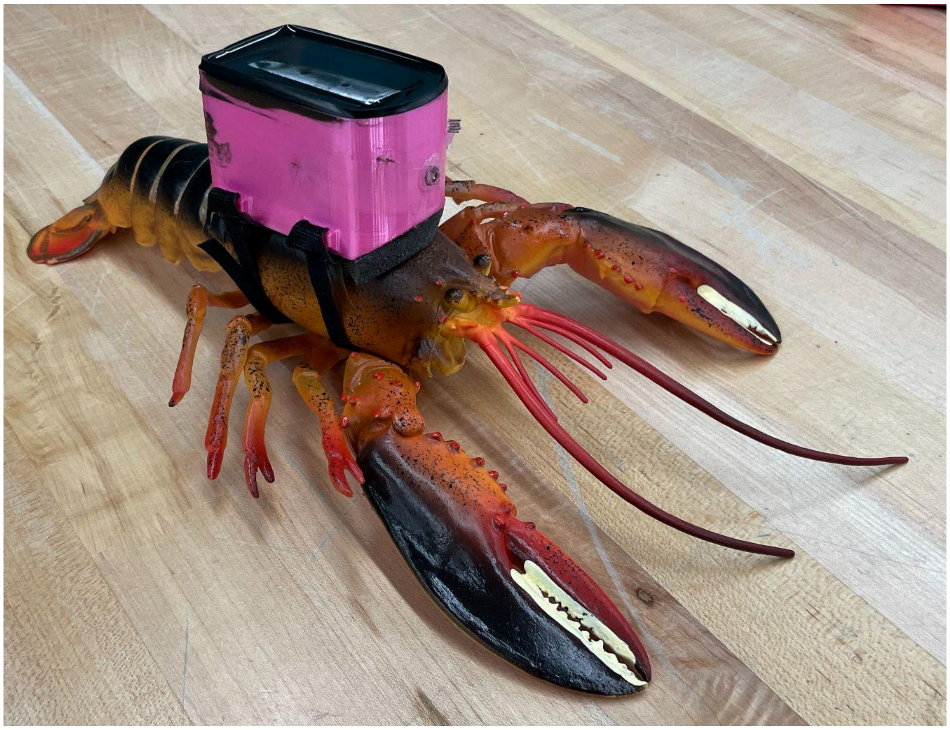
Improving a Biologging Tag for the Persistent Monitoring of American Lobster Physiology and Movement

April 29, 2024



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EXECUTIVE SUMMARY

Scientists would like to understand the causes and effects of environmental stress due to ocean noise on marine life from under sea construction and wind farms [2]. The American lobster can sense the frequencies and amplitudes of the sound produced by under sea construction and therefore may be at risk of elevated stress due to noise [3]. Previous research has shown a link between stress and heat rate in the American lobster [4]. The C-HAT (Crustacean Heart and Activity Tracker) is an open source biologger developed at the Department of Biological Sciences, University of New Hampshire that can continuously measure triaxial acceleration, compass heading, and heart rate of lobsters [4]. A shortcoming of this system is the large repurposed gopro case that is used as an air cavity to hold the electronics [1]. This bulk may impede the natural functions of the lobster due to the lobster not being able to fit into their burrow [5]. The goal of this project is to create a new packaging and mounting system for a lobster stress biologger that is less intrusive to the lobster while recording reliable and accurate measurements. This project will have an impact on the stakeholders by directly providing a solution to researchers and indirectly benefiting lobsters and related industries though the research performed. The highest priority design requirements relate to the optimal operation of the IR heart rate sensor. The next highest priority requirements relate to the packaging and mounting solution creating the least disturbance to the lobster. Photoplethysmography was determined to be the best method to measure stress non-invasively.

Concept generation was split though functional decomposition into two sections: sensing and packaging. In each section the team generated ideas collaboratively without closing the design space and then narrowed down the possible design solutions. A pugh chart was made to find a final solution.

The final design consists of a 3D printed skeleton that is potted to waterproof the electronics. A rubber foam seal blocks out IR light from reaching the IR sensor. The fully self contained design is fully potted in epoxy with the addition of a 5-pin interface for waterproof data retrieval. Another design called the Lobster Leash has a cable that connects the datalogger electronics out of the water for tank testing. Initial testing of the IR sensor was conducted and showed that a human pulse can be measured and used to accurately measure heart rate. After testing the infrared absorptivity of multiple different interface materials, the silicone suction cup was replaced with a rubber foam interface. This foam is more form fitting and better blocks out ambient infrared light, in addition to providing a firm attachment when paired with the velcro straps.

During the potting of the sensors in our build design (the lobster leash) and all of the electronics in the final design, we experienced an epoxy leak that damaged the lobster leash's IR sensor. There was also potential damage to the final design's IR sensor indicated by our inability to read our own heart rate with the C-HAT, but this may also have been caused by anatomical differences between us and lobsters. Due to these difficulties, we have also redesigned our verified mounting interface to also fit the currently used Go-Pro case housing. This design allows for the easy replacement of electronics and can be used immediately by our sponsor.

ABSTRACT

Noise from off-shore wind farm construction and operation will impact animals in these marine environments. Our project sponsor would like to investigate the relationship between ocean noise and stress on the American Lobster. Changes in heart rate and behavior have been used to quantify stress response in animals. The C-HAT biologger has been used to measure stress using an IR heart rate sensor, but is large compared to an adult lobster. Our project is focused on reducing tag size, improving attachment with the animal to enhance IR measurement quality and reduce impact to the lobster.

INTRODUCTION

With previous studies already linking changes in marine life behavior and physical injury to ocean noise created from offshore wind turbines, as well as the growing presence of wind farms in New England with the construction of Vineyard Wind, researchers at WHOI are concerned about the effects this noise will have on the American lobster. As such, they have asked us to improve upon the C-HAT, an open source biologger used to track the movement and physiology of a lobster. In this section, further background on the issue of ocean noise will be provided, along with information regarding the sound detection and stress response of the American lobster. Finally, we will introduce how the C-HAT functions and the requested design improvements.

