Final Report

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Client: Professor Matthew Spencer

Electronic Stabilizer Team 1
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Abstract

In Engineering 79, the core engineering class at Harvey Mudd College (HMC), teams of three students on rowboats deploy robots into pHake Lake. Robots are plugged into project boxes with electronics vulnerable to water damage. Currently, these project boxes are unsecured, and project boxes have been falling into the waterlogged stern—damaging valuable E79 resources. We then designed a nondisruptive setup to prevent these accidents. In this report, we show the steps taken during the design process to find the best solution for our clients' needs and to develop, understand, and build around our own design parameters. Our steps include gathering information from our client meetings, advisor meetings, and field research to best define our problem statement, constraints, and then objectives. One low-res "bike-basket" prototype was manufactured from cardboard to display the general form factor of the assembly and validate the structural rigidity of the geometric design. Two mathematical models (analyzing tension and shear) were developed to evaluate critical design parameters for the prototype—namely, the thickness of the basket "handles" required to hold up both itself and the weight of the electronics. The final design solution was developed in Solidworks CAD, adding new prototype features: extended hook, added pocket, and extra support on side panels. Finite element analysis tests our design through different realistic scenarios to understand areas with maximum stress and determine improvement for future design iterations. The significant outcome of our studies prove that our hooks will not break under 10kg downward load and 10kg side-inward load. Given these results, we conclude our final design solution solves the problem of damaging the electronic boxes. Over 200 HMC students would benefit every year from our accident prevention design, and reducing the electronics failures saves E79 funding and time for the HMC Engineering faculty.

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Introduction

Our Client

Dr. Matthew Spencer, Assistant Professor of Electrical Engineering at Harvey Mudd College

Project Background

In Harvey Mudd College's Introduction to Engineering Systems course (E79), students build robots over the semester and test the robots in a field experiment. The field experiment is performed out on pHake Lake, a manmade pond where students get on rowboats to collect data with robots submerged in the water. A proctor sits in the center bench to row the boat, while two students sit in the rear bench. These boats, while structurally sound, collect a small amount of water in the bottom due to small holes in its connection points that cannot reasonably be patched. To collect data, the two students must bring onto the boat a box holding expensive data acquisition electronics as an interface connecting an onboard computer and the robot by wires. While the robot can operate in water, the onboard computer and box of electronics must remain dry.

Over the past few years, Professor Spencer has encountered a few incidents where the students' box of electronics fell into the waterlogged stern of the boat, with the hard impact and water damaging the delicate electronics. Often the two students onboard focus on guiding the robot and monitoring the data on their laptop, leaving the box unattended and unsecured on the rear bench.

Design Need

Prof. Spencer has tasked us with finding a simple solution to secure this box to mitigate these accidents and prevent future electronics boxes from falling into the boat bottom and failing.

Revised Problem Statement

In Engineering 79, Harvey Mudd's core engineering class, teams of three students on rowboats deploy robots into pHake Lake. Robots are plugged into project boxes with electronics vulnerable to water damage. Currently, these project boxes are unsecured: resting on either the students' laps or the rear seat of the boat. Project boxes have been falling into the waterlogged stern—damaging valuable E79 resources. Design a new setup that prevents these accidents without disrupting the student/user experiences.

<u>Constraints, Objectives, and Metrics</u>

Table 1: Constraints

Constraints	Justification
No modifications made on the boat	The boats are not Harvey Mudd College property, they belong to the Bernard Field Station (client mtg. 1).
Be non-permanent	The boats are used for other purposes besides the E79 project, so any design must be removable (client mtg. 1).
Room for two students and one proctor to enter, sit, and move	The project is done in groups of three. These groups consist of two students who are testing their robot and one proctor who rows the boat (client mtg. 1).
Cannot inhibit proctor's rowing	Proctors are present to row the boats during the final project and their ability to do so is not to be limited in any way (client mtg. 1).
Needs to fit project box inside	The project box contains the electronics that require protection from water, so any design must be able to be able to fit the project box (client mtg. 1).
Keep design of box with holes	Prof Spencer often uses the electronics boxes in situations outside of the boat, such as in the test tank, so he does not want to lose the box he already has (client mtg. 1).
Proctor should not be responsible for the box (plugging things in/out)	Students are the ones who are responsible for the project box and plugging things in/out (client mtg. 1).

Table 2: Objectives and Metrics

Objectives	Metrics	Justification
Be safe and protective for the electronics	Probability that some piece of electronics could come into contact with water	Accomplishing this objective is the entire reason that the client approached us to create a design (problem statement).
Be affordable and easy to reproduce design	Materials/production cost	Prof. Spencer mentioned specifically that he wanted a simple design, and that comes specifically in the form of a reproducible design (client mtg. 1).
Be durable	Stress analysis for possibility of failure	The client mentioned during a review of a prototype that if the design broke quickly, it would have little value (client mtg. 2).
Be non-inhibiting to electronics inside box	Score based on how many hands are required to interact with electronics and how long it takes	The client mentioned during a review of a prototype that it was important to him that the box is easily accessible for students to plug their robots in (client mtg. 2).
Easily stored with a small footprint when not in use	Score based on footprint of any required additional storage	Prof. Spencer mentioned that he did not want our design taking up too much space in the E79 classroom when not in use (client mtg 1).

Table 3: Pairwise Comparison Chart to Rank Objectives

	Be safe and protective for the electronics	Be affordable and easy to reproduce design	Be durable	Be non-inhibiting to changing out electronics from box	Easily stored with a small footprint	Total
Be safe and protective for the electronics	...	1	1	1	1	4
Be affordable and easy to reproduce design	0	...	0	0	1	1
Be durable	0	1	...	1	1	3
Be non-inhibiting to changing out electronics from box	0	1	0	...	1	2
Easily stored with a small footprint	0	0	0	0	...	0

From the very first meeting, our client Professor Spencer made it clear that safety of the electronics was of the utmost importance. Having both batteries and data acquisition hardware inside the box, it ran the heavy risk of hindering the entire project if even a bit of water got inside. That is why we decided it to be important over other objectives, as it is what decided the success or failure of our model. Durability is also related to this, so we would want to make sure that our materials would be able to withstand the stress of the project, which we learned from our field research would include multiple forces, water, and even heat.

We also wanted it to be convenient for students to plug in their robots, or even to change out the electronics if needed, as we wanted to take the worry of the electronics box out of the students mind. This is as, in our second meeting, our client expressed worry of wanting the electronics to still be accessible and not just shut away in a box.

During multiple meetings, concerns were raised over the manufacturability and cost of our designs, so to satisfy those needs we wanted to make sure our design could be made from cheaper, sturdier materials and easily produced through laser cutting or 3D printing.

Finally, we also had to make sure whatever our solution was, it would have to be small and light enough that students would be able to easily take it out to the lake without hassle. If so we would also solve the problem of storing our design within the E79 project room.

Table 4: Metric for Objective #1

Objective	Metric: Various water level tests	
Be safe and protective for the electronics	Type of Scoring: Scale from 0 - 5	
	Description	Score
	Box lets more water in than the current design	0
	Box is as water resistant as current design	1
	Water cannot get inside box with 0-1 inch of water in the boat	2
	Water cannot get inside box with 1-3 inches of water in the boat	3
	Water cannot get inside box with 3-5 inches of water in the boat	4
	Box can be submerged in water and will not damage electronics	5

Table 5: Metric for Objectives #2

Objective	Metric: How long it takes to access electronics	
Be non-inhibiting to changing out electronics from box	Type of Scoring: Scale from 0 - 5	
	Description	Score
	Can't access box/electronics, no way to plug in wires	0
	>20 seconds	1
	15-20 seconds	2
	10-15 seconds	3
	5-10 seconds	4
	<5 seconds to reach electronics, no	5

Table 6: Metric for Objectives #3

Objective	Metric: Ease of storage	
Be stored with a small footprint when not in use	Type of Scoring: Scale from 0 - 5	
	Description	Score
	Can't store anywhere due to size, have to throw out after use each semester	0
	Have to find a new storage space	1
	Store with current equipment but inhibits access to them	2
	Store with current equipment but allow some access to them	3
	Store with current equipment with easy access to them	4
	Store with current equipment with complete access to other equipment	5

Final Design Solution

Our current final design solution is a laser cut acrylic box reminiscent of a "bike basket," attached to the center of the stern with two acrylic hooks, one on each side of the box. We decided to pursue this solution first because it could very easily be rapidly prototyped with low tolerance and it essentially has it's proof of concept in the established bike basket designs. The placement of this box will also keep the boat balanced. Additionally, the box is easy for the students to access, while not inhibiting any sort of movement since students sit in front of the box and enter through the bow or side, never the stern. Holes can be strategically placed in the sides of the box to allow for easy access to plugging and unplugging cables to the electronics inside (see **Appendix 1** *Review of Past Literature* for more details).

We made sure to round all the "inside" facing corners that bore load in order to mitigate the possibility of stress induced cracking over time. We also rounded the bottom corner of the box that rested along the inside of the boat, because a sharp corner with a force applied to it has a very high localized stress. Rounding a corner helps to disperse this better.

Lastly, we added a side pocket for the sensor board, a printed circuit board (PCB), that students plugged into this box. Since this also contained electronics that needed to be protected from the water, and usually this rests haphazardly on top of the project box, we devised a pocket with a slot that made the PCB easy to slide in and out for during equipment swaps, while still securing it in a manner such that none of the pins, connectors, or solder joints on the PCB bore excess load.

