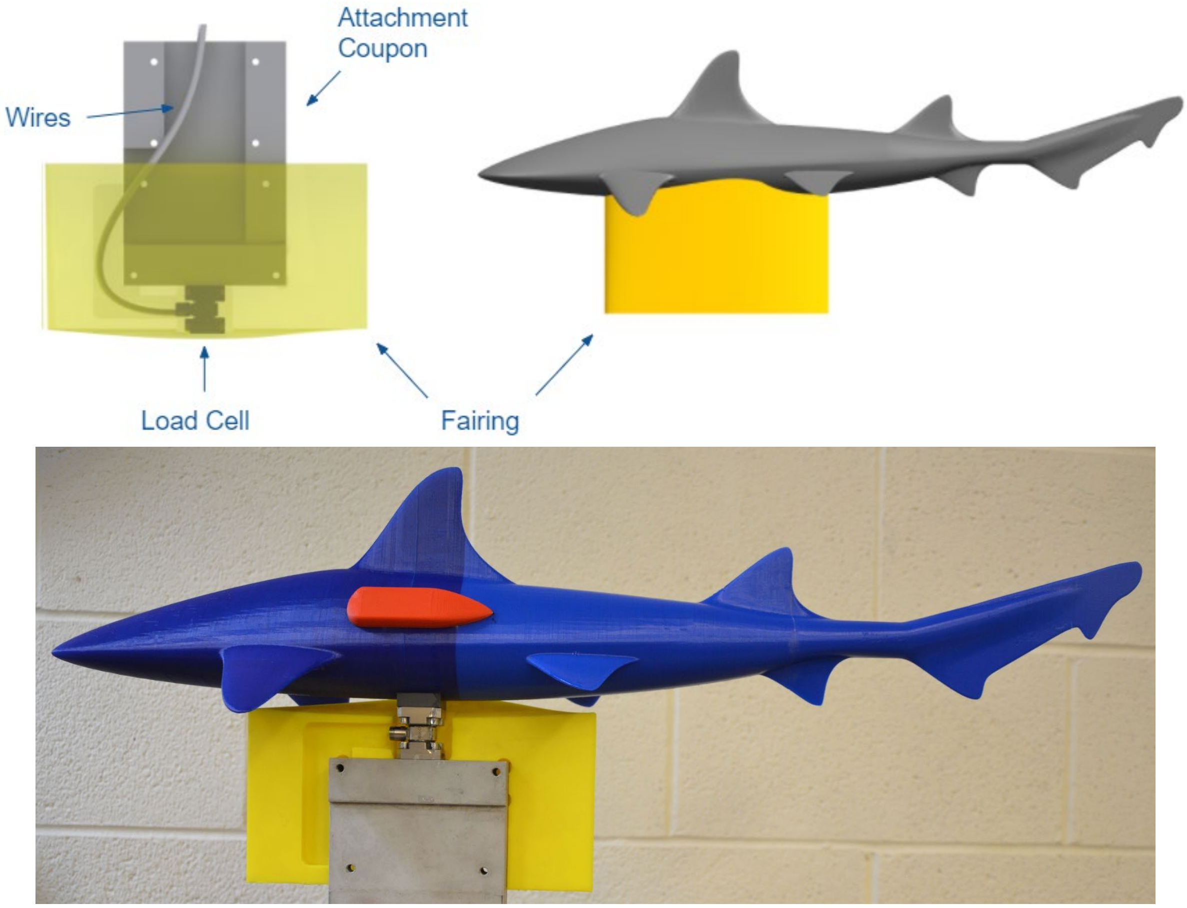


Figure 29: Attachment setup for tow tank testing of the shark. The shark was mounted upside down to minimize the impact of the fairing on the flow field around the tag. The visible gap in the bottom picture is intentional and allows for our design to be attached without interfering with load cell measurements.

Force measurements were taken using a Kistler Type 9317C load cell. Two runs were conducted in the tow tank for each velocity, and all data recording was done at 1000 Hz. For analysis, 25 seconds of measurements taken at steady speed were taken, yielding 25,000 data points for each run. This data includes time, position, and force measurements.

Due to the mechanical nature of the towing carriage, noise is introduced to the data that can artificially increase error. To negate this, a low pass filter is applied to the data. While a low cutoff value will smooth out data more, some unsteadiness in the force data should be expected because of the vortices being shed off of the shark. To estimate the value of this, the Strouhal number, *St*, is used, which is defined as follows:

$$St = \frac{fL}{u} \tag{1}$$

where *f* is shedding frequency, *L* is characteristic length, and *u* is flow velocity. This equation can be rearranged to calculate shedding frequency of a body with a known Strouhal number:

$$f = \frac{St \cdot u}{L} \tag{2}$$

For our setup, we estimate Strouhal based on a cylinder with a length twice the value of its diameter. In our flow regime, Strouhal number is rather insensitive to small increases or decreases in Reynolds number, and can be estimated to be 0.20 [19]. Flow velocity is 1.4, 1.9, or 2.4 m/s depending on the run. The characteristic length was chosen to be the length in the x-direction of the anal fin, which is the smallest on the dogfish. This fin is 57.6 mm in length. To err on the side of safety, the cutoff frequency was set to be double the calculated Strouhal number. For the given numbers here, this comes out to 9.72, 13.2, and 16.7 Hz for the 1.4, 1.9, and 2.4 m/s runs respectively.

To calculate velocity of the fluid, the position and time data recorded were used. The slope of the plot of position as a function of time was taken as the velocity for each run.

Limitations

There are several limitations that affect the results of the tow tank relative to our two stated purposes.

The first set of limitations are related to our first purpose of using tow tank results to validate CFD results. One potential limitation would be the difference in geometry due to the load cell and fairing geometry, but CFD runs were completed that included these geometries with corresponding mesh refinement around them. The following are outstanding limitations that can affect how well the tow tank and CFD results compare:

(1) While the CFD models the dogfish and tag as perfectly smooth, the dogfish and tag used in the tow tank have rather rough surfaces due to 3-D printing. Work is described later on in an effort to alleviate this.
(2) Interactions between the wake of the shark and a free surface were not modeled in CFD, but existed to some degree in the tow tank.

The second set of limitations are related to our second purpose of using the tow tank to test the attachment of our tagging system:

(1) The kinematics of the dogfish are not modeled. That is, the shark is modeled as moving perfectly straight as opposed to beating its tail from side-to-side or manipulating its fins to maneuver.

(2) The texture of the dogfish's skin is not matched.

(3) Any compliance of the surface of the dogfish is not taken into account. The surface of the 3-D printed model is rigid, while different parts of the dogfish have notable amounts of flexibility, such as the dorsal fin.

Results

Using the described methods, we were able to gather highly accurate data of drag as a function of velocity for the three different configurations (shark only, packages only, and full assembly). This data is shown in Figure 30.

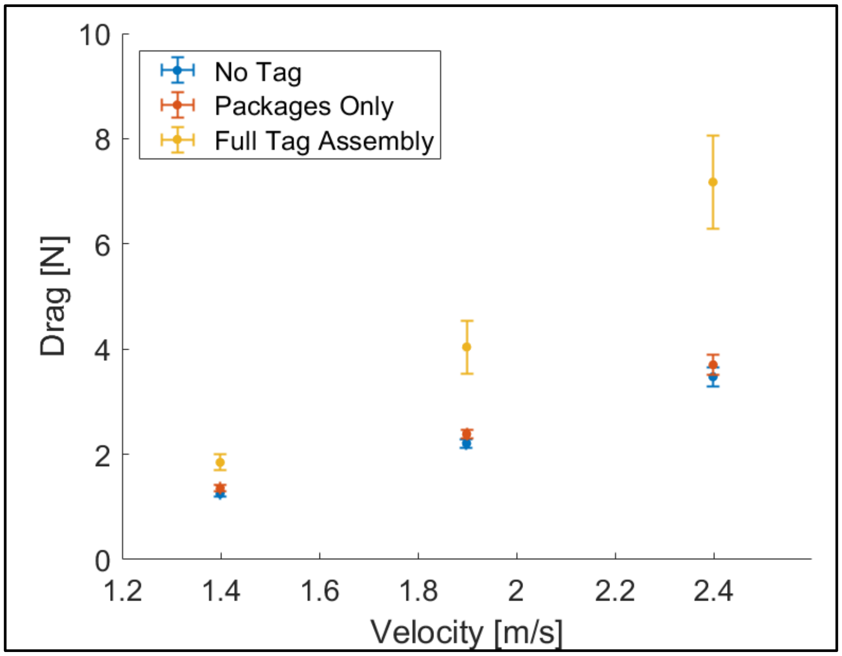


Figure 30: Drag as a function of velocity A plot of velocity vs the drag experienced by the shark and package both in the tow tank and in the CFD simulation.

While a comparison of these results to our CFD is discussed in the next section, there is one important observation related to how well the tag stayed attached to the shark. While at the two slower velocities, the tag stayed well-attached with no visible issues, the tag became visibly decoupled from the dogfish body at 2.4 m/s. Figure 31 shows this phenomenon, which we call “ballooning”. A possible cause of this is discussed in a later section.

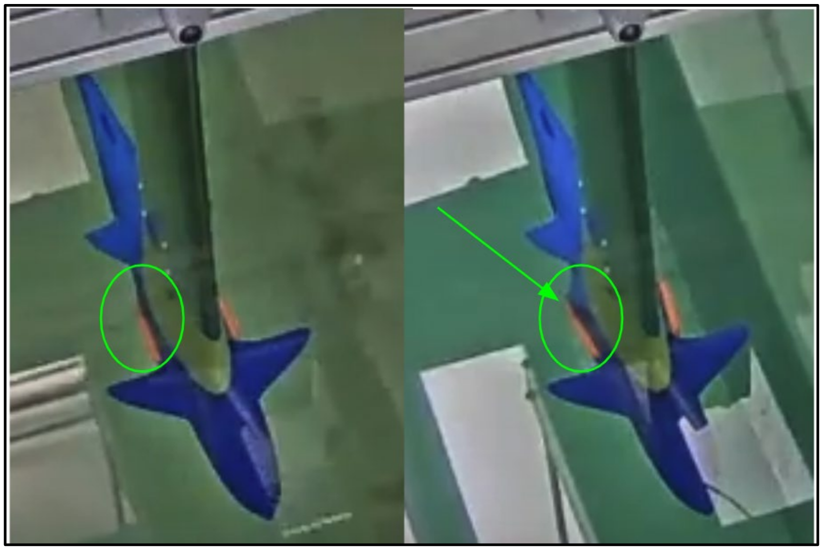


Figure 31: Ballooning effect that the tag exhibited at high velocities. Shown on the left is the tag in stagnant water, while the right shows the tag in flow of 2.4 m/s.

This ballooning effect is indicative that even at lower speeds, water is likely getting between the TheraBand® and the surface of the shark. This increase in wetted area would intuitively lead to an increase in viscous drag.

Comparison of CFD to Tow Tank Results

To make clear the differences that simply result from velocity increases as opposed to design variables, *CdA* is introduced. This is defined by the following equation:

$$CdA = \frac{2F_d}{\rho u^2} \tag{3}$$

where *CdA* is the drag coefficient multiplied by frontal area (design variables), F_D is drag, ρ is fluid density, and *u* is fluid velocity. Figure 32 shows *CdA* as a function of velocity from both the tow tank and CFD results. Runs of both the shark only and packages only are included, as the entire attachment system was not modeled in CFD. Several data points to compare are noted.