Ocean Noise

Offshore wind energy as an emerging industry offers great potential for meeting global decarbonization goals [6]. However, new research has also shown that offshore wind farms cause large levels of ocean noise throughout their lifetime. The duration of the key phases in a wind farm's lifetime (surveillance, construction, operation, and decommission) as well as the relative noise levels they produce, are shown below in Figure 1.

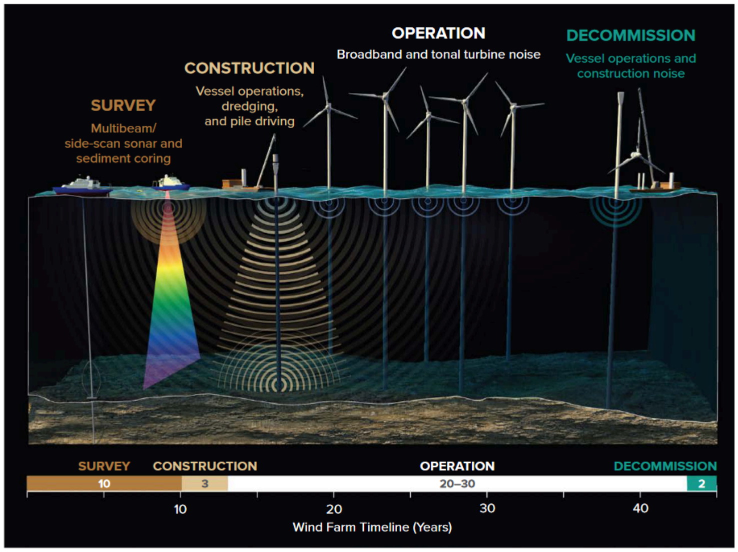


Figure 1: This graphic shows the length of offshore wind farm projects, with the length of the timeline shown here lasting roughly 45 years [2].

The most noise is generated during the construction of these sites, which require extensive undersea mining and pile driving. During the time of construction, sound pressure levels can reach the order of 220 dB re 1 μPa at a distance of 10 meters from the pile drivers, and 200 dB re 1 μPa when at a distance of 300 meters [2]. The frequency of the sounds produced by pile-driving are shown through a spectrogram of three impulse pile-driving signals in Figure 2a, which shows that the predominant energy of the wave lies below 500 Hz, with some energy reaching beyond 1 kHz. This range of frequencies directly overlaps with the auditory bandwidth of many fish and invertebrate species, meaning nearby marine life are subject to these loud, repetitive sounds around the construction sites [2]. The magnitude of the sound pressure produced by pile-driving at a given distance from the driving site is shown in Figure 2b.

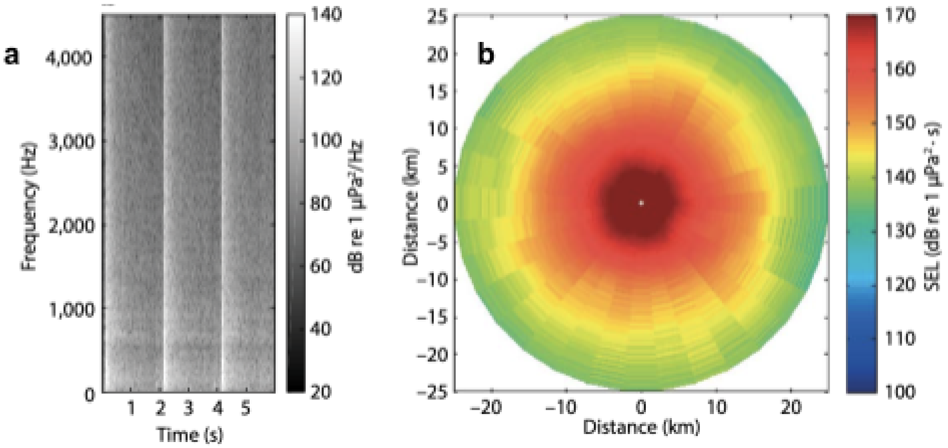


Figure 2: (a) A spectrogram of three impulse pile-driving signals recorded during the construction of the Block Island Wind Farm in Rhode Island and (b) the propagation of piling noise from a single strike (source magnitude of 226 dB re 1 μPa^2 · s) as a function of direction and distance. The three vertical lines in (a) represent strikes of the hammer hitting the pile at a time of 0, 2, and 4 seconds, while the intensity of the line shows the relative intensity of the sound at each frequency. Note that most of the energy occurs at frequencies below 500 Hz. The highest sound levels are shown to quickly drop off near the source in (b), but more moderate sound levels (140-170 dB) can propagate 25 km [2].

This construction is not the only ocean noise these wind farms are producing, though. The survey of the ocean floor before construction, the operation of the wind turbines, and their decommission all contribute significant amounts of noise to the surrounding waters. Surveyal typically produces sound pressures ranging from 200-250 dB re 1 μPa, which is fairly intense, but the frequency range of these sounds is outside the range detectable by fish and invertebrates. During operation, the sound pressure from a single turbine will range between 105-125 dB re 1 μPa at a distance of 100 meters, with the frequency range lying entirely below 1kHz [2]. While less data exists for the decommission of these wind farms, the decommissioning of a British wind turbine in Amrumbank West showed sound pressure levels of 198-199 dB re 1 μPa at frequencies ranging from 250-1,000 Hz [7].