Functions and Means

Our team has identified six prototype functions and the means to fulfill each of these functions:

First, the prototype must stabilize and lock down the project box, which is accomplished using hooks and protrusions.

Second, the prototype must block water from entering the box, which is accomplished using acrylic walls as a physical barrier.

Third, the prototype must store the electronics, which is accomplished by utilizing the original plastic box provided by E79.

Fourth, the prototype must intercept the box from dropping into the water, which is accomplished by using a hanging system.

Fifth, the prototype must connect the electronics and the robot, which is accomplished by creating an acrylic basket without a lid for the original plastic E79 box.

Sixth, the prototype must stabilize the PCB sensor board, which is accomplished by creating a side pocket from acrylic.

The Functions and Morph Chart in Appendix 2 details the alternative means for each function.

Evaluation of Design (math models, testing, computation modeling results, etc.)

For our first simulation of the First Principles Stress test on our final solution, the area of greatest stress with 10 kg of downward load was approximately 2,600 psi. According to McMaster-Carr and Matweb, acrylic's tensile strength is approximately 10,000 psi. Therefore, we are good to a factor of greater than 3.5. This means that our hooks are not going to break off under these conditions.

For our second simulation of the First Principles Stress test on our final solution, the area of greatest stress with 10 kg of downward load and 10 kg of side-load inwards was approximately 3,600 psi. According to McMaster-Carr and Matweb, acrylic's tensile strength is approximately 10,000 psi. Therefore, we are good to a factor of greater than 2.5. This means that our hooks are not going to break off under such a side-loading condition.

Bill of Materials

Box

Surface Area: 243.16in^2

Thickness of acrylic: 1/8in

Based on information found on McMaster-Carr, we would be able to procure enough acrylic of the corresponding thickness for around $15 dollars if we purchased a 12" by 24" sheet. This amount would be enough acrylic for the box itself.

PCB Pocket

Surface Area: 15.11in^2

Thickness of acrylic: 1/8in

Even with that 12" by 24" sheet, we would still have enough material left over such that the entire design could be made from one sheet, including the pocket. We would also be bonding the different pieces together through acrylic glue, which we could acquire easily through McMaster-Carr.

Table 7: Materials

Item No.	QTY.	Material	Description
1	2	Acrylic	Front and Back Wall
2	2	Acrylic	Side Walls with Hooks
3	1	Acrylic	Bottom
4	1	Acrylic	PCB Pocket
5	1	Acrylic Glue	Softens the surfaces

			of the acrylic and welds them together, chemically bonding all pieces into one

Table 8: Estimated Cost of Final Design

Item	**Dimensions**	**Model**	**Supplier**	**Unit Price**	**Quantity Required**	**Price**
1/2/3/4	24” by 12” ⅛” thick	8560K257	McMaster-Carr	**$16.70**	**1**	**$16.70**
5	4 oz.	7517A1	McMaster-Carr	**$9.22**	**1**	**$9.22**

Total Price	**$25.92**

<u>Impact of Design Solution</u>

Implementing our design solution would directly and significantly impact the Harvey Mudd College community. E79 is a course taken by all HMC students, so *over 200 new students would benefit every year* from our accident prevention design for as long as the E79 course is offered. Furthermore, eliminating the risk of falling electronics to zero saves both E79 funding and time for the HMC Engineering faculty (**Appendix 1** Client Meeting #1).

<u>Future Recommendations</u>

There are three key areas in our design that offer further opportunities for improvement:

First, the **side pocket readjustment**. As mentioned in Client Meeting #3 (**Appendix 1**), the side pocket in our final prototype could be modified to better hold the PCB. Currently all the weight of the PCB rests on the sensors. Rotating pocket by 90 degrees would put less strain on the PCB and better serve our Objective #1: “Be safe and protective of electronics.”

Second, **rubber guards**. After conducting our analysis and discussing with our advisor Prof. Duron, we identified a primary potential source of failure for the design—cracks in acrylic. After long term use, the brittle nature of acrylic may introduce cracks after many cycles of use, wear, and heat over time. Cracks would result in a failure of our design as the shear and tensile strength would be compromised as stress is applied to a smaller cross section. Then, the design could no longer support electronics on the boat. To address this and prevent cracks, applying pieces of rubber on the areas where the acrylic and boat contact (hook and rounded corner) would introduce a soft layer interface to reduce impacts between the hard surfaces.

Third, the **hook length**. Currently, our design is designed for a boat with a stern wall that is 1 inch thick. If the wall were thicker, then the hook could not fit and hang onto the wall. After discussing with Prof. Duron, our team concluded that adding a hinge to extend the hook would allow for general fit for any boat wall thickness. However, it is important to note that the hinge adds additional steps in the manufacturing process beyond laser cutting.

Altogether, our final recommendation would be to test the design out on the boats in pHake Lake. Although distance learning has forced the team to make judgements based on models and simulations, an in-person experiment would verify our analysis and assure that these three key areas are addressed.

Appendix 1: Identifying and Defining the Problem

<u>The Problem Statement</u>

The problem statement we first received from client Prof. Spencer is as follows:

> "In Engineering 79, Harvey Mudd's core engineering class, students deploy robots into pHake Lake during their final lab by lowering tethered PVC frames over the side of rowboats. The frames are tethered to project boxes which contain powerful batteries and delicate electronics, and dropping those boxes in the water breaks them. Though no boxes have gone overboard, the rowboats are leaky and the current method of securing them (telling a student to hold them in their lap) has resulted in a few falling into the waterlogged bottom of the boat. This project seeks a better method of securing E79 project boxes to rowboats so they won't fall into the water, but the new fixture needs to make sure it's still easy for students to find a place to sit and to electrically connect their robots."

For all the data/key findings that focused our design space, see the Client Meeting section.

Evidence and Justification for our Problem Statement Revision

In one example, Prof. Spencer's critical note on "the box falling backwards" appears in our new problem statement:

> "Project boxes have been falling into the waterlogged stern." (Revised)

Specifying the stern as the key area of failure improves upon the original statement:

> "...a few falling into the waterlogged bottom of the boat" (Initial)

Additionally, we reference our E4 textbook (Dym et al. 40) for techniques and tips to identify implied solutions. Learning from this reference and in lecture, we eliminated an implied solution in the original statement:

> "...securing E79 project boxes to rowboats" (Initial)

To reveal the core issue of the design problem that motivated the implied solution:

> "Design a new setup that prevents these accidents…" (Revised)

Our revised problem statement is as follows:

> "In Engineering 79, Harvey Mudd's core engineering class, teams of three students on rowboats deploy robots into pHake Lake. Robots are plugged into project boxes with electronics vulnerable to water damage. Currently, these project boxes are unsecured: resting on either the students' laps or the rear seat of the boat. Project boxes have been falling into the waterlogged stern—damaging valuable E79 resources. Design a new setup that prevents these accidents without disrupting the student/user experiences."

<u>Client Meetings</u>

2.19.2020: First Joint team meeting with Prof. Spencer in Parsons B171

Prof. Spencer, a member of the E79 teaching team, offered his clarifications on the problem statement. He outlined how the boats and electronics were used on a typical E79 test day: two students and a proctor are on a 3-bench rowboat. The proctor rows on the middle bench and the two students sit on the back bench managing the electronics box, submarine, and laptop. The process is also usually a high turnover situation, where the class divides up the three usable boats by allotting each team only 20 minutes at a time on the water. Once the team is out on the lake, a student usually tosses the robot and it's tether off of the side of the boat, and past failures involving the electronics box all involved the box falling backwards off of the bench and into water pooled up in the stern of the boat. Professor Spencer also noted that these boats were not Mudd property and that therefore a constraint was that we could not modify the boats. We were given an example box, and measured the weight of electronics in the box to be 2.4 lbs. Professor Spencer also noted that our design would be stored with the project boxes in the E79 classroom when not in use, and asked for the design to facilitate simple storage.

Table 9: Box Dimensions

	Blue Box	Clear Box
Height (in.)	5	5
Width (in.)	6	~6
Length (in.)	11 $\frac{1}{8}$	~10

3.19.2020: Second Client meeting with Prof. Spencer in Parsons 2358

During our second meeting with the client, Professor Spencer, we presented our first low-resolution cardboard prototype in order to solicit his feedback. The client mentioned that he was still concerned that if the boat were bumped or jostled, the box would fail and fall off. He said that he would be persuaded by the efficacy of the design if we were somehow able to show that this was not the case, possibly with real-world testing. In discussing choice for material, Prof. Spencer also mentioned that he wanted to ensure we chose a material that would last a while, as a solution that broke quickly had little value. He mentioned looking into wood as a possibility since acrylic could be brittle. In commenting on our placement, he also wanted to have us be aware of the possibility that the box was placed at an awkward angle, and that students would have a hard time accessing it in order to plug cables in or out of the electronics. In addition, Prof. Spencer brought up the fact that there was another PCB connected to the robot, usually outside the box and providing sensor data to the data acquisition system inside the box, that was in danger of getting wet. We agreed to come up with changes to our prototype in order to find a secure place to put it, that let students easily swap it in and out when the teams switched in and out of the boat. Lastly, Professor Spencer mentioned that he was happy with the dimensions of the “basket” part of the design, even though the project box sat on the rails of the box and not on the bottom of the basket. With the PCB now involved, we measured dimensions using calipers and recorded our findings below. Note: the “Sensor” is a pressure sensor plugged into the PCB during the E79 Field Experiment.