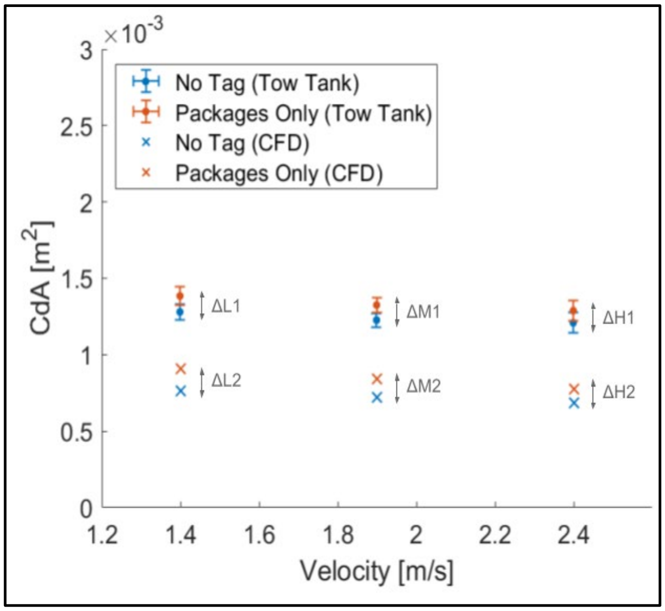


Figure 32: *CdA* as a function of velocity from both the tow tank and CFD results. No correction factors are applied.

The prediction of *CdA* increase from adding the tag shows good agreement with the tow tank results. To this we can compare differences denoted with the same letter (e.g., compare ΔL1 to ΔL2). This comparison shows that the predicted increase in *CdA* is higher than the measured increase by 26.4, 17.6, and 13.4% of the measured increase for 1.4, 1.9, and 2.4 m/s, respectively.

Conversely, there are notable discrepancies between the tow tank and CFD results with respect to absolute values of *CdA*. One of the limitations discussed for the tow tank related to the surface qualities of the 3-D printed model. In the following subsection, we attempt to control for this limitation.

Surface Roughness Correlation

It is known that the roughness of a surface has an effect on the viscous drag of a body moving through a fluid. Studies have been done to predict the effect of surface roughness of varying heights. From linearly interpolating between known viscous drag increases from a smooth surface to one of fine grit sandpaper, we can conclude that viscous drag increases 0.32% for each micron of roughness height [20].

Our 3-D printed model used a layer thickness of 0.15 mm. Using existing research and a similar linear interpolation, we can estimate the height of our roughness to be 66 μm [21]. This results in a viscous drag increase of 20.1%. Total drag including this correction factor is applied with the following equation:

$$F_{D,total} = F_{D,pressure} + C \cdot F_{D,viscous} \tag{4}$$

where $F_{D,\ total}$ is total drag, $F_{D,\ pressure}$ is pressure drag, C is the above correction factor of 0.201, and $F_{D,\ viscous}$ is viscous drag. A comparison of *CdA* after applying this correction factor can be seen is Figure 33.

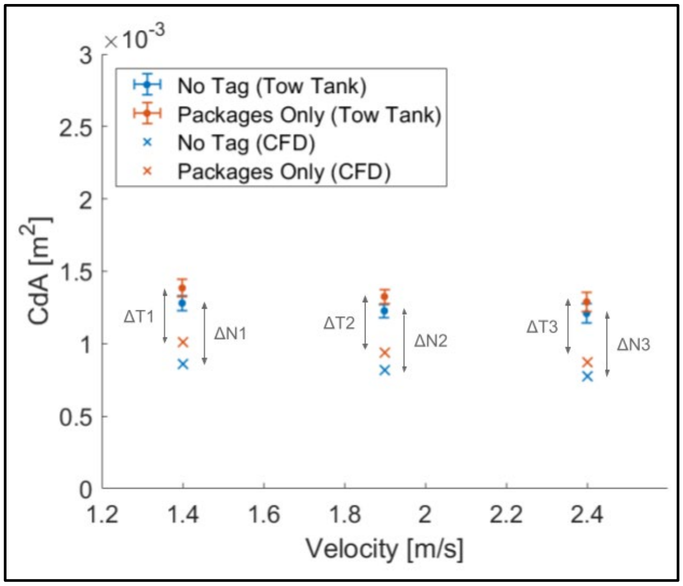


Figure 33: *CdA* as a function of velocity from both the tow tank and CFD results. The noted correction factor for viscous drag increase due to surface roughness is applied.

While this correction factor did bring the data points closer together, there is still a large difference. Differences marked with a “T” are for the tagged shark (with packages only), while “N” denotes a non-tagged dogfish. The values for the non-tagged dogfish show increases of 32.6, 33.6, and 36.0% from CFD results to tow tank results for 1.4, 1.9, and 2.4 m/s, respectively. The values for the dogfish with the packages attached show increases of 27.1, 29.1, and 32.5% from CFD results to tow tank results for 1.4, 1.9, and 2.4 m/s, respectively.

Testing on Live Dogfish

After the in-house testing of our solution discussed above, the final step was to test our solution on live dogfish. To do this, we shipped a final prototype to our stakeholders at WHOI where they have two live dogfish in captivity. The shark belt, along with two plastic packages attached to its sides, was then attached to a dogfish and it was observed for changes in natural behaviors, as well as for the performance of the belt.

From this testing, we gained valuable insight into the successes and failures of our prototyped design. One of the major successes was that the installation process of the package onto the animal was incredibly smooth, taking the researchers at WHOI much less than a minute in total as well as there being no need to remove the dogfish from the water. This was one of the aspects that our stakeholder who was responsible for the tagging was most excited about as he was able to limit animal distress upon installation as much as possible.

The second significant success of the testing was that, after a short period, the tagged animal fed in the tank. Feeding after being tagged is often an indication of the animal's comfort with the attachment as it is extremely common that the animal will not feed for weeks after attachment. Again, the fact that the animal did feed was another indication of success to the stakeholders at WHOI, one that they were very pleased with [22].

However, the animal seemed to exhibit some abnormal movements in the water after attaching the tag. One of these movements was one in which the animal turned and appeared to try and examine the attachment while stopping swimming, yielding a version of a barrel roll [22]. According to the stakeholder, this was not a behavior they had observed before. This change in behavior was an indication that the attachment was not going unnoticed by the animal and was in fact inhibiting normal behavior.

The second and most significant issue we saw, as seen below in Figure 34, was that after a short time, the entire attachment slid back on the shark. This caused the front of the band to collide with and put tension against the front of the dorsal fin.

Figure 34: Final Prototype on the dogfish at WHOI. (Top) The whole tag slid back on the body and put stress on the front of the first dorsal fin. (Bottom) The tag also decoupled from the dogfish body, multiple causes are possible [22].

It is evident in Figure 34 that the attachment has slid back and, in the bottom picture, there is significant ballooning of the back of the band. This ballooning, similar to the ballooning seen in the tow tank, is likely causing a significant increase in drag. Furthermore, the fact that the tag slid back against the fin will likely cause significant irritation to the soft, fleshy, dorsal fin of the animal.

Detailed Design Solution

The final design solution, shown in Figure 35, includes the TheraBand® Shark Belt concept with the clasp closure mechanism and two hydrodynamically favorable syntactic foam electronics packages.

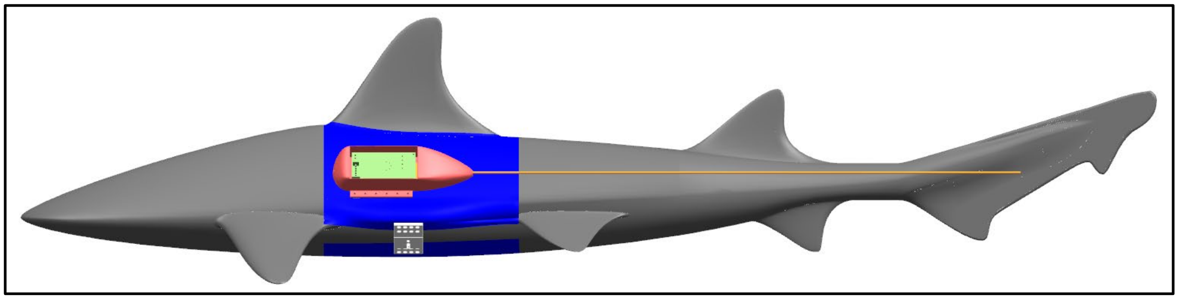


Figure 35: Side view of modeled final design on the virtual shark. Attachment is centered around the dorsal fin and attaches using an elastic band and a small clasp with a Nichrome wire threaded through the clasp.

The tag design is centered on the first dorsal fin with a package on either side of the body which provides symmetry and a near-even weight distribution on the animal. The final design is different from the final prototype in four key areas:

(1) The TheraBand® strap is closed with the clasp and a Nichrome wire instead of Velcro®
(2) The electronics packages are made of CNC machined syntactic foam
(3) The electronics packages include flanges which can be used to sew the parts into the belt material instead of gluing them
(4) The electronics packages have unique cavities to adequately fit each set of hardware

These changes were made based on observations from testing the final prototype and are intended to continue making progress toward achieving all requirements and specifications.

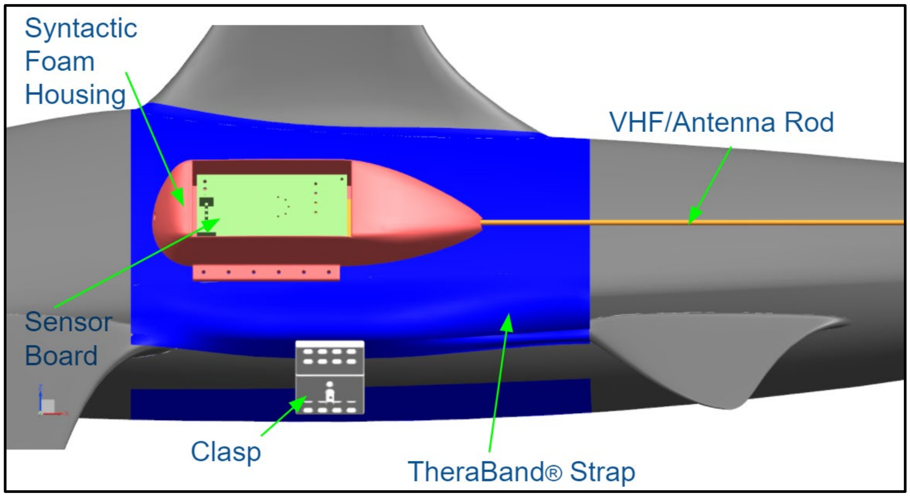


Figure 36: Side view of modeled final design on the virtual shark with key components labeled. The package housing the battery is located on the opposite side of the shark in a similar location.

TheraBand® Strap

The final design uses a similar strap concept as the final prototype. The TheraBand® material, an elastic material designed for physical therapy and exercise, is flexible and can easily form to the curvature of the dogfish body while minimizing unnecessary friction with the skin surface. The wider strap also provides a large area to secure the packages. Secured packages will reduce the noise in the data by ensuring that the tag only moves with the animal. The strap is currently sized for the dogfish at WHOI, but it would be simple to develop multiple strap sizes to accommodate a wider range of dogfish.

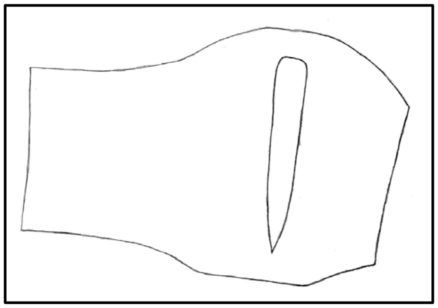


Figure 37: Template of TheraBand® strap for final design. Template is made to fit 64 cm dogfish when the image is scaled to dimensions 8.5” x 11”.

Electronics Packages

The electronics packages, shown in red in Figures 35 and 36 and grey in Figure 38, are designed to fit the iTag sensor board, a 750 mAh battery, and the VHF radio and antenna. The packages are intended to be machined out of syntactic foam, a low-density material that helps the entire system float to the surface of the water after detachment. The final design includes flanges on the sides of the two packages so they can be sewn directly into the strap. The flanges were added after observing how easily the packages could fall off the strap on the final prototype when they were just glued on. Sewing the packages into the strap offers added security and ensures that the package will remain attached to the harness throughout the 72-hour deployment.