The marine life subjected to this noise faces a wide range of effects. Within the construction phase especially, the high intensity of the sounds has shown to cause damage to hearing tissue in numerous fish and turtle species, with hearing loss occurring in turtles after sound exposure levels of just 160 dB re 1 $\mu Pa^2 \cdot s$ at 400 Hz [2], [8]. Many fish face damage to other organs as well, with this damage proving to be fatal to some species [9]. While the sounds of operation are unlikely to cause physical injury, multiple behavioral changes have been noted, including less structure in schools of European seabass and the delay of the metamorphosis of crab megalopae [2]. There has also been a notable reduction in the fish and mammal populations surrounding active wind farms as these animals will now avoid these areas. The typical range that various marine species will avoid around an active wind turbine are shown below in Table 1.

Table 1: Typical distances kept from offshore wind turbines by marine species [10].

Species	Calculated range for significant avoidance reaction [m]
Salmon	1400
Cod	5500
Dab	1600
Bottlenose Dolphin	4600
Harbour Porpoise	7400
Harbour Seal	2000

The American Lobster

American lobsters hold a place of great importance in New England. In a recent interview, a New England resident describes the lobster as "... integral to the culture and pride of New England…", even saying that "... lobster is a state of mind," [11]. Beyond the cultural significance, lobster fisheries have been a vital part of New England's economy, supporting 18,000 jobs and producing nearly $725 million in revenue in 2021. However, the American lobster and the industry it supports is facing a dramatic decline, with revenue dropping to only $388 million in 2022 due to climate change, declining lobster populations, and increasing fishing regulations [12]. In addition to these already diminishing numbers, the recent construction of Vineyard Wind off the coast of Massachusetts places a new wind farm near two high population migration zones of the American lobster, as shown in Figure 3, pg 8. As such, researchers at the Woods Hole Oceanographic Institute (WHOI) are concerned with how the ocean noise produced from wind farms will affect the local American lobster population [1].

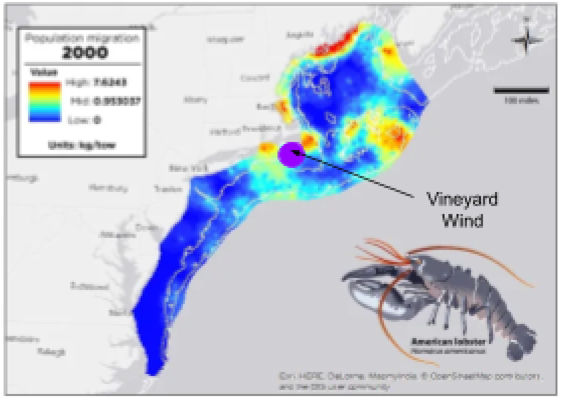


Figure 3: A map of the migration of the American lobster, with the location of Vineyard Wind noted [13].

A recent study conducted by WHOI determined that the American lobster detects sound using an array of hairfans that span a lobster's body. These hairfans allow the lobster to detect soundwaves between 80-250 Hz, and the sound pressure level (SPL) required for detection for this range of frequencies is shown below in Figure 4 [3].

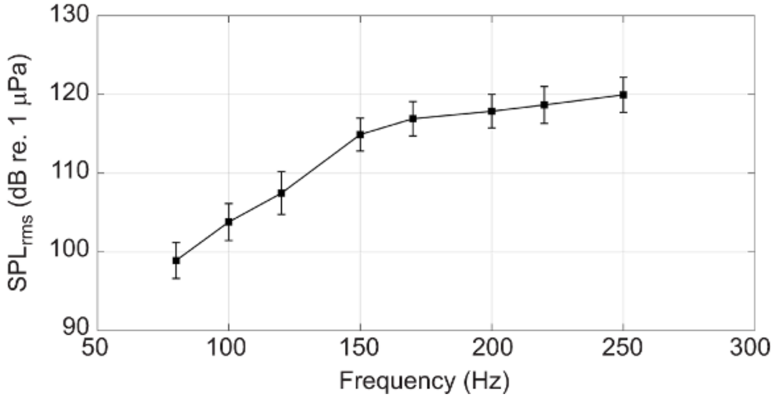


Figure 4: Sound pressure level (SPL) required for detection across the American lobster's range of hearing of 80-250Hz. Note the lobster is most sensitive to sounds with a frequency of 80-125Hz [3].

With turbines producing low frequency sound pressure levels of 105-125 dB re 1 µPa from 100 meters away, any nearby American lobster will be able to detect the constant, loud noises produced by a wind farm. Previous studies have linked other environmental changes, such as ocean temperature and salinity, to increased stress levels of the lobster [14], [15]. Elevated levels of stress in lobsters have been shown to directly correlate with a reduction in immune function as well as an increase in protein degradation [14], [16]. These elevated levels of stress are typically measured using molecular probes which measure the expression of genes coding for heat shock proteins (HSPs) via mRNA levels, or by measuring the levels of crustacean hyperglycemic hormone (CHH) in the lobsters' hemolymph [14], [15]. However, both of these methods require the analysis of a tissue or hemolymph sample from the lobster, so the stress levels cannot be actively measured by these means. A recent study by the Department of

Biological Sciences at the University of New Hampshire has shown a link between a lobster's detection of an external stressor and patterns within their heart rate, specifically a decrease in heart rate of at least 20%, followed by an increase in heart rate [4]. This method of measuring stress offers greater potential for the monitoring of the American lobster as it can be measured actively and non-invasively. A comparison of each of these methods can be seen in Table 2.

Table 2: Comparison of different methods of measuring stress in the American lobster.

Method of Measurement	Indicates Presence of Stress	Non-Invasive	Actively Measurable
CHH	✓	X	X
HSPs	✓	X	X
Heart Rate	✓	✓	✓

There are multiple methods used to measure heart rate in humans that could potentially be used here, including phonocardiography, blood pressure, electrocardiograms, and photoplethysmography [17], [18], [19], [20]. Phonocardiography detects and records heart sounds in order to measure heart rate [19], making it a non-invasive method, but with sound being the introduced stressor, any sensor will be subject to large amounts of environmental noise. While this noise would not be a problem for the blood pressure method, it would be difficult to measure non-invasively through the lobster's shell. Electrocardiograms have been successfully used on lobsters before, but require implanting electrodes [21].