Table 10: PCB Dimensions

	PCB	PCB + Sensor
Height (in.)	2.2	3.3
Thickness (in.)	.4785	.4785
Length (in.)	1.556	1.546

4.13.2020: Third Client meeting with Prof. Spencer on Zoom

Our third meeting with Professor Spencer was online, in which we presented the CAD model of our second prototype. This prototype included design changes that were inspired by our second client meeting, as well as advisor meetings. Professor Spencer first commented on the design of our side pocket, requesting that it be rotated 90 degrees (normal to the plane of the side of the box) such that the weight of the PCB would not rest on the pins of the pressure sensor, which would have been a concern with the current orientation since it would cause wear. He also commented on the lengthened basket “handles”, noting that this could cause the box to be harder to take on and off of the boat itself.

When we presented the stress test we ran on the first prototype with a Finite Element Analysis in Solidworks, Prof. Spencer expressed that he was most concerned about a panel falling off if the glue between them failed under load. He asked us to analyze the possibility of this happening, and also to analyze what would happen if someone accidentally leaned on it or brushed it as well.

<u>Background Research: Field Observations and Literature Review</u>

3.2.2020: Field Research at pHake Lake

Professor Wallace "Marty" Meyer, the Director of Bernard Station, is a key stakeholder as he manages the boats used for E79. Professor Meyer offered important insight on the boats. There are currently 3 boats out on the field, but only 2 of them are used for E79. We will call them "Tan boat" and "Blue boat" by their color. The third wide Whale® boat is not used. E79 also uses another boat very similar in size to the Tan boat, but it is currently the repair shop. Professor Meyer notes that boats are rotated in and out of shop because they're constantly breaking down with leaks. Layering/rivets make it hard for cracks to be found/sealed. In other words, the leaking problem itself can't be addressed, which limits our design space. New one-piece aluminum boats will be purchased, but in the distant future. He told us that the boat tips. Marty's proposed solution is a shelf at the stern attached to the back wall so it is out of the way and students can get in and out of the boat easily.

Figure 1: The back two benches of the blue boat, on which the proctor and two students sit.

Figure 2: Testing the tan boat in the same seating positions as E79 students.

Table 11: Boat Dimensions

	Blue Boat	Tan Boat
Material	Aluminum	Aluminum
Length (ft.)	~12	~14
Stern interior width (in.)	45	50
Stern side wall thickness (in.)	1	1
Last seat to stern (in.)	18 $\frac{3}{4}$	15
Stern height (in.)	15 $\frac{1}{2}$	15 $\frac{3}{4}$
Rear set width (in.)	12	15 $\frac{1}{2}$
Rear seat height (in.)	10	10

Boating Experience

Enter via the bow, the stern stays in the water. Students must balance in the middle while walking back and stepping over to benches to reach their assigned positions. Due to the precarious nature of this process, it is important that our design does not restrict any movement. Since the students sit in the rear and the proctor in the middle, the boat tilts towards the stern, which lets the water accumulate in the stern. This also makes it so that if the box slides anywhere, it would follow gravity to go backwards into this water. Additionally, when the box is placed between the two students, it is easily displaced by their thigh movement.

Review of Past Literature

After completing our field observations, we concluded that Marty's suggestion for a shelf/prototype at the back of the boat had very valid strengths. Specifically, the suggested location atop the stern adhered to both of our constraints relevant to prototype placement:

Constraint 1: "Room for two students and one proctor to enter, sit, and move."

Having the prototype in the stern is out of the way because students board and disembark through the bow.

Constraint 2: "Cannot inhibit proctor's rowing."

The proctor sits in the center of the boat. A prototype placed in the stern is located about 5 ft away and clear from the proctor's space.

However, we found Marty's shelf would require installation onto the boat, which infringes upon the constraints "No modifications to the boat" and "Be non-permanent." Therefore, we decided the stern location was optimal but the shelf was not. To find how we could use the stern location without using a shelf, we called for a literature search for brainstorming. Here are the two main sources:

Background Source 1, 2: Inspiration from A Bicycle Basket

After brainstorming, we proposed a bike basket that would hang from the stern wall, which replaces the shelf design. A typical wire bike basket like the one in the **United States Patent 4730768** was considered, but the cost of machining metal wire did not suit our objective "easy to manufacture."

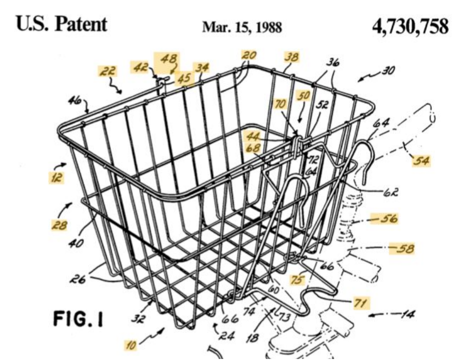

Figure 3: US Patent 4730768

The bike basket in the **U.S. Patent 803143S1** offered a more analogous structure applicable to our design space. This patent uses an "ornamental design for a bike basket" (Silver and Hort, 2015) has two hooks that could be used in our case to hang off the stern. Furthermore, the solid faces in this design are easier to manufacture tools available to us. Our prototypes contrast these patents as they are designed for laser-cutting.

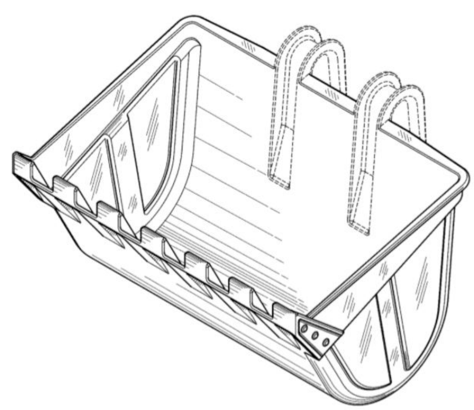

Figure 4: US Patent 803143S1

Background Source 3: Acrylic Material Substitute

To determine the appropriate material for these solid faces, we proposed acrylic as a good potential material as it could be laser-cut in the Harvey Mudd College Engineering Computational Facility (ECF). According to the **materials data source MatWeb**, the mechanical characteristics of Acrylic (PMMA) include "Shear Strength: 25.5 - 62.1 MPa" and "Tensile Strength, Yield: 64.8 - 83.4 MPa" (MatWeb). While the range of these numbers were indeed wide, the numbers were helpful as guidelines for relative comparisons when deciding the materials for our prototype, as well as our preliminary mathematical models. Later, we would use data provided by our acrylic manufacturer instead of MatWeb data for more precise analysis.

Reflecting on the design process as a whole, the field observations we made helped us empathize with the problem, and our background research was essential for the ideate and prototype stage.

Appendix 2: Developing Alternatives

Functions and Morph Chart

Table 12: Morphological Chart

Functions	Possible Means									
Stabilize/locks down project box	Velcro	Tape	Metal hook	Bungee Cord	Cage/cubby	Magnet	Suction cup	Clamp	Platform	Hooks and protrusions
Prevent water from entering box	Waterproof material	Waterproof seal	Suction seal	Smart hole shape and placement	Cable Seal	Acrylic walls				
Store electronics	Redesigned plastic Box	Plastic bag	Wood box	Waterproof electronic box	Original plastic box					
Intercepts box dropping into water	Net with metal rim	Pillows	Mini ball pit	Inflatable mattress retrofitted to boat shape	Stabilization proactively takes care of this	Hanging system				
Connects box and robot	Hole for cables on side of box	Ports on the box	Acrylic box/basket without lid							
Stabilizing the Sensor board	Cloth pocket	Plastic cup holder	Side acrylic pocket							

In order to broaden our design space and find many possible solutions to our design problem, we created a morphological chart that described which possible means we could achieve our functions. This helped generate a large list of possible designs to choose from, which we then narrowed down from there. Refer to the *Design Alternatives* subsection for an explanation of how the final design (in green) was chosen.

Design Alternatives

Table 13: Best-Of-Class Chart

Design Constraints (C) And Objectives (O)	Acrylic box with hooks	Strap down box to bench with bungee cord	Wire cage with metal hooks	Original box with cable seals
C: Room for two students and one proctor to enter, sit, and move		*		
C: Proctor should not be responsible for the box (plugging things in/out)				*
O: Be safe and protective for the electronics	1.5		1.5	
O: Be affordable and easy to reproduce design	1		2	
O: Be durable	2		1	
O: Be non-inhibiting to electronics inside box	1.5		1.5	
O: Easily stored with a small footprint when not in use	1.5		1.5	

The best-of-class chart is a method for ranking alternatives. The scores allow us to see that the acrylic box with hooks design is Pareto optimal (best in all categories). The design of strapping the box down with bungee cords fails to meet the constraint of having enough room for one student to sit on each side of the boat, as this currently is an issue Professor Spencer described to us in Client Meeting #1. The design of using the original box with cable seals violates the constraint of being able to plug cables in and out of the box. Our client also mentioned when teams switch off using the boat, they need to have easy access to the electronics to connect their robots.

From our chart, we can see that our two designs that do not violate constraints (acrylic box with hooks and metal cage with metal hooks) have similar performances in three of our objectives (being safe and protective for the electronics, being non-inhibiting to electronics inside the box, and easily stored with a small footprint when not in use). This makes sense because these are similar designs with the biggest difference in material. The acrylic one is easier to manufacture and reproduce while the metal one would be more durable.