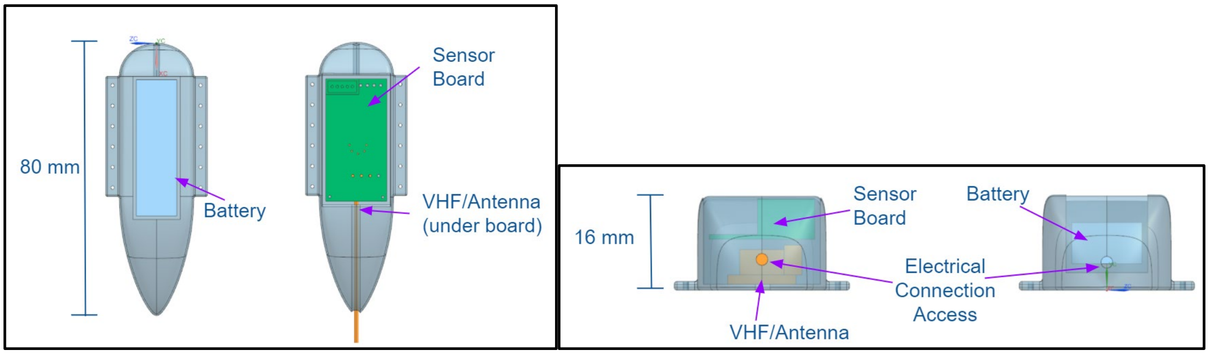


Figure 38: Syntactic foam packages with electronics in place. (Left) Top View of packages with electronics labeled. (Right) Front view of packages with electronics and holes for electrical wire to connect the packages labeled.

As shown in Figure 38, the electronics are split across the two packages to evenly distribute weight across the animal and ensure the antenna points out of the water upon release. The holes in the packages are designed to fit each hardware configuration so, even though the exterior shapes of the packages are identical, the interior cutouts are different. The electronics will be protected from water by filling the holes with epoxy after the hardware is installed, a technique which was also used in the iTag design.

The right image of Figure 38 highlights the two small holes in the front of each package which allow for a wired connection between the battery and the sensor board. This technique is uncommon and remains untested. While we believe this may work quite well, it could also be a point of failure if the wire breaks under the motion of the shark. This potential failure was discussed in the Risk Assessment on page 29.

One of the more significant differences between this design and the iTag design is the two-package approach. The iTag has one piece that rests along the top of the squid, but this design does not work as well for dogfish anatomy. The dogfish tag design enables the package to have a lower profile and ensures that there is not an uneven distribution of drag on the animal. If there was a single package on one side of the animal, it could inhibit the animal from swimming normally.

Clasp

The strap closure method proposed here is loosely based on the attachment method used for the iTag. The iTag included a small clip between the base and the package that was secured together with a Nichrome wire. The wire breaks under strong electrical currents which allows the package to stay attached to the base for 72 hours and release when a current passes through the wire. The success of this approach in the iTag encouraged us to explore similar attachment and release mechanisms.

The clasp design, shown in Figure 39, serves as the point of closure between the two sides of the TheraBand® strap. The two pieces of the clasp will be sewn into the TheraBand® through the holes labeled C and B in Figure 39. The two sides of this device interlock with each other, allowing for a Nichrome wire to run through hole A. This wire will originate in the tag itself, connected to the battery, and run from the underside of the clasp up through hole A and then ultimately wrap around the strut, labeled as D.

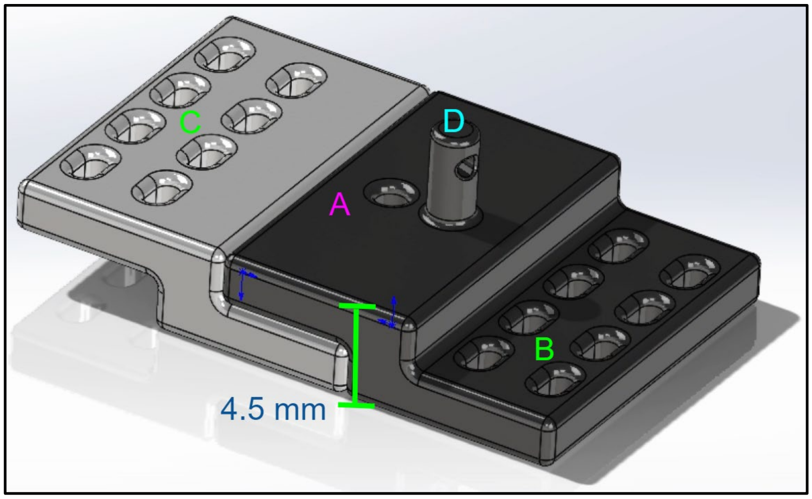


Figure 39: The detachment method is built around a clasp system where two halves are connected using a Nichrome wire through hole A. The two halves are sewn to either side of the attachment strap using the sets of holes B and C.

When a current is run through the wire, the section exposed to the salt water will burn and break. The time to break is directly related to the length of exposed wire; the more wire exposed, the more time it will take for that section to break. Thus, only a small length of wire is exposed to the water; most of the wire will be insulated from the sea water with petroleum grease, a method used with the squid attachment [5]. This small length will be the length of wire in hole A, a length of approximately 4.5 mm.

The primary goal of this method was to be as small and unobtrusive as possible because drag increases with every addition of material. To minimize clasp size, the height of the combined attachment (both sides connected as shown in Figure 39) is 8.5 mm to the top of the strut. The width of the plates, not including the strut, is only 4.5 mm.

This closure mechanism was designed based on observations of the final prototype Velcro® closure method. The Velcro® was convenient for easy attachment, removal, and adjustment of the tag and functioned quite well during testing. However, Velcro® would not work for autonomous detachment of a tag deployed in the wild. This clasp design builds off of the success of the Velcro® closure and the implementation of Nichrome wire from the iTag.

Buoyancy Analysis

The need for buoyancy analysis for the proposed design stems from the requirement related to package retrieval. The portion of the tag that will be retrieved must float to the surface of the ocean water with the antenna protruding from the surface so it can be located by the researchers. Throughout the optimization process, the water weight and density of the overall design were calculated to ensure the design meets this requirement. The density of the retrieved part of the tag must be less than 1.02 g/cm^3 and the region surrounding the antenna rod must be the least dense of the package to ensure that the antenna points out of the surface of the water at an angle of at least 20 degrees above the horizon.

The mass and volume of the electronics components were measured to calculate their density, and measurement tools within CAD were used to determine the volume and mass of the package designs using known density of the shallow foam material. The water weight of each component was calculated using Equation 5,

$$m_{H_2 0} = V \cdot \rho - m_{air} \tag{5}$$

where m_{H20} is the water weight (g), V is the volume (g/cm^3), ρ is the density of ocean water (1.02 g/cm^3), and m_{air} is the component weight in air (g). A positive water weight indicates a positively buoyant component while a negative water weight indicates negative buoyancy. The water weights of the electronics components are shown in Table 6.

Table 6: Electronics components all negatively buoyant

Component	Air Weight (g)	Volume (cubic cm)	Density (g/cubic cm) [Calculated]	Water Weight (g)
750 mah Battery	7.63	3.876	1.967	-3.672
VHF and Antenna	2.89	0.950	3.041	-1.921
Pressure Chimney	0.14	0.082	1.709	-0.056
Sensor Board	3.67	1.148	3.197	-2.499
Total			9.914	-8.148

As indicated in Table 6, all electronics components, which are the main components not under our internal design control, are negatively buoyant. Thus, the proposed design solution must provide sufficient buoyant force to overcome the weight of the electronics. We intended to use the same foam and epoxy already in use for the iTag to maintain consistency across tags so the density of the package materials were known. The water weight of our designed components were calculated using the same procedure, and the results are listed in Table 7.

Table 7: Designed components positively buoyant and account for electronics weight

Component	Air Weight (g)	Volume (cubic cm)	Density (g/cubic cm) [Known]	Water Weight (g)
Housing (board + VHF/ant pack)	1.709	9.965	0.171	8.455
Epoxy (board + VHF/ant pack)	9.035	9.220	0.980	0.369
Housing (battery pack)	2.386	13.958	0.171	11.851
Epoxy (battery pack)	7.374	7.524	0.980	0.301
Strap	4.720	4.995	0.945	0.375
Clasp	0.760	0.655	1.160	-0.092
Total				21.259

Since the total positive buoyant force of the designed components exceeds the negative buoyant force of the electronics components, the entire package will float in ocean water. Furthermore, the package which includes the antenna is more buoyant than the other package, so the antenna will protrude from the surface of the water. The entire tag, as it is currently designed, is very positively buoyant which may disrupt the typical behavior of the dogfish. The recommended design change would be to replace some of the package housing material with a denser plastic instead of using foam for the entire housing part. This will allow the tag to be closer to neutrally buoyant and limit the effects of the tag on dogfish behavior.

Final buoyancy determinations will likely be an empirical task since the weight of solder, thread, and epoxy may vary across iterations of the tag. However, replicating this analysis for verification is simple and can be completed quickly for each tag.

Verification

Multiple methods were used to verify our design solution with the proposed requirements and specifications. Some requirements were unable to be tested due to the time constraints of the project, but others were studied through written observations from our sponsor during testing on the WHOI dogfish, engineering calculations, and the success of previous, similar projects. The verification status and limitations of each of the requirements are shown in Table 8, another representation of Table 1.

Key

🟩	Design meets requirement
🟨	Design partially meets requirement
🟥	Design does not meet requirement
🟦	Requirement cannot be verified in current design state

Table 8: Verification status of requirements and specifications. Status colors correspond to the key above.

Status	Requirement	Specification
🟩	Attaches existing sensor board, battery, and radio antenna to dogfish	Secure 4.70 x 2.21 x 1.60 cm box, with 0.127 cm diameter rod of length 34.01 cm attached to smallest face, centered along 2.21 cm dimension, located at a height of 0.08 cm [4] to dogfish of length ≤ 1.5 m [8]
🟥	Is non-invasive	No significant change (≤ 5%) in behavior quantified by: - Tailbeat frequency [10] - Roll of animal [11] Ensure that animals interacting with the tagged dogfish have no behavior change, i.e. do not perceive tagged dogfish as weakened or injured [11]
🟨	Is durable	Withstand depth > 200 meters; Withstand pressure > 2120 kPa [8] [12]; Withstand > 10 deployments Secures to shark ≥ 72 hours at speeds ≤ 1.9 m/s & accelerations ≤ 31 m/s2 [13]
🟩	Allows for sensor package retrieval; Antenna must protrude out of package and point out of the surface of the water [10]	Has density of combined sensor and package upon release < 1.020 g/cm3 [14] Antenna oriented at least 20 degrees above the horizon when tag is on the surface
🟦	Does not disrupt sensor measurements	Has total error ≤ 5% [11]
🟩	Does not add to ocean pollution	Releases < 4.5 g of long-term material per use [4]
🟩	Has affordable cost	Costs < $100 / tag [11]

Attaches to Dogfish and Is Non-Invasive

Based on the success of our prototype securing to the WHOI dogfish during testing, and the designed dimensions of the package housing, we are confident that the proposed design solution meets the attachment requirement. The design was well-secured to the dogfish while swimming, but shortly after the tag was put on, it interfered with the dorsal fin, and prompted some unusual swimming behavior [22]. The influence on behavioral change was not quantified, but we do not believe that this design meets the tagged individual behavior change specification of non-invasive requirement. The specification related to other animal's interactions with the tagged individual is difficult to verify due to the current lack of information about fine-scale dogfish behavior. It should be studied further and investigated in future work.

Is Durable

The durability specifications can be verified through long duration testing of a design on live animals in a controlled environment. We anticipate that our design will meet the depth and pressure specifications because this solution uses the same electronics components as the iTag and the iTag has proven success in similar conditions. We were also unable to verify the deployment specification because the proposed solution did not meet the non-invasive requirements and testing for a longer duration could be harmful to the animal subjects. This specification could be verified in the future by deploying a non-invasive solution in a controlled environment for up to 72 hours ten times and examining the damage to the hardware.