Photoplethysmography offers a non-invasive method for monitoring rate. This method works by placing a small transmitter and receiver placing a small infrared sensor, consisting of an emitter and receiver, over a blood vessel. Depending on the amount of hemoglobin (or hemocyanin for lobsters) in the blood vessel, various amounts of light are reflected back to the receiver, allowing blood volume to be measured overtime. The rises and falls in this volume correlate to the systolic (high pressure) and diastolic (low pressure) phases of the heart beat and can then be used to find the heart rate [17], [22]. An image demonstrating this process in a finger blood oximeter can be seen in Figure 5 below.

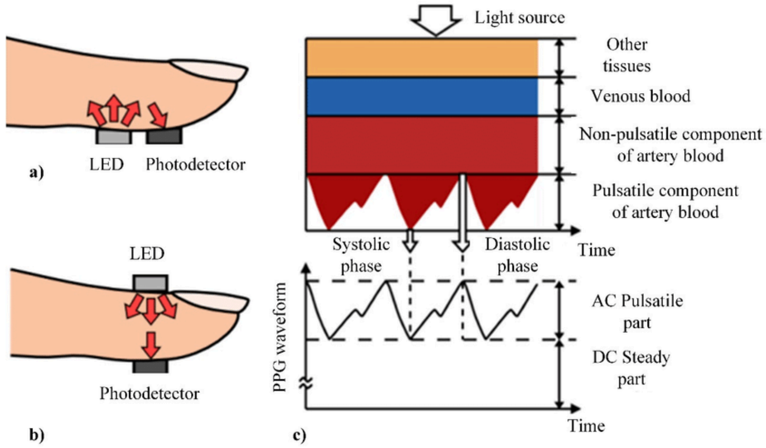


Figure 5: Potential placements for the transmitter and receiver on a finger blood oximeter (a) and (b), as well as a demonstration of how this measurement is used to determine heart rate (c) [22].

Thus, photoplethysmography offers an option where the heart rate of the lobster can be measured by simply placing an infrared sensor on the carapace of the lobster. A comparison of the viability of each of the mentioned methods to measure heart rate is shown below in Table 3.

Table 3: Comparison of different methods of measuring heart rate in the American lobster.

Method of Measurement	**Unaffected by Environmental Noise**	**Functional in the Field**	**Non-Invasive**
Phonocardiography	X	✓	✓
Blood Pressure	✓	X	X
Electrocardiograms	✓	✓	X
Photoplethysmography	✓	✓	✓

To get accurate heart rate measurements from a lobster using photoplethysmography, the IR sensor must be placed directly above a blood vessel of the American lobster. The largest blood vessels in a lobster are located just below the carapace on the lobster's back, as shown in Figure 6.

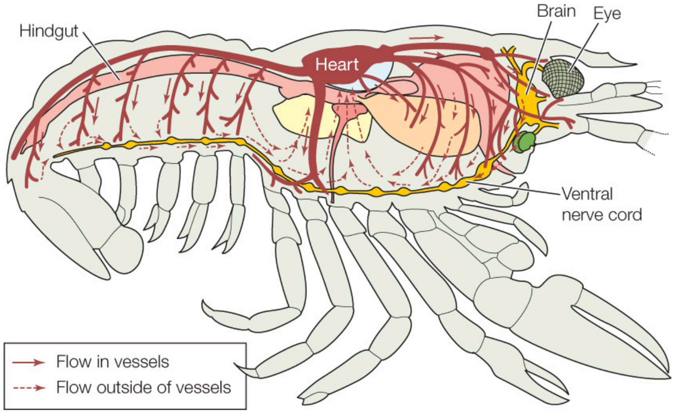


Figure 6: The circulatory system of the American lobster [23].

The C-HAT

In order to monitor this heart rate and the behavior of the American lobster, researchers at the Department of Biological Sciences at the University of New Hampshire developed the Crustacean Heart and Activity Tracker (C-HAT). This open source biologging tag consists of a temperature sensor and photoresistor to measure the environmental temperature and light, as well as a real time clock, accelerometer/digital compass, infrared sensor, and an Adafruit Feather 32u4 Adalogger. The lobster's movement can be monitored using the time data, a movement index found from the triaxial acceleration, and the compass heading through linear regression in a dead reckoning algorithm, while the heart rate is measured using photoplethysmography [4]. The initial design of this tag housed these components, along with a battery, in a repurposed gopro case as seen in Figure 7a, pg 11. An image of a lobster with the C-HAT during field testing can be seen in Figure 7b, pg 11.

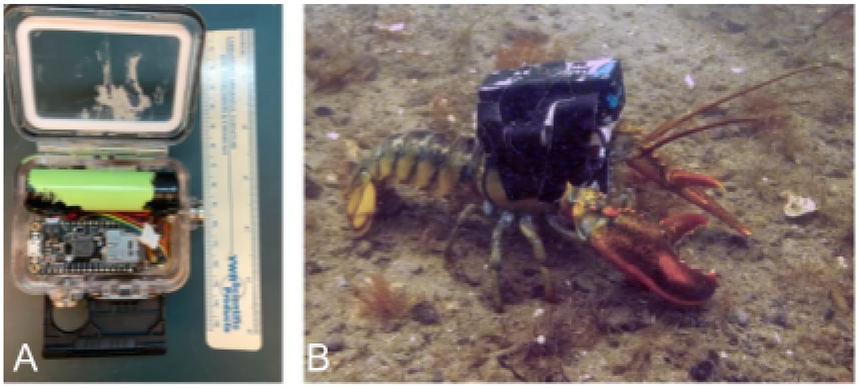


Figure 7: The (a) C-HAT circuit fully assembled with a power supply and housed in a repurposed gopro case. (b) The case is then mounted on a lobster using zip ties, duct tape, and cyanoacrylate superglue for field testing [4].