We can not make a final decision on which design is better solely based on this chart, as the objectives have not been considered to have different weights, but it does allow us to evaluate our alternatives with respect to results for each metric.

Ultimately, we concluded that the acrylic box with hook design is better suited for our project because it only requires one step to manufacture on the laser cutter, which would allow us to make multiple prototypes with cardboard, then our final design with acrylic.

Prototype 1: Low-Resolution Prototype

In designing our first prototype, we developed two mathematical models to evaluate critical design parameters for the prototype, namely, how thick we needed the “handles” to be for the basket to be able to hold up both itself and the weight of the electronics. One modeled the shear force where the handle met the basket, and the other modeled the tension force where the handle met the basket. These models account for a large factor of safety (5x) added to the load, to account for real life usage where rough handling or other circumstances could increase the load on the design. A large factor or safety greater than 2 means our design is robust so it will last longer in the long run. Since we are not mass producing this design, a little extra material will not end up adding significantly to the cost. It is also important to note, however, that these models did not take each other into account, but rather modeled each possible load as if it were isolated. These models predicted that we essentially did not have to worry about the thickness of the handle in regards to the planned load of the electronics box. In reality, this structure needs to be able to handle much more external force, such as accidental bumps or brushing, in semi-random directions, so we opted for very thick handles to provide as much structural integrity as possible, as thicker handles would not add much to the overall cost while increasing the safety of the entire design.

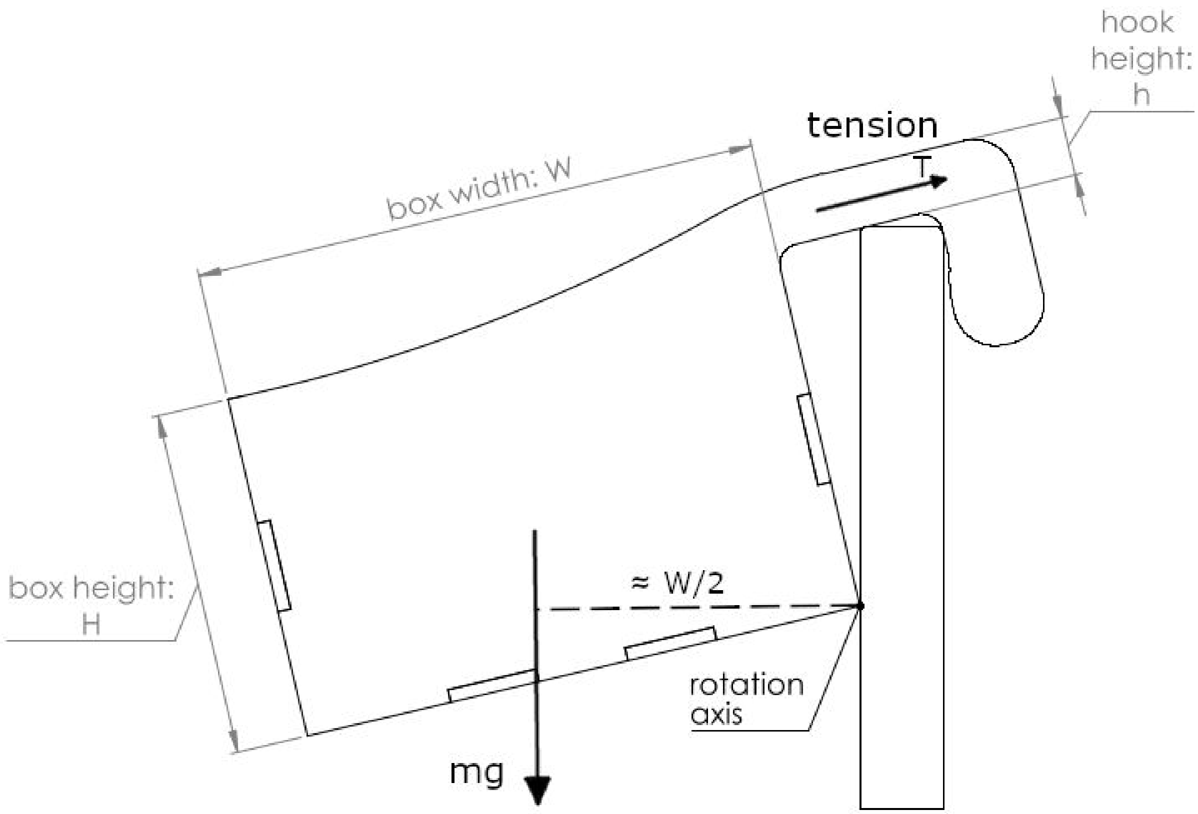

Figure 5: Diagram depicting the tensile load on the acrylic.

We can model part of the stress in this design as if the box were attempting to rotate around the bottom point of contact. Since the box is at rest,

$$\Sigma\tau = 0, \;\Rightarrow\; mg\frac{W}{2} = 2TH\,.$$

The maximum tension a material can handle is given by its yield strength:

$$\frac{F}{A_0} = \sigma$$

Given a thickness *t*, minimum height *h*, and force *T*, $T = \sigma th$. So

$$\frac{mgW}{4H} = \sigma th \;\Rightarrow\; h = \frac{mgW}{4H\sigma t}$$

Given $m = 2 * 5\ kg$ (including a safety factor of 5), $g = 10\ \frac{m}{2^2}$, $W = 16\ cm$, $H = 10cm$, $\sigma = 10.4\ MPa,\ t = 3.175mm$, then

$$h > 0.12\ mm$$

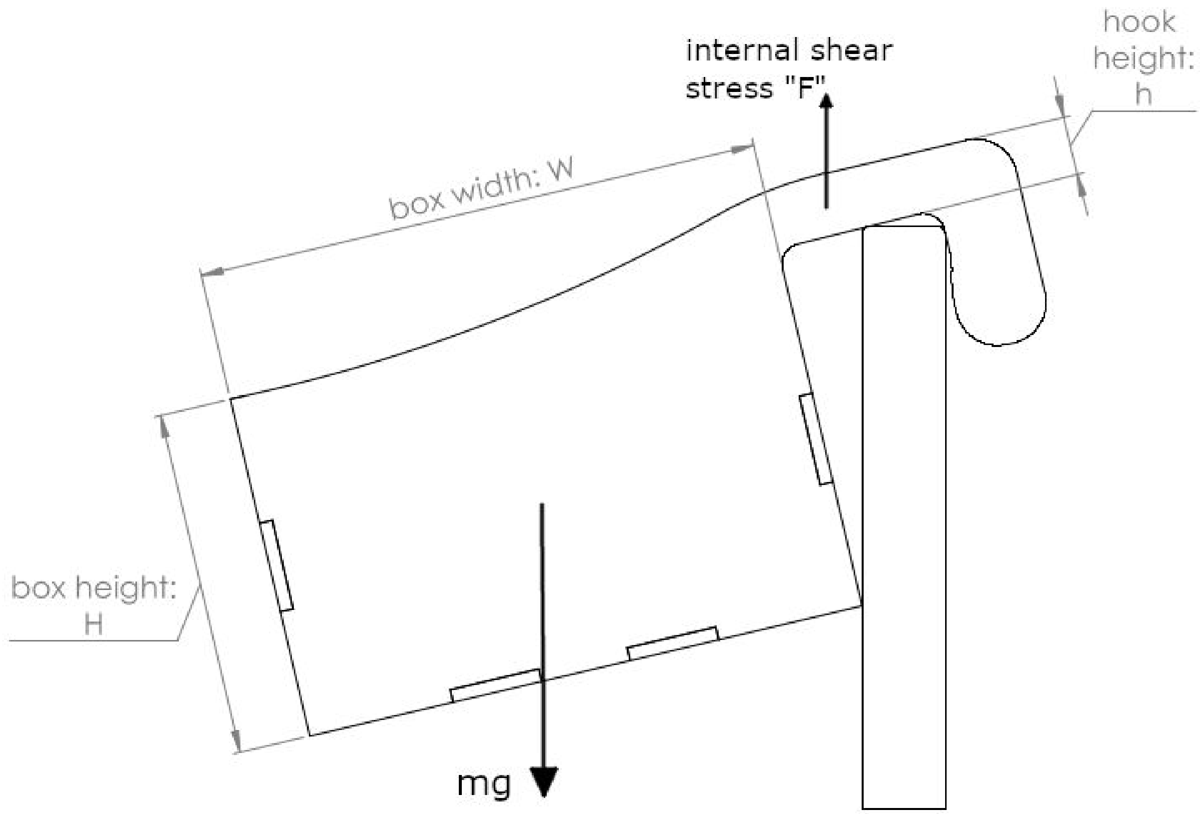

Figure 6: Diagram depicting the shear stress on the acrylic.

Some stress in the system could be modeled as a shear stress:

$$\Sigma F = 0 \Rightarrow mg \approx 2F$$

Max Shear Strength can be modeled by $\sigma = \frac{F}{A}$. So with shear strength σ, internal shear force F, a thickness t, and minimum height h, we get

$$F = \sigma h t \Rightarrow mg = 2\sigma h t \Rightarrow h = \frac{mg}{2\sigma t}$$

Given $m = 2 * 5\ kg$ (with a safety factor of 5), $g = 10\frac{m}{s^2}$, $t = 3.175mm$, and $\sigma = 25.5\ MPa$ then

$$h > 0.6mm$$

These models indicate that the height of the handles did not have to be very big at all in order to hold the weight of the electronics box under normal load (approximately 1 millimeter). We decided while this bode well for our design, we should still make the handles thick in order for the box to be able to handle accidental bumps and loads, so that it would remain sturdy for a long period of time.