Allows for Sensor Package Retrieval

The retrieval specifications are largely dependent on the detachment method and the density of each component. The detachment method has been designed, but not prototyped with the full design so we cannot verify that it works as expected, simply due to the time constraints of the project. Verification of the combined density and ensuring the antenna would protrude out of the surface of the water upon release was determined through the buoyancy analysis discussed on page 43. The calculated density of the entire package is 0.56 g/cm^3 which is less than the specification to float of a density of 1.02 g/cm^3.

Does Not Disrupt Sensor Measurements

Evaluation of the impact of the tag design on sensor measurements is possible but designing and executing the experiment to verify the specification was not realistic in the time frame of this project. Thus, this specification is not verified.

Limits Ocean Pollution

The iTag deposited approximately 4.5 g of plastic into the ocean for each tag that was deployed, and proposed solution meets the specification that less material is left in the dogfish environment. The design solution would not leave any material behind, and the entire tag could hypothetically be deployed multiple times to reduce material demands. Based on the design intent, we believe that the design solution meets this requirement.

Has Affordable Cost

The total design cost of this project is well below $100 and multiple prototypes were developed so each individual tag will be significantly below the cost requirement set here. The design also uses materials readily available to our sponsors to reduce additional costs of future development.

Discussion and Recommendations

The final design proposed in this report is the culmination of approximately three months of work. Throughout this effort, we have explored novel marine tagging methods, established an effective process to run CFD on dogfish models, and verified the CFD with tow tank experiments. These achievements can be used throughout the remainder of the design process for the dogfish tag and future tag designs. The dogfish tag does not currently meet all of the requirements, but it can be deployed in controlled environments, and with a few changes, could be deployed in the wild.

Strengths of Proposed Design

The Shark Belt design makes very good progress toward achieving a novel non-invasive dogfish tag and provides a strong starting point for future development. One of the strengths of the design is the quick and easy attachment to the animal. In live testing, attachment took less than one minute and was simple and straightforward for the researchers deploying the tag. The researchers were able to attach the band while the dogfish was still mostly submerged, which induced less stress than fully removing the animal from the water.

Another strength of the dogfish tag is the redesigned packages. The new packages cause a small amount of drag increase, verified both in CFD and in the tow tank testing. The transition away from a single larger package to two smaller packages reduces tag-induced impacts on the roll of the animal. Having two smaller packages also makes a wider variety of attachment regions available which could be useful in tag applications for other small marine animals.

Limitations of Proposed Design

Though the design could be useful in controlled environment experiments, it does have some significant drawbacks. During testing on live dogfish at WHOI, the Shark Belt design caused some visible discomfort to the animal. The tagged individual expressed some unusual behavior that the researchers observed, including the barrel roll described previously.

The attachment mechanism also slid back against the individual’s dorsal fin a short time after deployment. This additional stress on the dorsal fin may cause the animal distress and thus will impact normal behavior and may injure the animal. Furthermore, the elastic band was under high tension when it slid back on the dorsal fin which may fatigue the material and cause it to break during deployment. Strap failure would significantly impact the integrity of the data and potentially the well-being of the animal.

Finally, the current design does not include a fully tested or validated detachment mechanism so it could not be implemented in an uncontrolled environment.

Comparison of CFD to Tow Tank Conclusions

At the nominal dogfish speed of 1.9 m/s, the predicted increase in drag from adding the tag was within 18% between CFD predictions and tow tank measurements. For steady-state RANS CFD, this difference is comparable to values seen in industry [23]. Therefore, we have a reasonable level of confidence in the reported results of both the location testing and shape optimization.

Recommended Design Changes

Based on the limitations of the design and the results from experimental tests, we have conceptually explored alternative design choices which would improve the performance of the dogfish tag. These recommendations have not been verified but could be used in future work.

Band Material

The TheraBand® material used in prototyping was rated to reach 100% elongation under 25.8 N of force. Due to the ballooning of the design prototype in testing at high speeds, and the slippage on the live dogfish in testing, we recommend using a stiffer resistance band material. We believe that a band rated to reach 100% elongation at 45.4 N, which comes in Silver from the TheraBand® brand, may be better suited for this design. We recommend this over a completely different material because we found its thin profile to be advantageous in minimizing invasiveness while still allowing for tag placement near the first dorsal fin. The rubbery texture of the material also increases static friction with the shark skin which helps to prevent slippage. Due to the lack of existing knowledge on this species we do not know how this material could affect their skin over a long period of time, so it may be best to use a thermoplastic elastomer version of the resistance band that is latex-free, due to skin irritations caused by latex in other species.

Electronics Packages

The positive buoyant force of the package housing greatly exceeded the negative buoyant force of the electronics hardware, resulting in a total water weight of approximately positive 13 g. The ideal tag would be neutrally buoyant while it is attached to the animal and deposit material, so it is positively buoyant upon release. To approach neutral buoyancy for the dogfish tag, we recommend manufacturing housing that is partially constructed out of a denser 3-D printed plastic and partially foam. The proportion of plastic to foam should be determined once the attachment design is finalized, but we believe the overall shape of the electronics packages will be simple to maintain. Additionally, for plans to continue reducing the drag of the entire tag, we recommend focusing on hydrodynamic optimization of the attachment mechanism rather than the electronics packages, because the former was the cause of the majority of measured drag in the tow tank, while the latter was the focus of the present work.

Band Closure

The first key step in working with the closure design is to test the mechanics of the clasp with the Nichrome wire for secure closure and smooth release. We also believe that implementing a small counterweight that is held between the clasp plates during attachment and released with the tag could benefit the overall buoyancy of the tag. Including the counterweight would help the tag reach neutral buoyancy during attachment and it would separate from the tag during release so that the tag alone would be positively buoyant and float to the surface for retrieval.

Ethics Statement

It is important to consider the ethics behind the need for a non-invasive design. The humane care and use of animals for scientific purposes is guided by the ethical framework of the three R's: replacement, reduction, and refinement, as shown and briefly defined in Figure 40 [24].

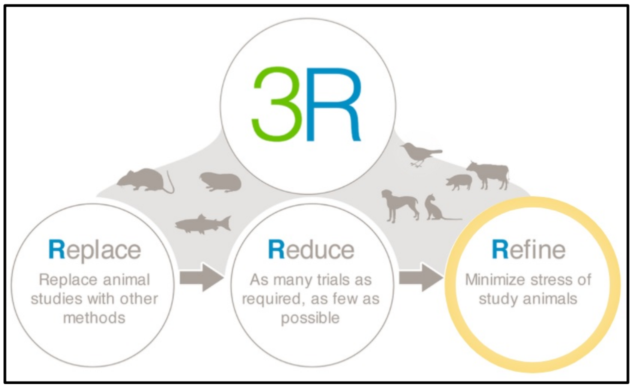


Figure 40: The ethical framework of the three R's: Replacement, Reduction, and Refinement. [25]

Initially, we believed that our project would primarily focus on the third R, refinement. However, as we continued moving forward it became clear that we must focus on all three, replacement, reduction, and refinement, to protect the animals we are working with. To replace the dogfish with other testing methods, we 3-D printed an entire model of a dogfish. Using the dogfish model avoided causing unnecessary stress to the live dogfish while still enabling preliminary testing for prototypes. This also allowed us to delay testing prototypes on live animals until we have high confidence in the success of the tag.

Finally, focusing on refinement, emphasis is placed on the design to be non-invasive to ensure that the stress experienced by the dogfish is minimized. In addition, evidence suggests that pain and suffering can alter an animal's typical habits and behaviors [26]. For that reason, it is important for the design to be non-invasive to ensure that the data collected is accurate and representative of the normal habits and behaviors of dogfish in their natural habitat.

Conclusion

The smooth dogfish is currently classified as a “near-threatened” species due to vulnerabilities that lead to overfishing. There is currently minimal research on the fine-scale behavior of the species, which poses challenges when looking for ways to protect them. Researchers at the Woods Hole Oceanographic Institution hope to learn more about the species by attaching a biologging tag while the dogfish are in local coastal waters. To conduct this study, they have tasked us with developing a non-invasive attachment method to secure a biologging tag for up to 72 hours. Our final design was successfully attached to the model dogfish and tested on live dogfish at WHOI. From this testing we were able to verify drag measurements from CFD analysis and the concept’s functionality. The final prototype includes an attachment belt, a belt closure mechanism, and a pair of redesigned electronics packages. While our design is not currently ready for deployment, we believe that with limited redesign it can be ready for deployment by the researchers this summer.

Key Stakeholders and Project Team

Sponsor Background

The sponsors of our project are Dr. Aran Mooney and Ph.D. student Seth Cones. Dr. Aran Mooney received a Ph.D. in zoology with an emphasis on marine biology from the University of Hawaii at Manoa in 2008. He now leads the Sensory Ecology and Bioacoustics Lab at WHOI. His main area of research focuses on how animals detect the world around them, including how they hear, find food, communicate, navigate, avoid predators, and how humans impact an animal's sensory biology [27]. Seth Cones is currently pursuing a Ph.D. in the MIT-WHOI Joint Program in Oceanography/Applied Ocean Science & Engineering [28]. His research focuses on squid movement behavior, environmental influences and energetics. He has previous experience in biologging squid with the same electronics that we used in our design.

Team Background

Sarah Armbruster is a 4th year Mechanical Engineering student at the University of Michigan. She is interested in the development of sensors and systems for advancing vehicle technology to create safer and more efficient transportation. She currently spends most of her free time fostering and training puppies to become service dogs.

Connor Boerman is a 3rd year Mechanical Engineering student at the University of Michigan. From his time on the Michigan Solar Car Team, he has developed an interest in using aerodynamic design optimization to improve the efficiency of vehicles, both on the ground and in the air. In his free time, he enjoys traveling, hiking, and quality time with friends.

Tobias (Toby) Cormack is a 4th year student at University of Michigan majoring in Mechanical Engineering and Computer Science set to graduate in 2022. He is interested in the intersection of mechanical systems and software design. Outside of school, he likes to rock climb and ski and is looking forward to spending time with people not over Zoom after COVID.

Cameron LaVallee is a 5th year Mechanical Engineering student at the University of Michigan participating in a dual-degree program with Albion College where he will receive a degree in Applied Physics with a minor in Mathematics. He is interested in the design and development of mechanical systems, as well as clean energy systems. In his free time, he enjoys traveling, hiking, and adventuring with his two dogs.

Leah Paborsky is a 4th year Mechanical Engineering student with a minor in Space Sciences and Engineering and plans to pursue a master's degree in Aerospace Engineering at the University of Colorado at Boulder in the Fall of 2021. She is interested in a career that combines science and engineering principles through sensor and payload design. In her free time, she enjoys baking, running, and spending time outside.

Acknowledgements

This project was made possible with enthusiastic support from several key individuals. We would like to thank Professor Alex Shorter of the University of Michigan Mechanical Engineering department for his insightful discussions and guidance throughout this project. We would also like to express our gratitude to the Sensory Ecology and Bioacoustics Lab at WHOI for sponsoring this project, especially Seth Cones and Dr. T Aran Mooney for their direct support and engagement. We are grateful to the University of Michigan Marine Hydrodynamics Laboratory for their support in preparation for and execution of the tow tank testing. We would also like to thank Dr. Victor Petrov of the Nuclear Engineering and Radiological Sciences for use of the ECMF-Lab's high-power computing cluster, which allowed the quantity and quality of CFD results produced. We also deeply appreciate the expertise and support of the University of Michigan Mechanical Engineering student machine shop for their help throughout the prototype manufacturing process.

Information Sources

[1] Bograd, SJ, et al. “Biologging Technologies: New Tools for Conservation. Introduction.” *Endangered Species Research*, vol. 10, 2010, pp. 1–7., doi:10.3354/esr00269.

[2] “Electronic Tagging of Marine Animals,” Census of Marine Life, Accessed on February 3, 2021, http://www.coml.org/comlfiles/scor/SCOR-tagging.pdf

[3] Broadbent, H., 2012, “A CTD Biotag for Mid-Size Marine Predators,” Scholar Commons, Accessed on February 3, 2021, https://core.ac.uk/download/pdf/71951826.pdf

[4] Personal Communications with Seth Cones and Aran Mooney (Sponsors), January 28, 2021.