As shown in Figure 7b, the currently used gopro case housing is incredibly bulky, nearly tripling the lobster's height. This will not only create additional drag, impeding lobster movement at high speeds, but this will also prevent typical lobster behavior like burrowing. A lobster burrow typically has a circular cross section with a diameter twice the diameter of a lobster, with a diagram of a typical lobster burrow shown in Figure 8 [5]. With the current size of the C-HAT sensor, the lobster will be unable to enter these habitats. The method used in Figure 7b also involves using cyanoacrylate superglue to attach the case to the lobster's back, before using duct tape and zip ties to further secure it. This makes the attachment and detachment of the C-HAT incredibly difficult and time consuming, and if it is done poorly it can greatly impede the movement of the lobster.

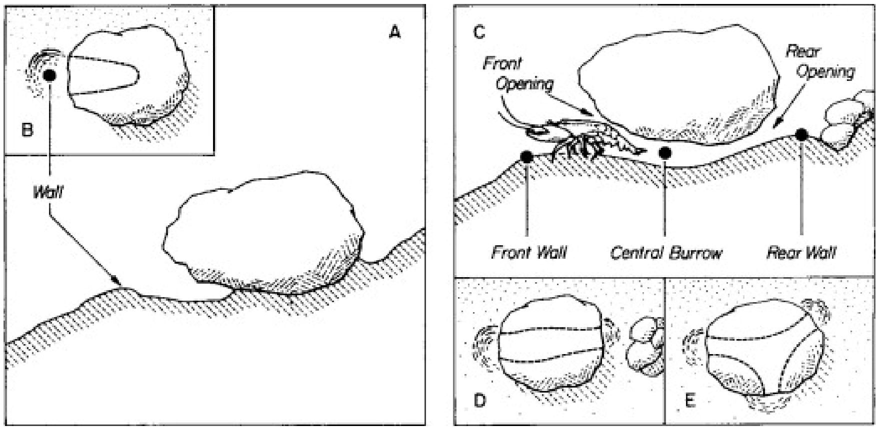


Figure 8: Schematic of of various burrow types of lobsters, including (a) a longitudinal section of a typical burrow with one opening, (b) the semicircular shaped walls of the burrow, (c) a longitudinal section of a burrow with two openings, (d) an extension of a burrow under a rock, and (e) a burrow with three openings [5].

Figure 9 below shows the data from the initial field test, including the IR sensor reading in volts and the lobster's calculated heart rate, as well as the heading, forward acceleration, and movement index of the freely moving lobster.

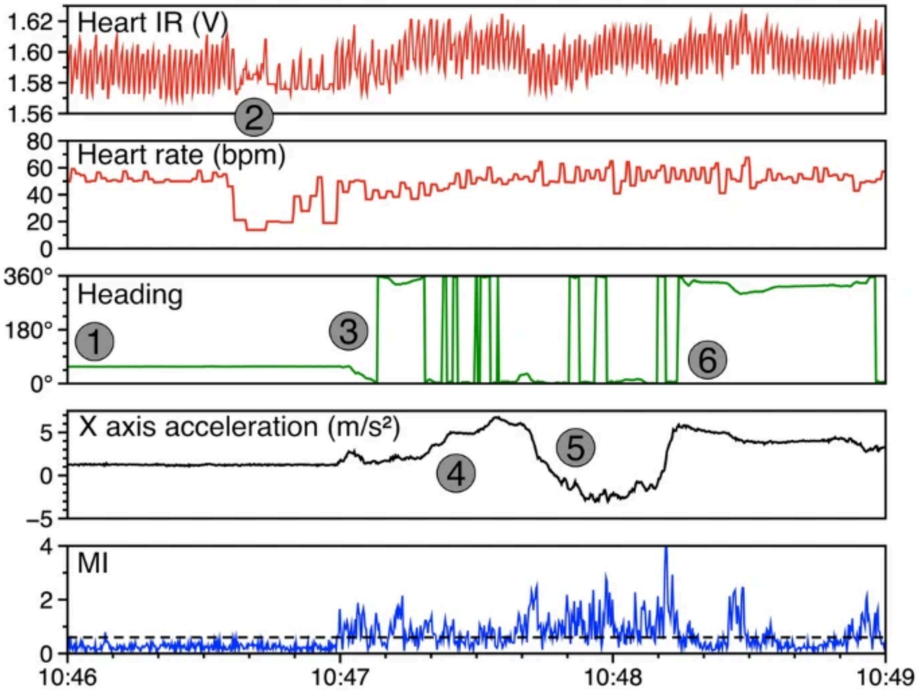


Figure 9: The stress response associated with the initiation of movement in a freely moving lobster in the wild. The lobster was initially facing northeast (1), then detected the stressor (2) and turned north (3). The lobster then moved forward (4), backed away (5), and then finally moved forward and to the left (6). Note that the stress response is identifiable by the brief decrease in heart rate at (2), followed by an increase in heart rate [4].

Testing of the C-HAT's IR sensor done by researchers at WHOI has shown that the amount of noise in the IR sensor reading is mainly determined by the placement of the IR sensor on the lobster and ambient light conditions. Figure 10, pg. 13, shows the signal received by the IR sensor as it is moved across the body of the lobster in both ambient and low light conditions. As shown in Figure 10, the IR sensor receives a much stronger signal in low light when compared to the signal with ambient light. The strength of the signal peaks in both conditions around 500 seconds, which corresponds to when the IR sensor was held directly over the lobster's heart.