Figure 7: Our first prototype, a cardboard "bike basket" design

Our first prototype, made in cardboard in order to reduce cost, showed the general form factor of the assembly and gave us a feel for the structural rigidity of the box. Our design started with a box automatically generated from the website makercase.com, which let us easily insert finger edge joints for ease of construction and structural support. We modified this box to then include hooks with rounded edges to reduce the possibility of stress induced fractures. This design was then laser cut and glued together with hot glue for testing.

The question we wanted to answer with this original prototype was if the geometry of this model was secure and structurally sound enough to safely hold the electronics.

To answer this question, we had decided to simulate the actual use of this cardboard prototype on the boat to understand how the geometry of the prototype (despite the weaker material) performed. By using cardboard, we could look for possible points of failure, visible tears, wrinkles, or stresses in the cardboard, and any other disadvantages that we did not predict. Cardboard fails much more quickly than acrylic (exact tensile and shear strength parameters vary widely and are not easily accessible), and is much less brittle, so using cardboard enabled us to visualize stresses in real life that are under the yield tensile and shear stresses of acrylic.

Unfortunately, due to the constraints imposed by the Covid-19 outbreak, we were unable to test the box in the actual boat, but were still able to test it in our classroom.

We initially tested this model by hanging it from a vertical "wall" with a similar width to that of the boat wall, and putting the electronics box inside. This managed to hold up very well. We did notice, however, that sometimes if the handle was brushed laterally (if we accidentally bumped it, for example), that the cardboard wrinkled slightly. While we attributed this to the fact that the cardboat flexed much more easily than acrylic, we decided to test a side-load in subsequent models to see if the acrylic would be able to handle this.

We ultimately decided that while this model was relatively durable due to the fact that the cardboard prototype made of weaker material than acrylic was able to uphold the electronic box with just some wrinkles where hooks connect to the box. Further simulation of the acrylic model was required to see if it could withstand large bumps and accidental forces that it might encounter in the real world.

We also ran stress analysis tests of this prototype in order to verify that this design would work in acrylic. We initially wanted to test whether or not our design would be able to hold the weight of the electronic box, which is about 2.5 pounds. Since our factor of safety model proved that none of the parts were in danger of breaking, we then ran the same test again but with 100 pounds of pressure. We wanted to be sure that the acrylic would not break under the pressure of someone trying to use it when they got up from the boat.

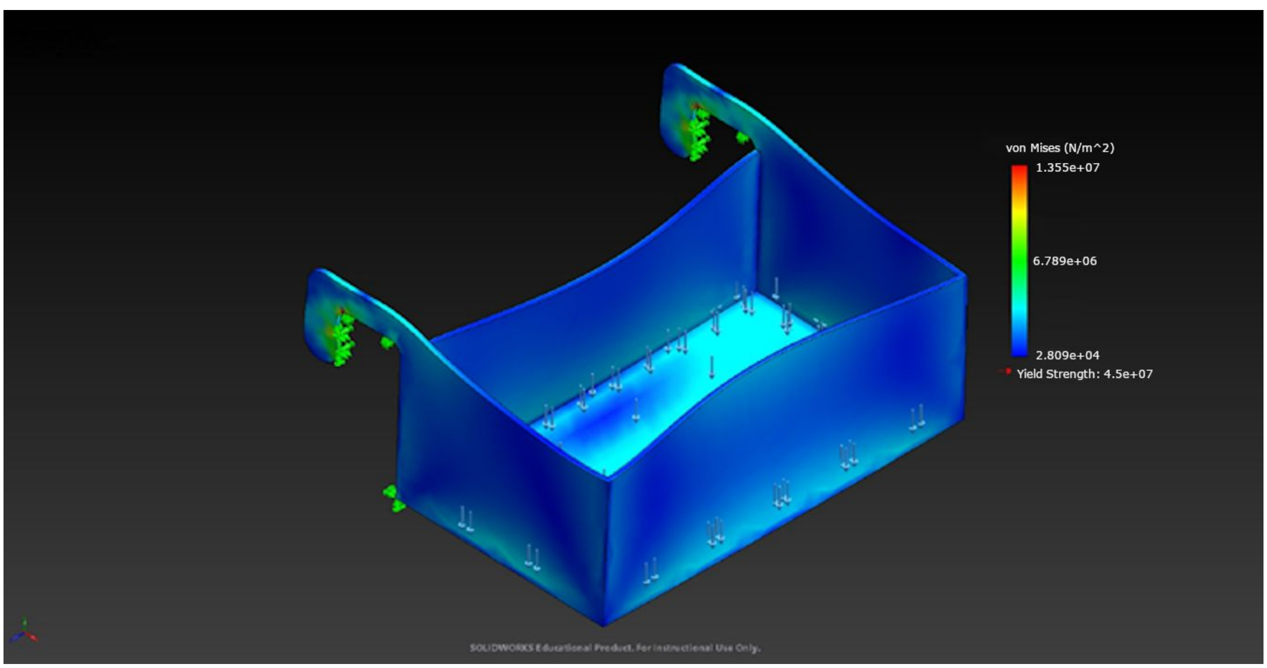

Figure 8: Stress analysis test of our first prototype (acrylic) with a 100 lb downward load

The diagram above shows the points where our prototype would experience stress and as well shows how it would deform. We made this model with the assumption that it would be fixed around the hooks and the bottom edge as they are all points of the contact with the boat. So we see here that the points of stress (in red) are going to be higher in those areas in contact with the boat, however even with an unreasonably large force acting on it we see that the yield strength of the material is well above anything experienced by its parts.

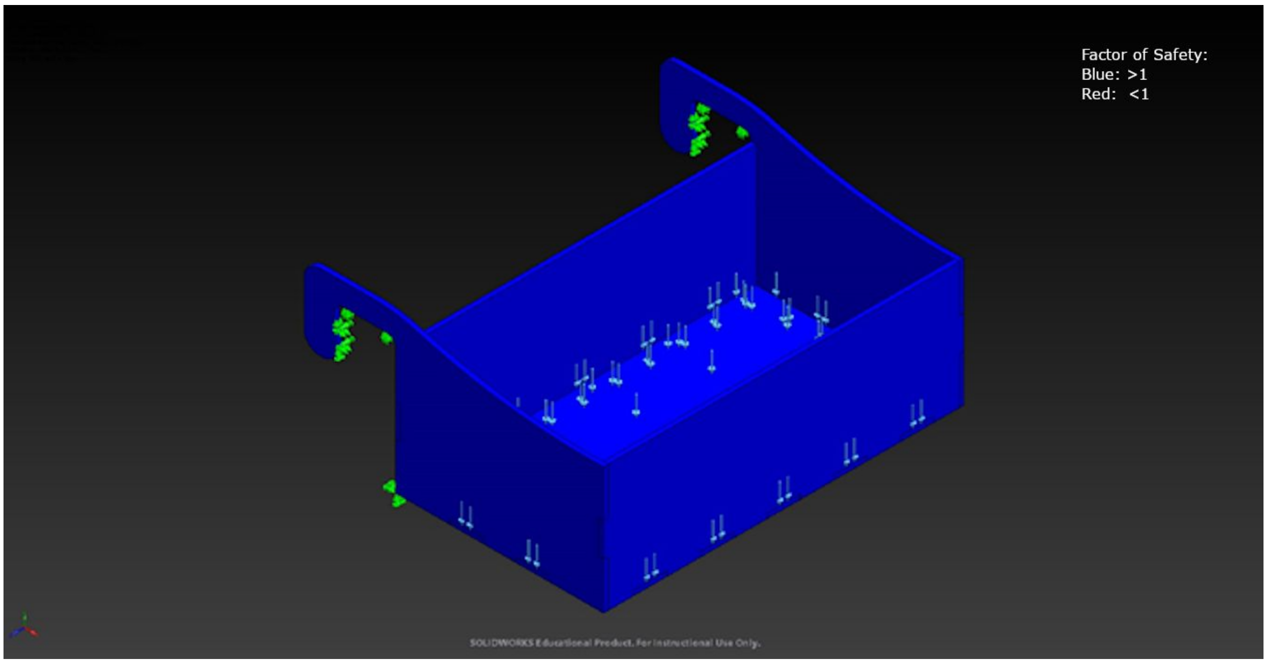

Figure 9: Factor of safety model of our first prototype (acrylic) with a 100 lb downward load

This diagram shows how likely and where our prototype might fail with a 100 lb downward load on the bottom of the box. Regions in blue demonstrate locations that lack risk of failing, where the safety factor is more than 1. The factor of safety of the model is above 1 in all regions, representing that the model will be very resilient under these conditions.

Due to the electronics box only being around 2.5 lbs, and the fact that it is unlikely for someone to fall on it due to its position on the boat, we believe it is safe to assume the box will be unlikely to break.

We also acknowledge the fact that forces might not come solely in the downward direction and, in future stress tests, have modeled such possible behavior.