[5] Mooney, T.A., Katija, K., Shorter, K.A. et al, “ITAG: an eco-sensor for fine-scale behavioral measurements of soft-bodied marine invertebrates,” Animal Biotelemetry 3, 31 (2015). https://doi.org/10.1186/s40317-015-0076-1

[6] Bigelow, H. B., Schroeder, W. C., “Fishes of the Gulf of Maine,” United States Government Printing Office, Bulletin 74, vol. 53, p 244, http://gma.org/fogm/Mustelus_canis.htm

[7] “Smooth Dogfishes,” Marine Bio, Accessed on February 3, 2021, https://marinebio.org/species/smooth-dogfishes/mustelus-canis/

[8] Bester, C., “Discover Fishes: Mustelus canis,” Florida Museum, accessed January 29, 2021, https://www.floridamuseum.ufl.edu/discover-fish/species-profiles/mustelus-canis/

[9] Kelly, Hazel. “Save the Sharks!” *The California State University*, 28 June 2018, www2.calstate.edu/csu-system/news/Pages/Save-The-Sharks.aspx

[10] Fontes, J., Baeyaert, J., Prieto, R., Graca, G., Afonso, P., (2018), “New non-invasive methods for short-term electronic tagging of pelagic sharks and rays,” Mar Biol 165, 34 (2018). https://doi-org.proxy.lib.umich.edu/10.1007/s00227-018-3289-z

[11] Personal Communications with Seth Cones (Sponsor), February 2, 2021.

[12] “Water Pressures at Ocean Depths,” NOAA, Accessed on January 31, 2021, https://www.pmel.noaa.gov/eoi/nemo1998/education/pressure.html

[13] Domenici, P., Standen, E. M., Levine, R. P., 2004, “Escape manoeuvres in the spiny dogfish (Squalus acanthias),” Journal of Experimental Biology, 207, pp. 2339-2349.

[14] Pawlowicz, R. (2013) Key Physical Variables in the Ocean: Temperature, Salinity, and Density. Nature Education Knowledge 4(4):13

[15] Kyte, A., Pass, C., Pemberton, R., Sharman, M. and McKnight, J.C. (2019), A computational fluid dynamics (CFD) based method for assessing the hydrodynamic impact of animal borne data loggers on host marine mammals. Mar. Mam. Sci., 35: 364-394. https://doi-org.proxy.lib.umich.edu/10.1111/mms.12540.

[16] Aranake, A., Lakshminarayan, V., and Duraisamy, K. (2012), Assessment of Transition Model and CFD Methodology for Wind Turbine Flows. 42nd AIAA Fluid Dynamics Conference and Exhibit. https://arc-aiaa-org.proxy.lib.umich.edu/doi/pdf/10.2514/6.2012-2720.

[17] [jousefm]. (2020, November 6). *What is y+ (yplus)?* [Online Forum Post] SimScale. https://www.simscale.com/forum/t/what-is-y-yplus/82394

[18] Cherry, G. (April 20, 2017). U-M's one-of-a-kind hydrodynamics lab to get fresh look, new name. The Michigan Engineer News Center. https://news.engin.umich.edu/2017/04/hydrodynamics-lab-fresh-look/

[19] Choi and Kwon. 2000. Determination of Strouhal Number Based on the Aerodynamic Behavior of Rectangular Cylinders. Wind and Structures An International Journal, 3. https://www.researchgate.net/publication/239938324_Determination_of_the_Strouhal_Number_Based_on_the_Aerodynamic_Behavior_of_Rectangular_Cylinders

[20] Shapiro, T. 2004. "The Effect of Surface Roughness on Hydrodynamic Drag and Turbulence". https://apps.dtic.mil/sti/pdfs/ADA424978.pdf

[21] E. R. Biglete *et al.*, "Surface Roughness Analysis of 3D Printed Parts Using Response Surface Modeling," *2020 11th IEEE Control and System Graduate Research Colloquium (ICSGRC)*, 2020, pp. 191-196, doi: 10.1109/ICSGRC49013.2020.9232561. https://ieeexplore-ieee-org.proxy.lib.umich.edu/document/9232561

[22] Personal Communications with Seth Cones (Sponsor), April 12, 2021.

[23] Personal Communications with Jason Bundoff (MHL), April 8, 2021.

[24] "The 3Rs." *National Centre for the Replacement, Refinement, & Reduction of Animals in Research*, nc3rs.org.uk/the-3rs.

[25] Macri, Audra, and JH Bloomberg School of Public Health. "Research and Practice in Replacement Reduction and Refinement." *Johns Hopkins Bloomberg School of Public Health*, 21 Apr. 2020, ehe.jhu.edu/graduate/masters-programs/master-of-science-in-toxicology-for-human-risk-assessment/research-and-practice-in-risk-assessment.html.

[26] Bennett, Rhett, Bruce R. Ellender, Tuuli Mäkinen, Tshoanelo Miya, Paula Pattrick, Ryan J. Wasserman, Darragh J. Woodford, & Olaf L.F. Weyl. "Ethical considerations for field research on fishes." *Koedoe* [Online], 58.1 (2016). https://doi.org/10.4102/koedoe.v58i1.1353

[27] “Staff Profile: Aran Mooney” WHOI, accessed January 28, 2021, https://www.whoi.edu/profile/amooney/

[28] “Staff Profile: Seth Cones,” WHOI, accessed January 28, 2021 https://www.whoi.edu/profile/scones/

[29] Nassar, J.M., Khan, S.M., Velling, S.J. et al, “Compliant lightweight non-invasive standalone “Marine Skin” tagging system,” npj Flex Electron 2, 13 (2018), https://doi.org/10.1038/s41528-018-0025-1

Appendix 1: Concept Development

We used a variety of idea generation tools to build off of these initial ideas and iterate through new designs. Through this process, we arrived at two concepts to prototype and evaluate for further development.

Hoop Around Body

The “hoop around body” concept was initially just a generic method to secure the tag using the streamlined nature of the dogfish body. The first continuation of that idea consisted of two bands around the middle of the shark body. These bands would both be between the first and second dorsal fins with the biologging tag secured between the two bands. A counterweight was initially envisioned to detach from the hoop design when the package is ready to be collected. This would allow for collection of the sensor package and straps, as they could float to the surface. The researchers would then be able to reuse the harness, only needing to replace the counterweight.

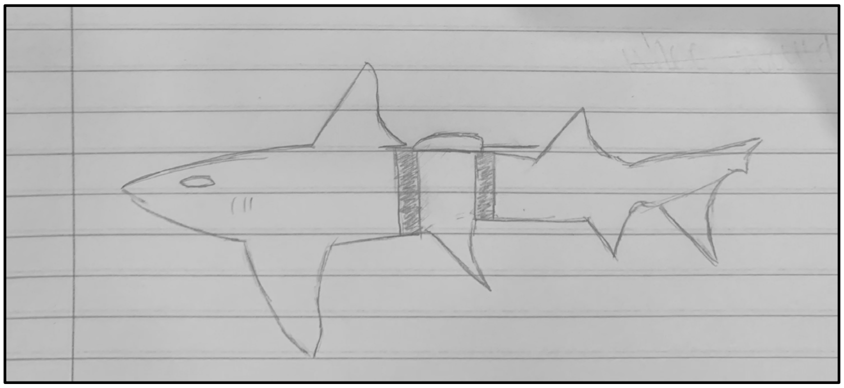


Figure A1.1: Hoop Around Body concept sketch consisting of two bands around the dogfish with the sensor package secured on either end by the bands.

We used idea generation tools to develop this design and investigate the feasibility of attaching a tag around the body of the dogfish. We used Design Heuristics to help iterate the concept and develop it further. After considering these Design Heuristics, we chose to add a natural feature as the counterweight. Doing so prevents the deposition of any unnatural material into the ocean when the tag is released from the dogfish. This tool also prompted us to consider changing the design of the geometry of the biologging tag so that it would wrap around the body of the dogfish. This would reduce the resistance to the dogfish when they flex their body to swim and provide more accurate data regarding the movements of the dogfish. The modified tag design also reduces material, because only one band around the body is needed to mount this tag as opposed to two.

Body Clip

When developing the body clip for the shark, morphological analysis was used to break down the device into numerous types of functionality, and then individually designing for each functionality, as shown in Figure A1.2.

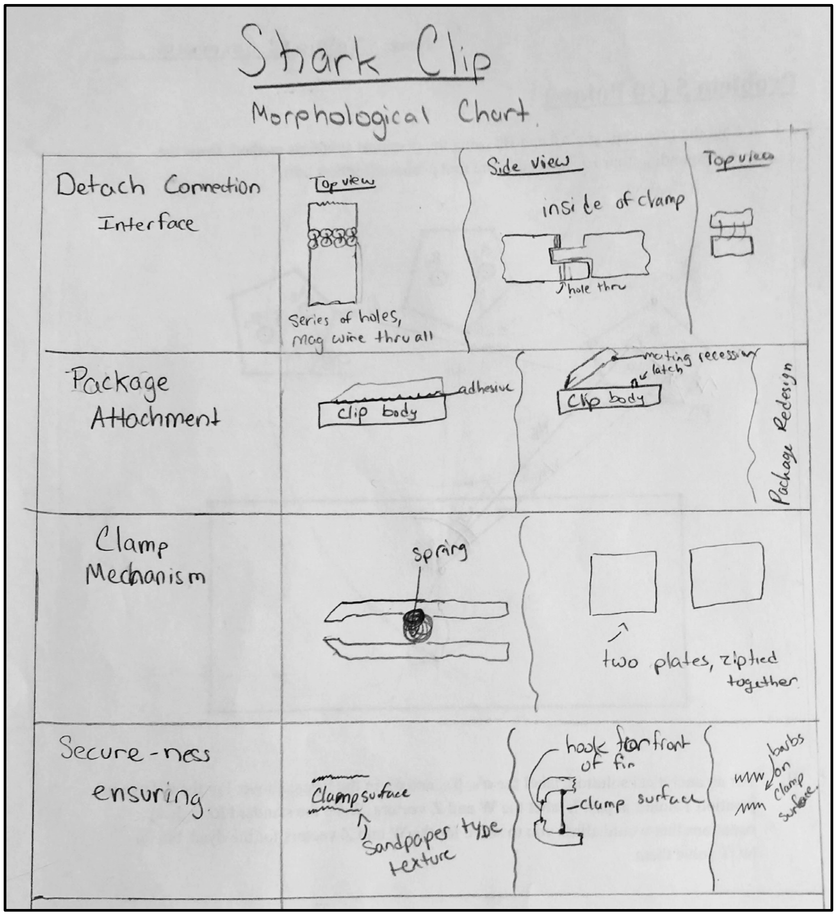


Figure A1.2: Morphological chart based on functions relating to the Fin Clip.

When attempting to refine our design, we had a couple of major functional groups to develop. We first considered the detachment mechanism. One option for the separation mechanism of a solid body included using a set of coincident hollow cylinders which a Nichrome wire would run through. When this wire dissolved, the two pieces would fall apart from each other. The second was a tab and slot mechanism, similar to the first, but the moment on the cross section was held partly by the solid body itself as opposed to just the wire. And the last option was a flat mating surface with a wire run through, similar to the first but with a larger contact area. While the third was seemingly better than the first, it still relied heavily on the wire for structural support whereas we preferred the wire to be a more passive mechanism. For this reason, a tab and slot mechanism was chosen for initial prototyping.

We then addressed attaching the sensor package to the attachment device. The first option was to keep the package the same as it was for the squid tag and recreate the clipping mechanism from that base to attach the package to this device. The second was to use an adhesive to permanently attach the package to the device, and lastly there was a broad ‘idea’ to redesign the package. This would allow us to create the package to be more suited to our concept as needed. Our design could incorporate the old package, either glued on or could be altered to include a clipping mechanism, or it could facilitate a new package design.