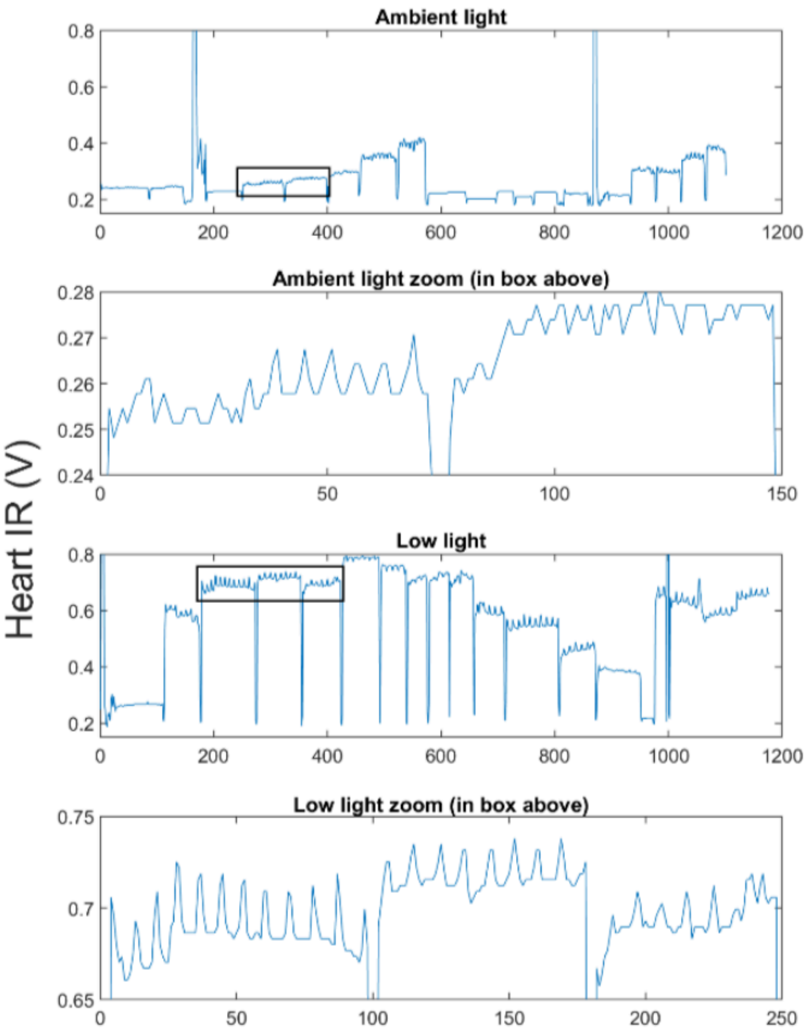


Figure 10: The signal received from the infrared sensor as the sensor is moved across the lobster's back in both ambient light and low light conditions [1]. Note that the signal is strongest in low light conditions and when placed over the lobster's heart.

Our Task

With the initial success of the C-HAT, the researchers at WHOI have asked us to improve upon this first design for further research into the American lobster's behavior and the effects they experience from offshore wind farms. Namely, in a meeting with Dr. Andrea Salas, she requested that we redesign the housing and mounting method of the sensors, as well as reduce the signal to noise ratio of the infrared sensor [1]. To accomplish this, we will first redesign the mounting mechanism of the IR sensor to securely attach it above the lobster's heart while blocking out ambient light. We will then reduce the size of the casing around the electronic components without impeding the data collection.

DESIGN PROCESS

Our custom design process was created as a hybrid of two previously existing design processes, the *Alexander and Clarkson* Model [24], also known as the V-Model, and the *ME Capstone Design Process* [25]. Both of these models are explained in detail in the appendix. To complete the goals of our project to the best of our ability, we decided to combine aspects of both the *Alexander and Clarkson* Model and the ME Capstone Design Process into a single, stage-based model. We valued the V-Model's priority on validation, as it was important for us to create and iterate multiple designs to determine that we have met the stakeholder's goals. Through the use of this hybrid model, our team was able to create two different design prototypes. First, we created the leash prototype, which featured the sensors connected to a long strand of wires that directly connected to an external computer. This allowed our team to verify the results from the sensors before potting. Next, we were able to create our second prototype, which was the potted system in which all of our components are contained inside the packaging. This made verifying and validating our design much easier than it would have been in other models. Using the V-Model, we were able to apply its recursive process to ensure that our C-HAT design addressed the design requirements and specifications as best it can. Additionally, we were able to apply the detailed design processes of the ME capstone design process, which ensured that we consistently considered the ethics, inclusivity, and stakeholder engagement throughout the timeline of our project. In addition, we used our combined knowledge of Mechanical Engineering and evidence-based decision making to ensure the project's success. Overall, by implementing features of both models, we ensured that our design can be the best it can be. In Figure 11, shown below, a visualization of our hybrid design process we used can be found, which implements a loop that helped us that we continued to validate the device.

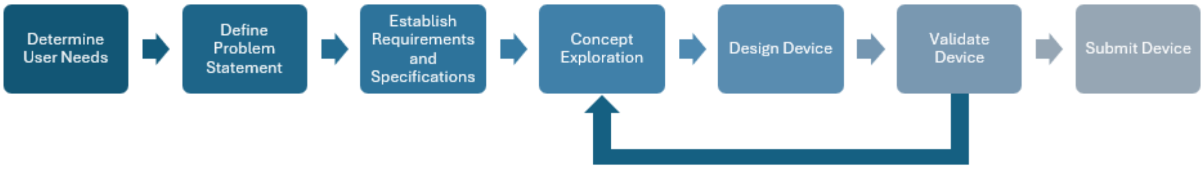


Figure 11: This block diagram shows the hybrid design process our team has followed for this project

DESIGN CONTEXT

The primary stakeholders of our redesign for this biosensor include our sponsor's researchers, our team, and the lobsters themselves. These stakeholders are visualized in a stakeholder map in Figure 12, pg 15. Our sponsor wants to get accurate data about how lobsters respond to noise. Our team stands to get engineering experience that we can use to further our careers. The lobsters that use our sensors will have to deal with whatever outcome comes from having our sensor strap onto them. Our design needs to be able to accurately track their acceleration and heart rate without impeding movement or injuring it.