Prototype 2: CAD and Computational Model

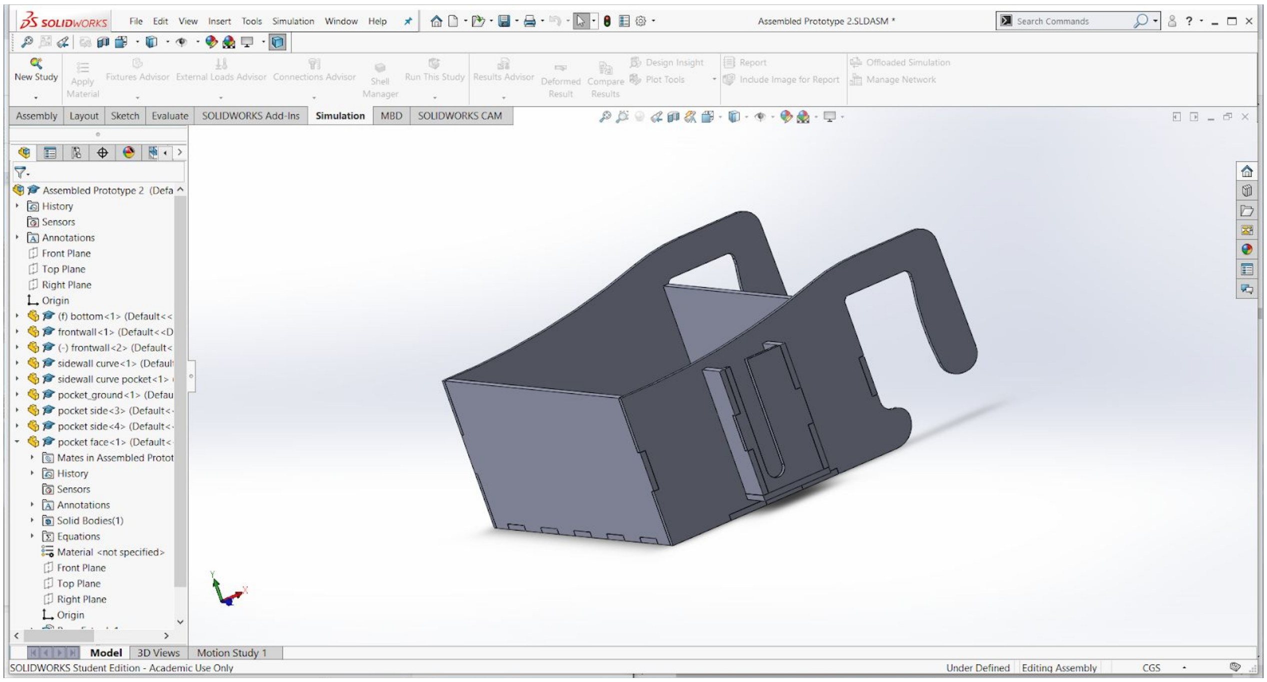

Figure 10: Second prototype on CAD with added features of extended hook, added pocket, and extra support on side panels

Using our feedback from Design Review One, second Client Meeting, and Advisor Meeting, we made our second prototype on Solidworks CAD. Since our client, Professor Spencer, was worried about our box falling into the lake if the boat bumped into another boat or bushes, we extended the hooks of our box. He also pointed out another function for our design that we were not aware of, which is that it needs to hold the sensor board (that connects to the electronic box and robot) in place. Thus, we added a vertical pocket with a slot so the sensor board can slide into it while the cable connecting it to the robot can still come out. Lastly, Professor Duron voiced his concerns about too much stress on the bottom outside edge of the box in contact with the boat. To address this, we added a protrusion for extra support on the side panels of the box.

Computational Results: FEA Stress Analysis

For the FEA of our new box, we modeled the loads on the box more realistically, particularly by better modeling the *hanging* interaction that the hooks perform, rather than having the hooks fixed in space. Since our objectives include the box being durable and being safe and protective for the electronic, we want to be sure that it would not break under real conditions. We also wanted to model possible interactions with the box, such as a student bumping or hitting it. Thus, we added pressure on the sides of the box, where the thin hooks are weak.

To accomplish this in a stress study in SolidWorks, we used a basic model of a 1 inch boat wall with filleted edges. We then also overhauled the way we defined every individual piece to be connected to each other in the assembly. Instead of including a 'global bond' contact, the SolidWorks default, we individually modeled a bonding force between every face of each tooth of each wall that interacted with another wall. We then made the two side walls of the box interact with the side wall using "component contact," without penetration, for the most realistic results. Note that this means the box was not bonded in any way to the wall itself, which is crucial to correctly modeling this system. The sides of the wall were fixed. The external loads we modeled included gravity on the box (letting SolidWorks calculate the weight of the box using its density for acrylic), and a simple 100N (~10 kg at sea level) downwards force on the bottom of the box.

We also decided to change the type of stress we chose to model. Our original type was the default on Solidworks, Von Mises, which is a theoretical measure of stress used to estimate yield failure criteria in ductile materials. Since acrylic is a brittle material, and in consultation with our advisor, we decided to measure the first principal stress, which is a more directly measurable stress and allows us to identify where this box could fail. The first principal stress is the stress that is normal to the plane where there is no shear stress. For a brittle material like acrylic, this gives us a stress force that we can compare with tensile strength values from the manufacturer's data sheets.

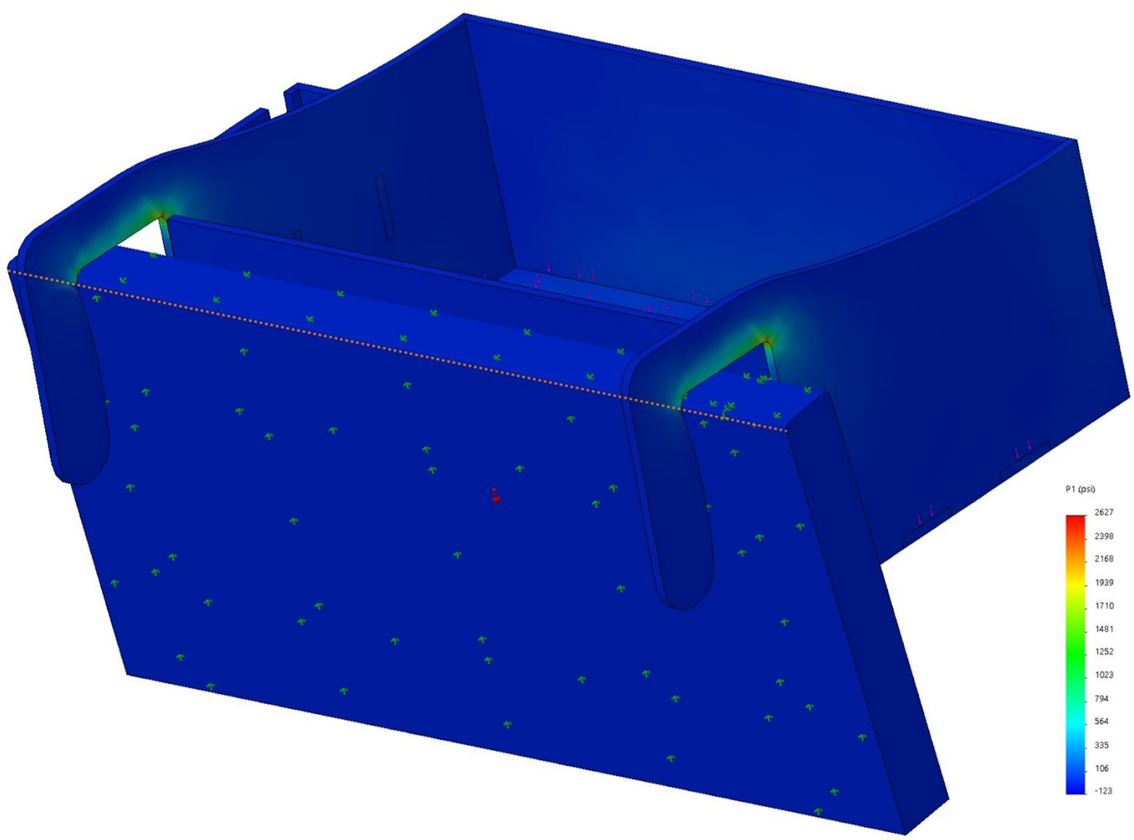

Figure 11: First Principal stress of the box hanging off the wall with 10kg downward load

This model shows where our prototype would experience stress with the least amount of stress in blue and most amount of stress in red. The area with the most amount of red is in the corner of the bottom side of the hooks.