The third major category was the clamping mechanism. For this, we drew from past experience and benchmarking. The first idea was using a concept similar to that of a clothes pin. The second concept was to use zip ties, or a similar securing method, to attach two sheets of plastic over the fin as we had seen implemented for another small shark species in prior research. This complicated the detachment mechanism as zip ties do not dissolve, but it was still included for completeness. For the first prototype, we decided to move forward with the clothes pin method as it seemed like the other was going to be much harder to find a detachment mechanism for and single use plastics (zip-ties) would be a large component of the design.

Lastly, we discussed methods to ensure good contact and gripping strength between the device and the fin so that it would stay mounted for at least 72 hours. We talked about using a sandpaper-like surface as the connection interface, as well as a hooked end to the device that latched on to the front of the fin. The last was designing a system that meshed with the barbed structure of shark skin to hold the device in place. The last design, through conversations with our stakeholder as well as research, seemed to create issues for the non-invasive requirement as digging into scales could cause serious issues after 72 hours of swimming with the device. Currently, we intend on using some sort of combination of the first and second ideas, with a hook method to hold it in place, and perhaps an interface made of rubber infused with sand to create a malleable, yet grippy, surface to mesh with the shark skin. This option will be tested once a prototype is created and we can run simulations in and out of the water.

Concept Development Tool: Model Fins

We used the virtual shark model to isolate the shape of the dorsal fin and replicate a flexible fin to test the prototype’s efficacy on flexible surfaces. We printed five shark fin prototypes using three different flexible materials to try to best replicate the dogfish fin texture. As seen in Figure A1.3, we printed using thermoplastic polyurethane (TPU) in black, thermoplastic elastomer (TPE) in red and polypropylene in white. We printed the TPE fin in two additional printing patterns to improve the flexibility of the part and ultimately selected a version of TPE as our representative fin. This model will allow us to perform proof of concept evaluations for designs that attach to the first dorsal fin.

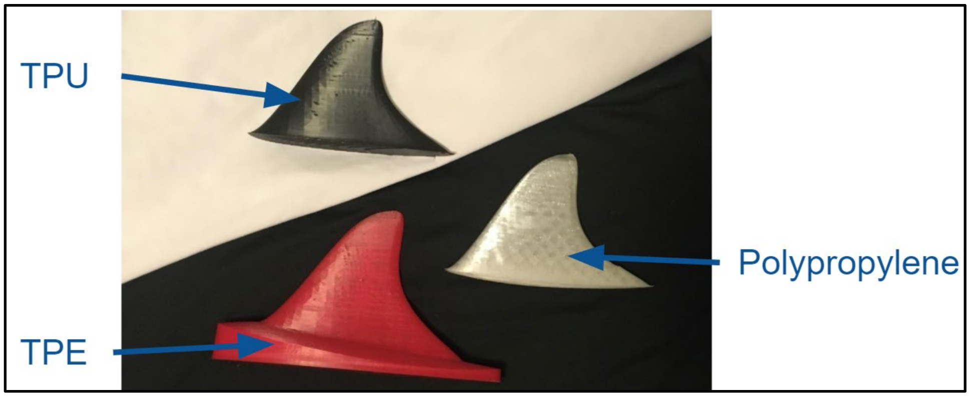


Figure A1.3: Three prototype fins have been printed to be used to test our tag designs. They are 3-D printed using TPU (Black), TPE (Red) and Polypropylene (White).

Appendix 2: Fin Clip

The second concept we developed is a Fin Clip. This consists of a design similar to that of a clothes pin, with two jaws that compress on the dorsal fin

Version 1

After the concept generation stage for the Fin Clip, we started to design an initial concept for the clip based on the desired qualities outlined in Figure A1.2 above. Our initial prototype had a couple of main goals; the clip needed to be able to attach to a fin using a clamping mechanism, allow for the fin to move uninhibited by the device, and finally have a method for autonomous detachment. Our first attempt at achieving these goals is shown in Figure A2.1 which shows two views of the initial CAD design.

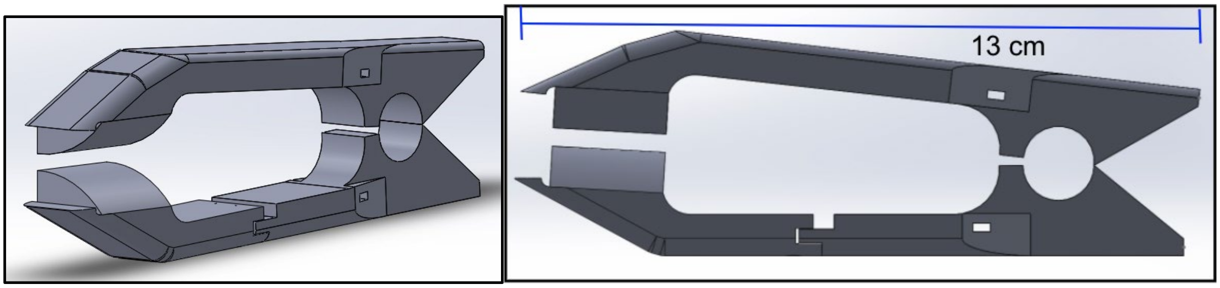


Figure A2.1: Two images of the CAD model for the Fin Clip, isometric view (left), and side view (right).

The first design challenge was creating the clamping surface that would interact with the fin. The initial interface, the curved surface on the left side of Figure A2.1, was designed in this manner to accommodate the curve of the fin and maintain even pressure across the whole surface. The shape of this curve was designed based on initial measurements of a dogfish so that it would mirror the curvature of the fin to better fit on it.

One of the problems with this attachment method was the fleshy texture of the fin. The fin of these animals is very fluid and non-rigid. This presented an issue when designing an attachment that relied on a rigid clamping surface. We believed our design would work as it was intended to only clamp on to a few centimeters at the front of the fin, which was much more rigid than the middle or back.

The fin, as mentioned above, is very mobile and bends and moves when swimming and performing fast direction changes. To accommodate for this movement and ensure the shark is impacted as little as possible, we left a large open space towards the middle of the clip, as seen in both Figure A2.1 above and Figure A2.2 below, that would allow free motion of the fin.

Figure A2.2 also shows a close up view of the detachment method that was implemented in this version of the fin clip. This part of the clip must allow the clip to detach after 72 hours from the shark and ultimately float to the surface.

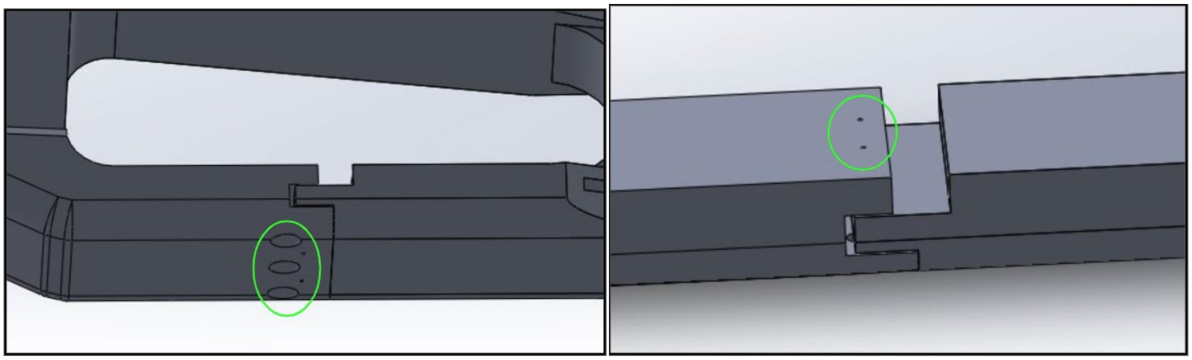


Figure A2.2: Detachment mechanism for Fin Clip concept. A wire will be threaded through the two small holes seen circled in the image to the right which, when burned, will break apart the two pieces. Furthermore, seen circled in the image to the left, the three holes on the bottom of the part create water pressure pushing these two pieces apart.

In this design, we created a tab and slot mechanism that connects the two halves of the bottom clip. This intersection is held together by a piece of Nichrome wire that runs through the two small holes seen in the right image in Figure A2.2. When a charge is run through this wire, it will dissolve and the two parts will separate. To encourage this separation, we included three holes in the bottom of the part, exposed to water, where we believe the water flow will help facilitate separation. This method of separation arose from ideation and remains untested, but we intended to test and develop on the idea.

To see the clip attached to the dogfish, we combined our CAD model of the shark with that of the clip. This allowed us to get perspective on the relative size of these two objects to better understand their interaction before printing. This relationship and relative size can be seen in Figure A2.3.

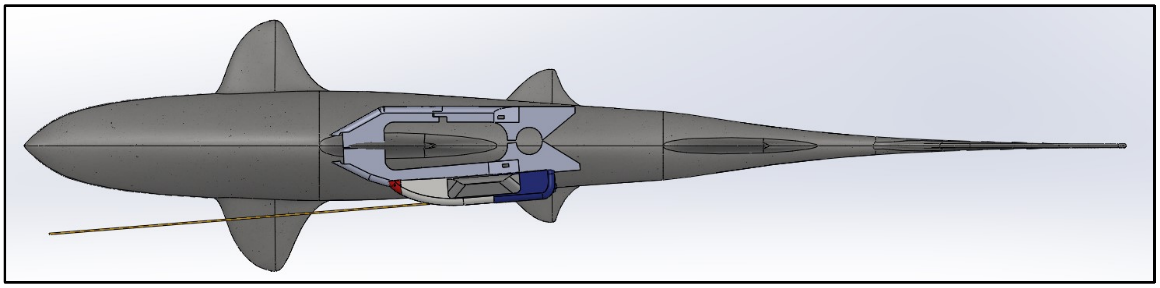


Figure A2.3: Top view of the dogfish with the Fin Clip in its intended location to scale.

In this figure, we can see the clip attached to the shark, the gap in the clip to make room for the fin movement, as well as the iTag attached to the clip. While we do not know if a package redesign will occur, we used this picture to gain perspective about the relative size of these objects.

After the initial design stage, we 3-D-printed the Fin Clip both as a proof of concept and to gain physical insight into the changes necessary to have a functional Fin Clip. The 3-D print of Version 1 of the Fin Clip can be seen in Figure A2.4.

Figure A2.4: Side view of the 3-D printed model for Version 1 of the Fin Clip.

It became apparent after printing Version 1 that there were several issues with the design that needed to be addressed. One such issue was that once the spring was installed, the clip began to twist itself out of the proper positioning as can be seen in Figure A2.4 above. A second issue was that the clearances for many of the features of the clip were too small. These included the clearances for the slot and tab interface, which can be seen in Figure A2.5, and the clearance for the spring. Both of these surfaces would need significant sanding to work properly.

Figure A2.5: (Left) the Fin Clip tab surface that was sanded down. (Right) The parts fit together cleanly after sanding.

In Figure A2.5, the sanding that was required to allow the two parts to fit together is shown to have tarnished the surface of the interface and unevenly changed the width of the tab. While these two pieces still fit together, as can be seen on the right of Figure A2.5, they did not fit as well as intended or as well as we believe is necessary for functionality.

We also learned that we had incorrectly placed the center of rotation at the center right of the spring, instead of at the center of the spring. As opposed to the spring remaining in contact with both the upper and lower parts of the clip upon opening, it separated from both of these sides as it rotated around the back of its mating surface, as seen in Figure A2.6.

Figure A2.6: The clip with the spring installed, highlighting the incorrect placement of the center of rotation.

Another issue with Version 1 of the clip was that the holes for the detachment method were too small to be resolved by the 3-D printed part. The holes either did not get printed, or they were far too small to fit a wire through.

Finally, the most glaring issue with the first version of the clip was the overall size of the clip in comparison to the shark. The size would need to be drastically reduced for the clip to be feasible in its current state, it was well above ½ the size of the fin.

Version 2

Based on the problems that arose from the first prototype, we developed the second iteration of the Fin Clip, shown in Figure A2.7. The main issues that were addressed included clearances in the spring location as well as the tab and slot joint, the kinematics of rotation for the clip when opening and closing, the twisting of the clip with respect to itself, and the overall size of the clip.