Other secondary and tertiary stakeholders include wind farms, other marine industries that work closely with lobsters, and environmental activists. Wind farms are one of the potential noise sources negatively impacting the lobsters, so the data learned from observing lobsters might force a change in how they are operated or where they can be constructed. Lobster fishermen may be affected though legislation that ultimately increases the number of lobsters in the area. Seafood restaurants and markets may also face a reduction in the number or quality of lobsters caught. Environmental activists may be an affected bystander to our project. Some environmental activists may not like that lobsters are forced to wear a potentially uncomfortable sensor that could be a source of stress.

We prioritized lobster safety throughout the project as they are our most important stakeholder, since they are the most directly affected by our project. Our decisions in the design process kept the lobster's safety in mind as we proceeded.

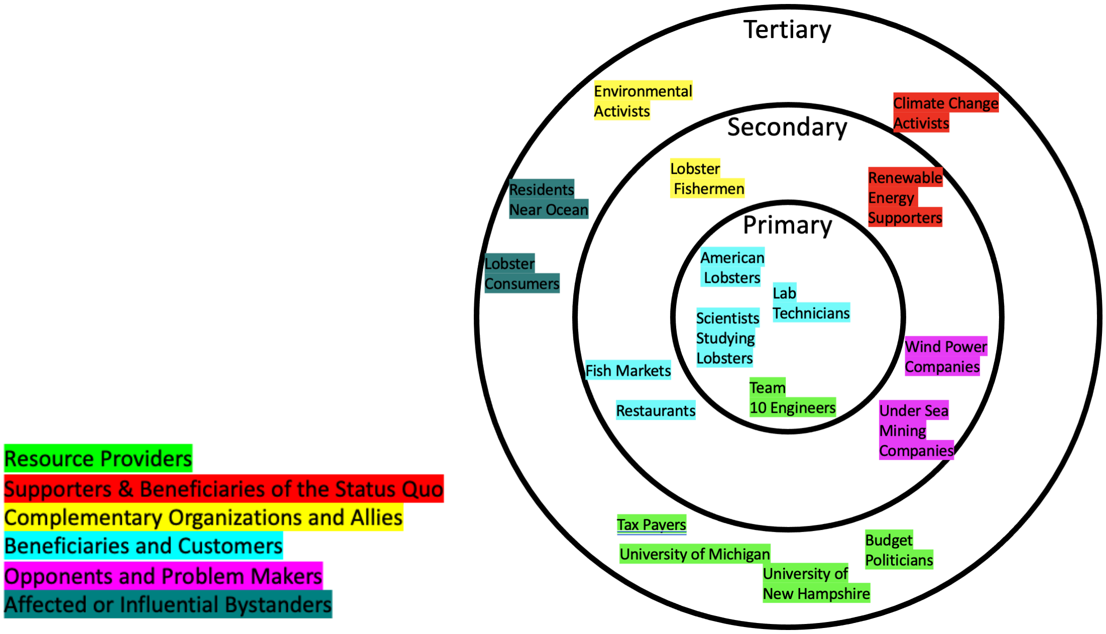


Figure 12: Stakeholder map for C-HAT packaging redesign

USER REQUIREMENTS AND ENGINEERING SPECIFICATIONS

We prioritized our user requirements by how critical each one was for the sensor to function properly. Requirements that include improvements to the C-HAT design specifically asked for by our sponsor Dr. Andrea Salas are shown in gray in Table 4, pg 16, and Table 5, pg 17.

Table 4: Requirements and Specifications with priorities and testing methods for C-HAT's sensors. Note that rows highlighted in gray are priorities of our sponsor.

Priority	Requirement	Specification	Testing Method	Source
High	Blocks Ambient Light near IR Sensor	IR sensor fully enclosed	Confirm opaque seal around lobster body	[1]
High	IR Sensor centrally placed above heart	IR sensor placed 20-40 mm from head	Test on lobster model	[1]
High	IR Sensor placed at optimal height above heart	IR Sensor placed $2.5\frac{-2.3}{+12.5}$ mm	Test on lobster model	[26]
Medium	Accelerometer data is purely from C-HAT movement	Accelerometer does not move within packaging	Motion testing in packaging	[1]
Low	Ambient Light Sensor does not receive excess light from emitter	Ambient Light Sensor is placed away from IR Sensor	Met by Design	[1]

Infrared Sensor Requirements and Specifications

The IR sensor is a cornerstone of our project, and therefore, the requirements and specifications for our design must be rigorous. As seen in Table 4, we have three requirements for the IR sensor, all of which are labeled as high priority. This is because we need to ensure that we are taking accurate measurements for the Lobster's heart rate, otherwise the work to package and mount the sensors will be in vain. The first of the three IR sensor requirements is that we block the ambient light to the IR sensor. Due to how the IR sensor functions, it is key that the transmitter component of the sensor only receives light from the emitter component of the sensor. This will combat the effects of noise in our data due to other forms of light interfering with the sensor. Our specification for this will be that the sensor is fully enclosed from its surroundings, so that it only interacts with the carapace of the lobster. To test this, we will visually confirm our design meets that specification, and possibly perform empirical testing to confirm that no ambient light is reaching the sensor.

Additionally, the second requirement and third requirement in our table relate to the position of the IR sensor. This is to ensure that the IR sensor is placed directly over the heart of the lobster and that it is placed at the optimal height over the heart. Similar to the first requirement, the placement of the sensor ensures that the data we receive from the sensor is accurate, and therefore can provide a more accurate heart rate for the lobster. We specified each of these requirements with a distance relative to the lobster. For the central placement, we estimated the distance where the heart would be from the lobster's head using our model lobster. For the height requirement, we used information from the IR sensor's datasheet to determine the optimal distance that the sensor should be placed above the lobster. We plan to test these both using our model lobster, although there is a possibility that we do further testing on our own body to determine the effectiveness of the IR sensor at different locations.