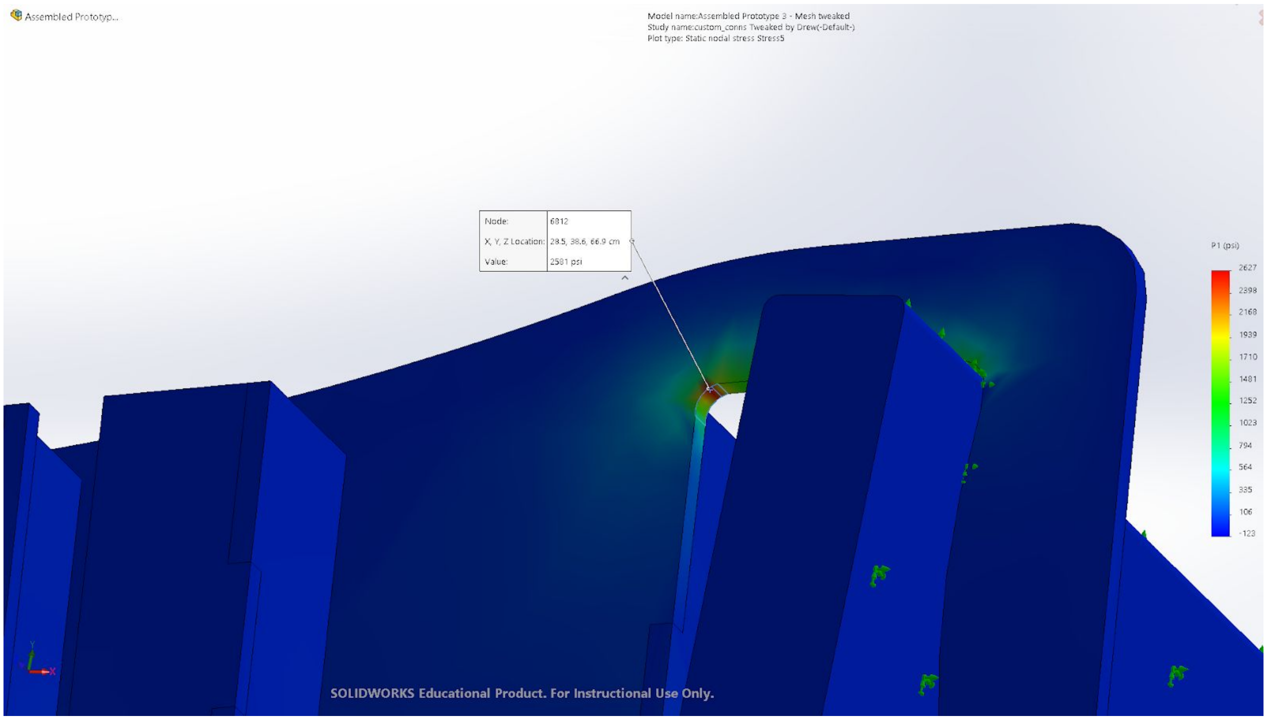

Figure 12: First Principal stress at greatest stress point with 10 kg downward load

The probe is at the area of greatest stress for the 10 kg load simulation. The stress reads at approximately 2,600 psi. According to McMaster-Carr and Matweb, acrylic's tensile strength is approximately 10,000 psi. Therefore, we are good to a factor of greater than 3.5. This means that our hooks are not going to break off under these conditions.

We also tested this model in a possible real-world situation of someone bumping into the box, where a 100N force is applied to the side of the box, as well as the original 100N load of the electronics box and gravity acting on the mass of the model. We applied this force to the front panel, pointing inwards towards the box, in order to be able to model a relatively concentrated force onto the box. In this model, we also increased the friction of the box on the wall to .99 in order to make the box internalize all the stress, rather than let it slide across the wall.

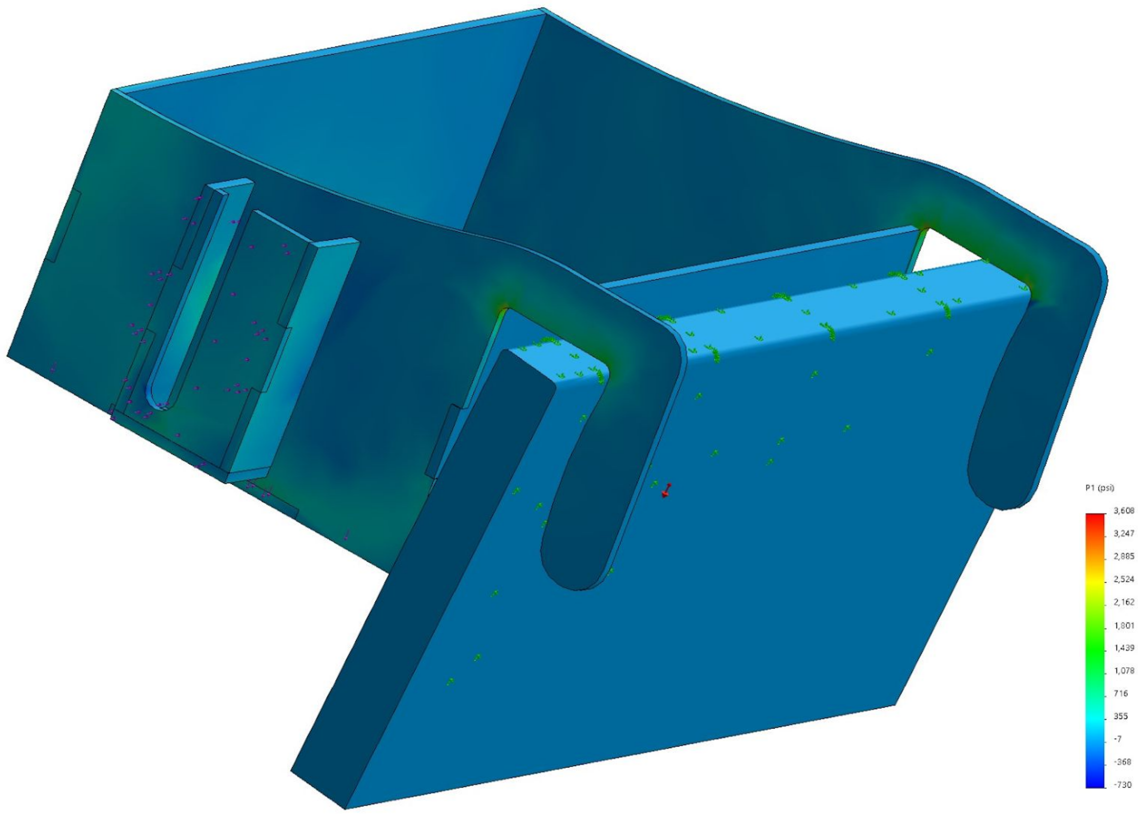

Figure 13: First principal stress on model with 10 kg downward load and 10 kg side-load on pocket

This model displays the additional 10 kg side-load on the pocket, pointing inward with purple arrows. The simulation identifies where our prototype would experience the most negative amount of stress in blue and most positive amount of stress in red. Similar to the last test, the area with the most amount of red is in the corner of the bottom side of the hooks. Note that the axis shows that the model experiences, at its minimum, an approximately -700 psi stress, which is compressive. This is well within what MatWeb lists as 16000 psi for acrylic's compressive yield strength.

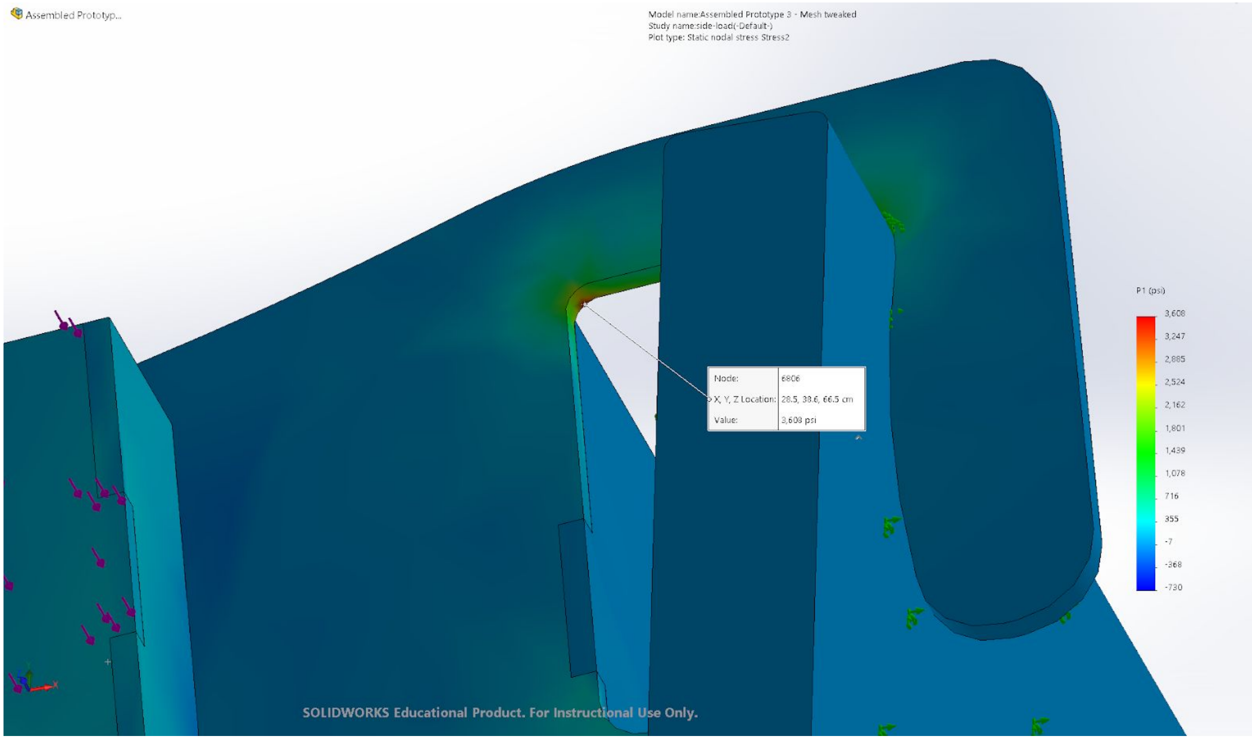

Figure 14: First Principal stress at greatest stress point with 10 kg downward load and 10 kg side-load on pocket

The probe is at the area of greatest stress for the 10 kg downward load and 10 kg side-load on pocket. The stress reads at approximately 3,600 psi. According to McMaster-Carr and Matweb, acrylic's tensile strength is approximately 10,000 psi. Therefore, we are good to a factor of greater than 2.5. This means that our hooks are not going to break off under such a side-loading condition.