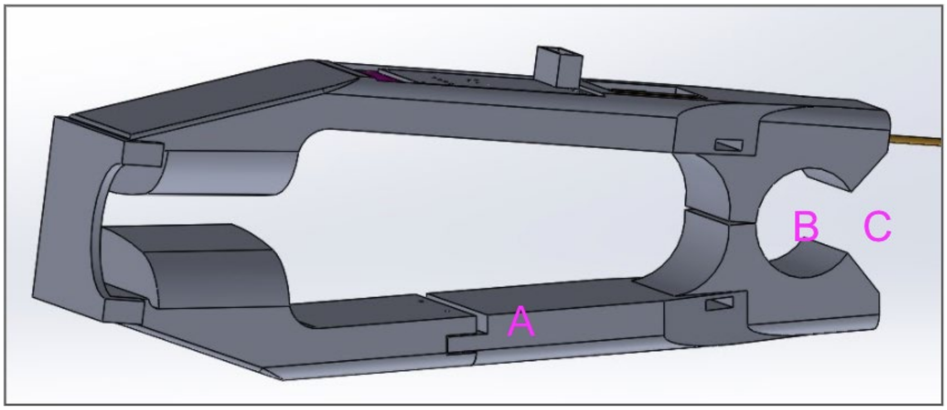


Figure A2.7: The newly designed clip, with the sensor package integrated.

For clearances, the solutions were quite simple; for the tab and slot joint (Point A), we merely increased the clearance for that intersection, and for the spring, we again widened the diameter to have a larger clearance at Point B. For the rotation point, we got rid of the intersection point behind the clip (Point C) so that the clip would rotate about the center of the spring.

The next problem that we were attempting to solve was the need to attach the iTag, or a similar package, to the clip. The proposed solution is shown in Figure A2.8.

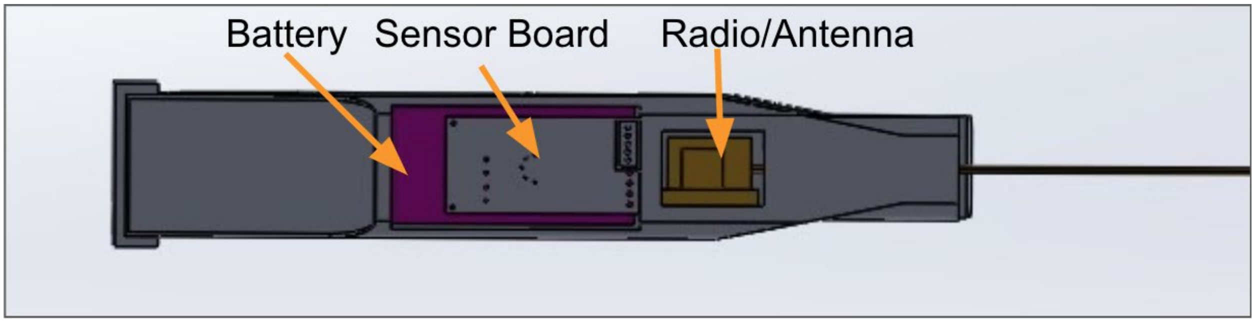


Figure A2.8: A top view of the clip with the electronics integrated into the top half of the clip.

This aspect of the redesign attempted to address the bulkiness of the clip. To attach the hardware to the Version 1 clip, we planned on attaching the iTag to the clip body. This made the part as a whole much larger which would create issues both with attachment and drag. To try and combat this, we instead integrated the electronics into the body of the clip as shown in Figure A2.8. This integration both lowered the profile and reduced the complexity of the part.

The next problem that needed to be addressed was the twisting of the clip discussed in the prototyping section of Version 1. In Version 1, the clip did not stay as one part when the spring was installed. To solve this, we worked on designing a bracket to hold the clip in place. As the spring holds the back of the clip together, we decided to locate the bracket on the front. The design we settled on can be seen in Figure A2.9.

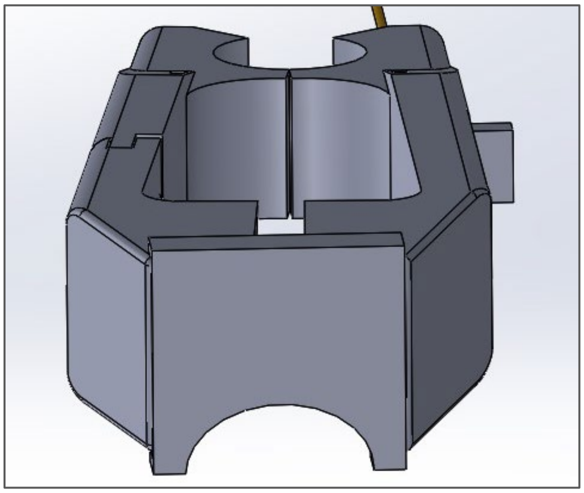


Figure A2.9: The redesigned front end is shown which helps to restrict twisting of the two halves of the clip as well as the sliding back of the clip on the fin.

The bracket above extrudes from the left half of the clip and intersects with the right half. This holds the two pieces from twisting with respect to each other. The spring itself is holding the back end from rotating. This design, we believed, would give us a stable clip.

During this redesign, we also sought to reduce the size of the clip as the first version of this clip was too large with respect to the shark. To do this, we reduced the size of the entire clip by 80%. The reduced size of the clip placed on the shark can be seen in Figure A2.10.

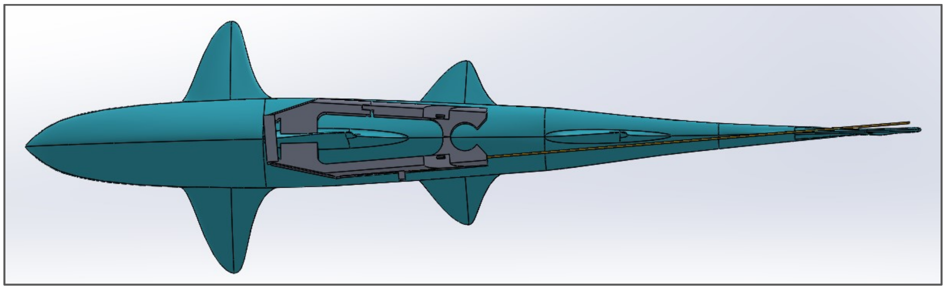


Figure A2.10: The new clip on the shark. As seen, this clip remains quite large with respect to the size of the shark.

Once we had solved the issues that became apparent from the first physical prototyping, we printed a new version of the clip to gain physical insight into the new design. The 3-D print of the Version 2 clip can be seen, attached to a model fin, in Figure A2.11.

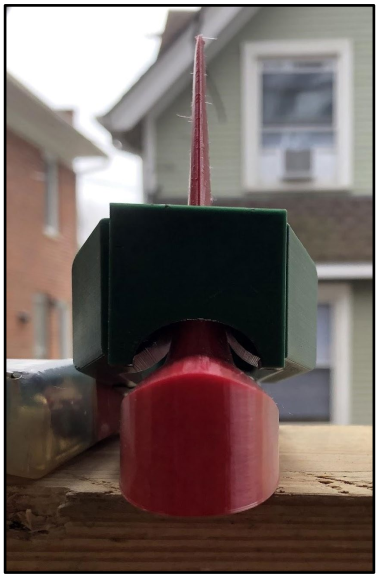


Figure A2.11: The front view of the clip attached to a model dorsal fin.

In Figure A2.11 and Figure A2.12, the clip is attached to the model dorsal fin, and the spring is installed. This highlights the improvements from Version 1 because previously the clip could not stay together, and as seen in this image the clip now clamps, to some degree, to a model fin.

Figure A2.12: Top view of the clip attached to a model fin.

While the clip does attach to the fin, it is still quite large relative to the dogfish body. Figure A2.12 shows that, while this clip is 80% of the size of Version 1, it still appears to be too large. With this version, we were not convinced that, given the need to both attach to the fin and hold the electronics to it, the clip could get much smaller.

As mentioned in Version 1, there was not enough clearance for some parts to fit together. To solve this, we changed the clearances to double their previous values. Figure 30 shows the new tab and slot mechanism that was redesigned in Version 2.

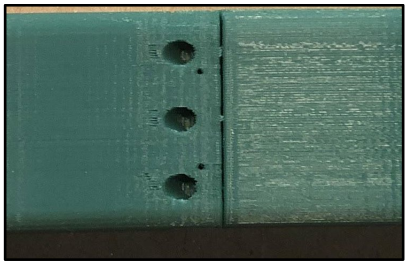


Figure A2.13: New intersection of the tab and slot joint. In this iteration, the printed holes came through but the clearance remained slightly too tight.

In this iteration, we kept the holes to allow for water to help separate the bottom of the clip and made the holes for the wire larger, which as can be seen in Figure A2.13 did get printed in Version 2. However, the clearance of the tab and slot remained too tight and significant sanding would be required for the two parts to actually separate autonomously. While again there was not enough clearance, from this print it became clear that this mechanism could work with a bit more of an adjustment to the clearance.

Finally, Figure A2.14 shows the side of the clip which includes cutouts to secure the electronics.

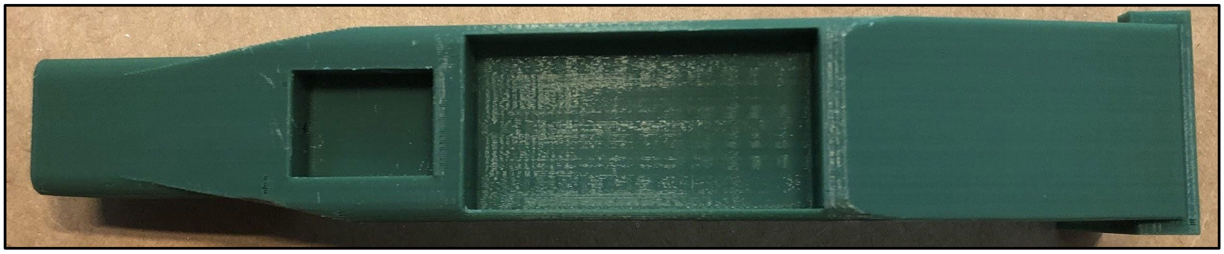


Figure A2.14: The hardware fit inside these cutouts, but actually installing them, presented many challenges.

This area, designed to have a significant amount of clearance, fit the battery and sensor board well. The antenna and radio, however, were blocked by the small barrier between the two recessions. To solve this, that barrier could be simply removed, and the two separate extrusions could be combined into one, which would likely make the assembly of the part, as well as the electronics connections between the two sets of components, much simpler.

Many of the issues that we had in Version 1 were solved quite well in Version 2 of the Fin Clip. For example, the new housing for the package was much more feasible and hydrodynamic than reusing the old package and merely attaching that to the clip. Additionally, the Version 2 clip successfully attached to the fin whereas Version 1 did not. Even though some of our changes were successful, we found some hindrances that we deemed quite significant.

The biggest hindrance is that the tag feels bulky and unstable. The clip is a static device that attaches to a very dynamic object, the dogfish. We had significant concern about how well the clip would stay on over the course of 72 hours when compared to a more fluid design, for example the shark belt or shark saddle, discussed below. When looking at the size of the tag, we see that it is roughly half the height of the fin, and almost double its length. While the fish could likely swim, to some degree, with this clip attached, our goal of minimal invasiveness and affect on behaviour is very unlikely to be met with this tag. For this reason, it was after this Version 2 prototyping that the focus on this design was shifted away into more promising design spaces, like the shark belt and shark saddle, and how to further improve on those concepts.

Appendix 3: Shark Belt Initial Iterations

The Shark Belt prototypes currently in progress are proof of concepts to investigate the feasibility of this design before moving forward with more intricate features of the design. Two prototypes will initially be evaluated for this purpose. The first prototype consists of a one-inch elastic band fitted to the circumference of the dogfish just in front of the first dorsal fin. The band has Velcro® on each end to secure it around the dogfish, shown in Figure A3.1. Since this design is only one band, it will require a package redesign to wrap around the circumference of the body. We have begun this redesign, which will be prototyped if the single band satisfies our requirements in testing.

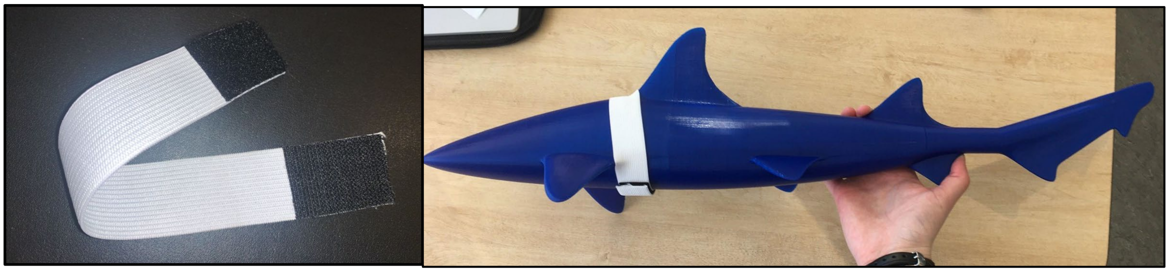


Figure A3.1: Images of the first Shark Belt proof of concept, consisting of one elastic band to be placed in front of the first dorsal fin.

The second prototype includes two one-inch-wide elastic bands around the circumference of the body. A nylon strap is sewn in to connect the two bands, on which the biologging tag will be mounted, shown in Figure A3.2. This concept aims to fit the existing tag design. Doing so would reduce cost and avoid potential issues in the field that a new tag design may bring.

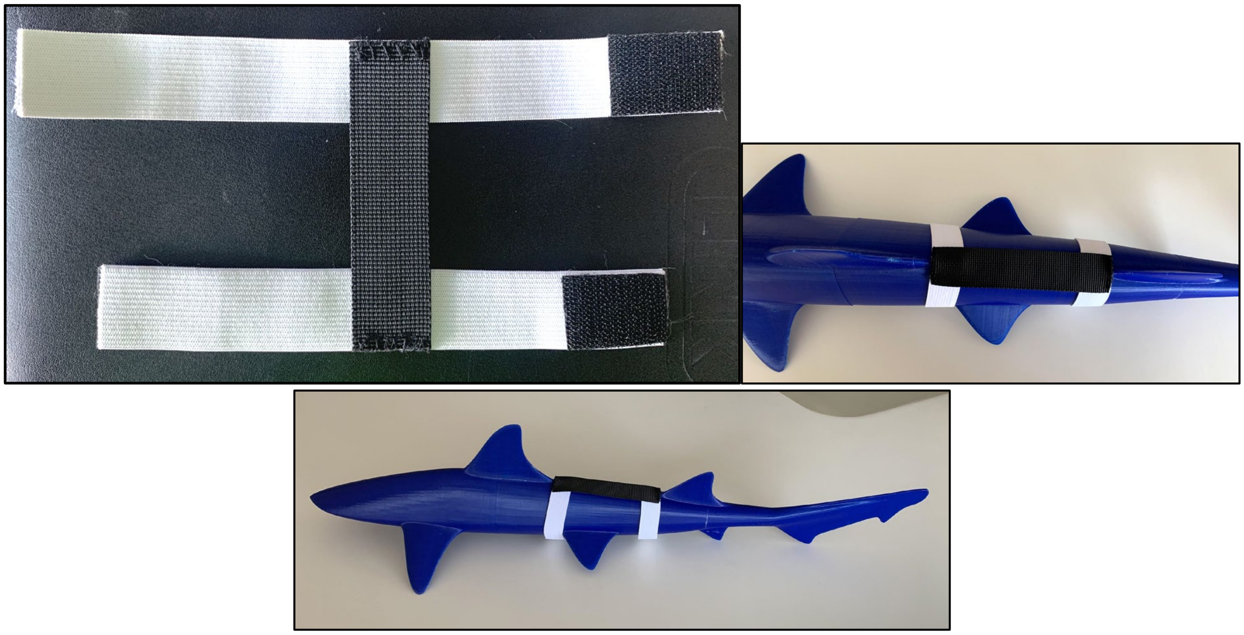


Figure A3.2: Images of the second Shark Belt proof of concept. Two elastic bands are connected by a nylon strap and outfitted with Velcro® to attach and detach from a shark body.

We chose to further develop the two strap elastic design from one of the initial concepts. This was the most secure of initial designs. In the updated design we used ¾ inch elastic to reduce the interference of the first strap with the dorsal and pectoral fins, shown in Figure A3.3. The nylon strap was also lengthened to 11 cm to maximize the available space on the back of the dogfish. This design still does not fit the existing tag from WHOI, which is 12.3 cm long. We may, however, be able to use this design with the original tag if we choose to tag larger dogfish than the one we chose to test our designs on. The 3-D printed dogfish is 64 cm in length, but the species can reach 100 to 150 cm when fully grown. Using proportions, we anticipate that dogfish over 72 cm in length would be able to fit the original tag with this design. Due to the lack of research on the species we do not know if they keep the same proportions as they grow, so we anticipate the lower length limit to be closer to 80 cm to ensure adequate room for the tag with this design.

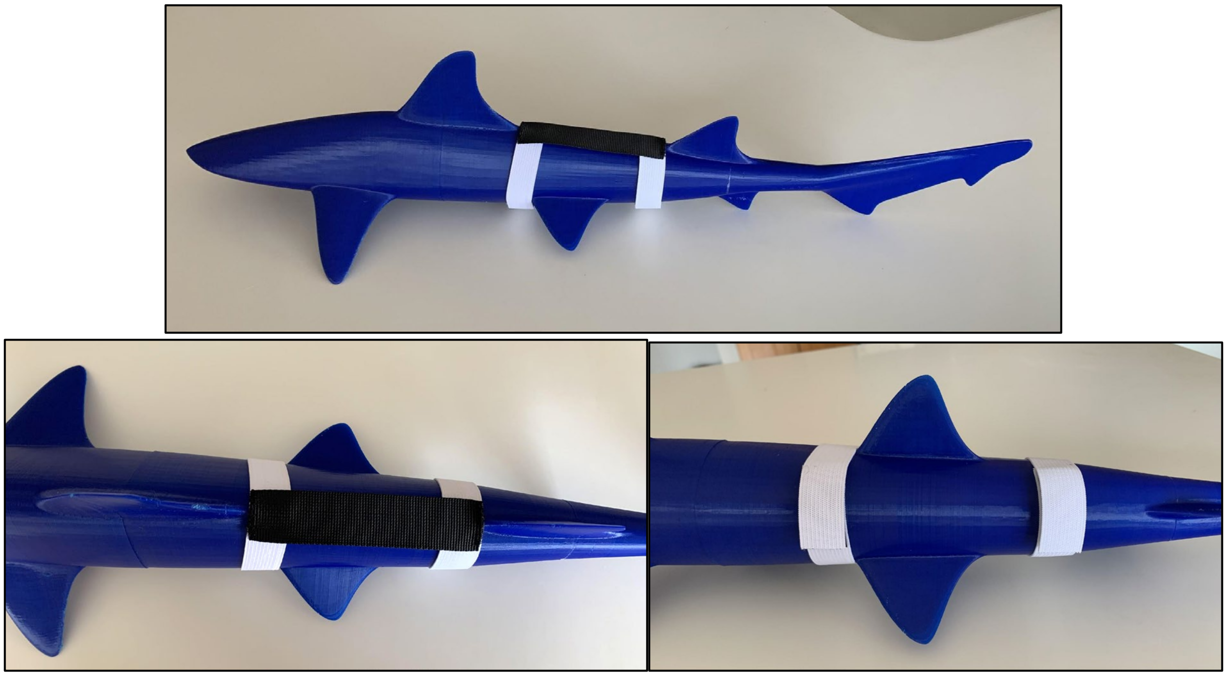


Figure A3.3: Images of modified two strap elastic belt design.

Appendix 4: Required Supplemental Appendices

Engineering Standards

Formal engineering standards were not used in this project, largely because the project is supporting academic research. Since we are contributing to research and advancements in the marine biologging field, we largely adhered to research best practices rather than codified standards. Through consistent communication with our sponsor, we ensured that the ethics of The Sensory Ecology and Bioacoustics Lab were upheld throughout this project.

Engineering Inclusivity

We recognized the inherent power that we, as the design team, held over the intended users of the product. To return power to our sponsors (and users) we met regularly with our sponsor and asked open-ended questions about their vision for the project and how our design choices may affect their work. We sought feedback from our sponsor about associated risks for the design and incorporated their feedback into our work. Furthermore, we were aware of the potential harm we could cause on the live dogfish users and decided to delay testing on live dogfish from the original date until we had more thoroughly tested the design on our virtual and model dogfish. This ensured that we were more confident in the potential success of our solution and did not cause unnecessary harm on the animal subjects. We also incorporated aspects of the design that could be altered to accommodate dogfish of varying size so that our design is not exclusive to dogfish of a certain size and data can be collected from a range of individuals.

Environmental Context Assessment

Evaluating the environmental impacts of a design can be challenging and complex. To gain a high-level understanding of the environmental sustainability of the design, we considered the two questions listed and answered below.

Does the system make significant progress toward an unmet and important environmental or social challenge?
This question seeks to justify the use of resources and cost associated with product development, manufacture, use, and disposal. A successful shark belt tag design would make significant progress to support research of dogfish behavior in the wild. This research can be used to understand the anthropogenic impacts on marine habitats and how human processes (e.g., commercial fishing) may affect the life cycle and ecosystem of comparable shark species. Understanding the survival rate of bycatch species can also provide motivation for changes in policy to protect marine species and support species diversity in marine ecosystems.

Is there potential for the system to lead to undesirable consequences in its lifecycle that overshadow the environmental or social benefits?
This question checks that the proposed solution does not generate new environmental or social problems while attempting to solve others. The potential for the shark belt tag design to lead to

undesirable consequences in its lifecycle is low. The current design plan does not deposit any unnatural material to the marine environment and, though we were unable to verify the requirement, the durability requirement is intended to be met by the design solution. Both factors reduce environmental damage of the design by maintaining the species' environment and limiting the material demands by a larger scale project. Also, the design could be fully functional using manufacturing processes and materials that are readily available to our sponsors, so there would be no additional environmental damage caused by purchasing and integrating new machines or supplies.

Social Context Assessment

Similar to the environmental context assessment, comprehensive evaluation of the social impacts of a design is incredibly demanding. However, a broad understanding of the social impacts is important to consider throughout the design process. The following three questions were considered in our social context assessment:

Is the system likely to be adopted and self-sustaining in the market?
This question checks if the solution is economically viable. The proposed final design for the shark belt has a relatively affordable price, especially for the research labs that would likely implement the design. Since the tag has a low manufacturing price and details of future iterations of the design will likely be published in future papers, we believe that other interested researchers may adopt the same or similar designs to study small marine animals.

Is the system so likely to succeed economically that planetary/social systems will be worse off?
This question ensures that there are realistic limits to reduce the likelihood of overconsumption due to the success of the proposed design. Due to the limited target audience for this design, the likelihood of harming planetary or social systems after implementing this design is very low.

Is the sustainable technology resilient to disruptions in business as usual?
This question ensures that a design will stay relevant for many years and can support stakeholder needs despite changing circumstances. The shark belt tag can easily be modified for deployment on other marine animals, so even if dogfish research is widely conducted, the design will still be relevant to marine researchers.

Ethical Decision Making

Since this project was centered around designing a product to be used on live animal research subjects, ethical considerations were very important throughout the whole process. As discussed in the Ethics Statement above, we followed the ethical framework of the three R's: replacement, reduction, and refinement. Following this framework helped the team decide to delay initial deployment on the dogfish subjects until after further testing was conducted on the model dogfish in the Marine Hydrodynamics Laboratory tow tank and qualitatively by the team. This ensured that we did not induce unnecessary stress on the dogfish subjects and that we had relatively high confidence in the prototype before testing it on live animals. We also focused heavily on developing a non-invasive product to limit the harm to the dogfish and maintain their wellbeing.