Appendix 3: Technical Drawings of Final Prototype Components

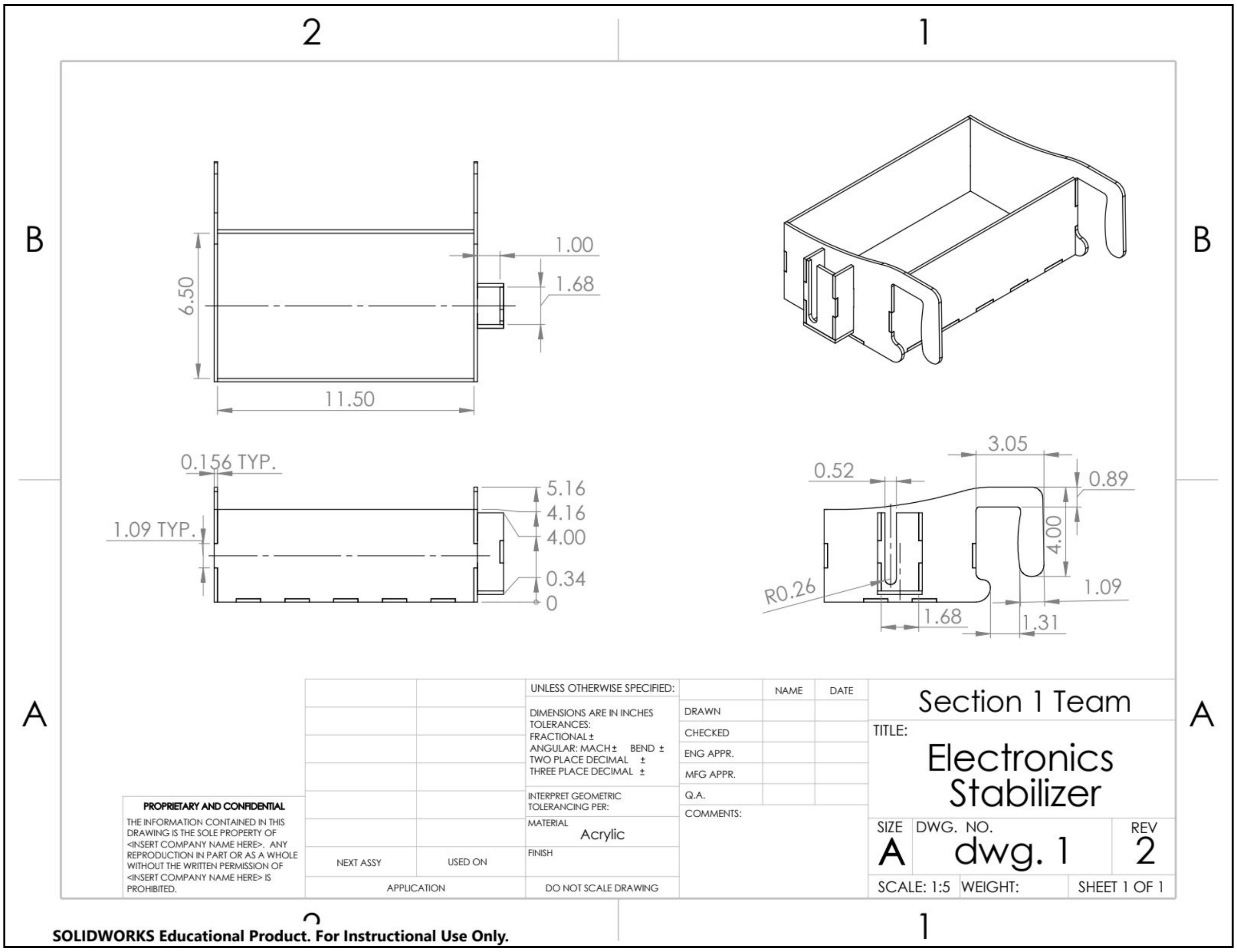

Figure 15: Technical drawing of second prototype

Appendix 4: Logistics

Project Management

We used the Gantt Chart to keep track of the details for each project and who was in charge of each part. Here is a link for the Gantt Chart.

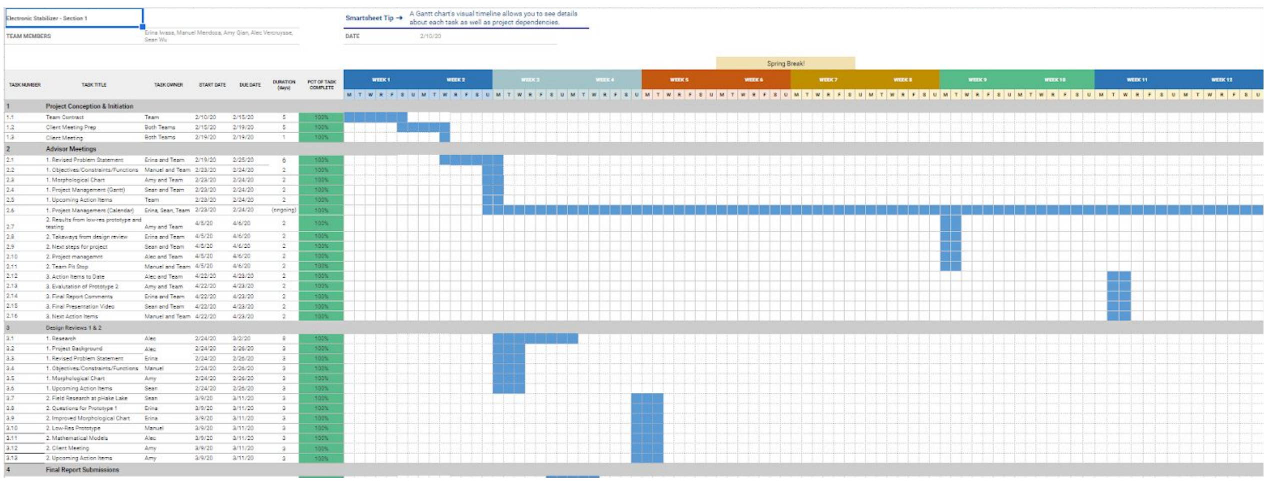

Figure 16: Gantt Chart

We also created a calendar with our main meetings and deadlines. Here is the link for the full calendar.

Included on the following page is a timeline of our main meetings and deadlines from our calendar in 2020. Eleven of the twelve Monday (and periodic Sunday) weekly team meetings were not included on the timeline to reduce redundancy.

Figure 17: Timeline of E4 Project

Project management reflection

From our E4 project, we learned that communication and planning ahead is important for project management. We learned to clearly communicate with each other about our goals, responsibility, performance, expectations and feedback. Specific examples include communicating when to schedule our team, client, and advisor meetings because we want to find a time that works for as many people as possible. We actively practice being comfortable, open, and honest with each other. For instance, when we were brainstorming potential means on our morphological chart, everyone proposed ideas without fear of judgement. Nobody was mocked for their ideas. We recognized everyone has something important to say, and practicing how we express ourselves will help us improve. Instead, we offered perspective for each other to reflect on strengths and weaknesses of each idea. Bringing up ideas and thinking out loud lets us review our blindspots and combine our experiences. We ask each other for clarification on prototyping ideas. We often found that sharing a visual helped us understand each other's ideas better. After all, our current prototype was inspired from an existing idea of a bike basket. Practicing psychological safety helps us feel free and work effectively. We also learned to plan ahead, as there are many deadlines for our project. With our Gantt Chart and calendar, we are always looking ahead at least a week in advance to make sure we complete all the deliverables on time. Also, we remind each other about meeting times in our Facebook Messenger group chat.

The project management tool that was most helpful was the team calendar we created. It was concise and easy to refer to. It is beneficial to see the visual layout of meeting dates and deadlines. The Gantt Chart was more difficult to use because it took much more time to fill out all the details of each project. We found it more helpful to directly refer to the Project Handbook on the E4 website. Also, we do most of our work during team meetings, where we split up the work but can ask each other questions during the meeting and get more feedback efficiently.

In future projects, we would want to use Trello, a collaboration tool that organizes your projects into boards. We heard that some clinic teams use Trello and it is a better organizational tool so we can have all our resources in one place instead of using both the team calendar and the Gantt chart. Trello tells you what's being worked on, who's working on what, and where something is in a process. This would be even more helpful when we switched to working with our team remotely.

Budget

For our first prototype made of cardboard we gathered the materials from the Rapid Prototyping Lab (RPL) inside the E4 classroom. Corrugated cardboard can be found cheap online and using the fact that our first prototype had a surface area of 238.88in^2, a \$2 30”x40” sheet would be more than enough to fully assemble it. We also put the prototype together with hot glue, which can be bought for less than \$5. Thus our first prototype would have been under \$7 to fully manufacture. It is important to note that these materials were taken for free from the RPL so these costs are just estimates of what would have actually needed to be spent. As well, no personal protective equipment was necessary to acquire for this project.

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