Assorted Sensor Requirements and Specifications
Along with the IR sensor, there are other sensors that we must consider. As seen in Table 4, there are two other requirements that relate to the other sensors in our system. The first of these is that the accelerometer data is only from the movement of the entire C-HAT. That is to say that there is no internal movement of the accelerometer within our packaging such that it would alter the data recorded. We plan to test this by performing motion tests on the design to determine the quality of the data recorded when the accelerometer is attached securely versus when it is loose. Additionally, our last requirement on Table 4 is that the ambient light sensor does not receive light from the IR transmitter. This is to ensure that the data recorded by the sensor is just as accurate as it would be if it was the only sensor in the system. We plan to test this by designing around this requirement, placing the IR sensor within an opaque body such that no light gets in or out.

Table 5: Requirements and Specifications with priorities and testing methods for the packaging and mounting of the C-HAT to the Lobster. Note that rows highlighted in gray are priorities of our sponsor.

Priority	Requirement	Specification	Testing Method	Source
High	Waterproof	IP68 rated at 20 meters and 48 hours	Submerge product for 48 hours, check for leaks	[27]
Medium	Neutrally Buoyant	Density must be equal to that of Seawater, 1.03 g/cm^3	Mass and volume analysis	[28]
Medium	Functional at lobster habitat depth	Able to withstand depth of 20 meters	FEA analysis	[29]
Medium	Lobster retains full mobility	All joints must have the ability to move to full range of motion	Testing on lobster model	[27]
Medium	Does not impede lobster movement	Can enter a burrow twice the diameter of the lobster	Measure height of lobster and lobster with sensor	[5]
Low	Long battery life	Battery life of 36 hours	Find power draw and capacity of battery	[1]
Low	Easy to place on lobster	Can place on lobster in less than 1 minute	Test time to install on lobster model	[1]
Low	Fits various sizes of lobster	Able to fit lobster between .75 lbs and 1.25 lbs	Put sensors on various sized lobsters in CAD	[1]

Functional Requirements and Specifications
As seen in Table 5, our first three requirements all relate the functionality of the design. The first of these requirements is that the design is waterproof. This is prioritized as high because the

sensors are electronics components that are subject to degradation and destruction in seawater, so the ability to keep them dry and functional is very important. We specified this requirement with an IP rating, which is a standard way of rating how waterproof something is. We aim to have a rating of IP68, which means that our design is dust-tight, so that no dust can enter the system, and that it can be submerged underwater for long periods of time. However, to achieve a rating, an independent review would have to be conducted, which is outside of the scope of our project. Therefore, we plan to test how waterproof our design is by testing, submerging our design into water at different lengths of time and pressures.

Additionally, the second requirement we have is that the packaging is neutrally buoyant. This is important because we do not want to affect the lobster's ability to swim underwater while wearing the C-HAT. We specify this using the density of seawater, and plan to test this through mass and volume measurements and analysis. Finally, our last functional requirement is that our design is functional at lobster depth. This is to ensure that our design can withstand the pressure at the seafloor where lobsters reside. We specified the requirement at a depth of 20 meters, which is the depth that American Lobsters reside that we sourced. We plan on testing this using FEA analysis.

Mobility Requirements and Specifications

Our team also specified requirements for the mobility of the lobster user when wearing the device. These requirements can be seen in Table 5, and include "lobster retains full mobility" and "does not impede lobster movement". Both of these requirements are ranked as medium priority, as they are not integral to the success of the device, but do play an important part in the overall success of our design. The first of these requirements, "lobster retains full mobility" was specifically asked for by our sponsor. These requirements were both created to ensure that our device will cause as little disruption as possible to the lobsters movement as possible, which will help keep the lobster's nominal stress levels at a normal level. The difference between these requirements is that the "lobster retains full mobility" is defined as how the lobster moves around on the seafloor, either by swimming or walking, and "does not impede lobster movement" defines the ability of the lobster to enter and exit its burrows as it does naturally, without the size of our device impeding it. The first of these requirements is specified by allowing the lobster to have its normal full range of motion, and will be tested using the model lobster to ensure that it does. The specification for the second requirement is that the lobster can enter a burrow twice the height of the lobster, which was found as the average size of the burrow a lobster will inhabit. We will test this by measuring the height of our sensor and comparing it to the expected lobster size.

Device Size Requirements and Specifications

The final requirements that are shown in Table 5 are the device size requirements. These requirements are both prioritized as low priority due to the fact that the device can still function well without these requirements, but meeting these requirements would go a long way for ease of use for our product. The first requirement is "easy to place on the lobster", which was specifically asked for by our sponsor, relates to how easy it is to mount the device on the lobster. By keeping the mounting process low, we cause less stress on the lobster and help the lobster maintain its normal levels of stress. It is specified by allowing a researcher to place the device on the lobster in less than 1 minute. This will be tested using our model lobster, which can be seen in Figure 13 below. The second requirement is “fits various sizes of lobsters”, which ensures that the device can be used on multiple different lobsters of different sizes, rather than just the model lobster we are testing on. We specified this with a size range of lobster, from ¾ of a lb to 1.25 lbs, which are based on the average sizes of american lobsters. We will test this using various models of lobsters in CAD.

Figure 13: Lobster model owned by sponsor and engineering team.

PROBLEM ANALYSIS AND ITERATION

After examining the feasibility of each idea, considering factors such as time and cost of operation we selected 5 potential concepts for mounting and 4 concepts for packaging. These concepts were then evaluated in a Pugh Chart in order to choose the concept that best fit our requirements as shown in Appendix C, pg 45. The selected design with velcro straps, a suction cup, and a potted sensor served as the basis for our alpha design.

To realize the alpha prototype, the team will need to have knowledge of IR sensors, electronics and coding, and mechanics and materials. The team has extensively researched the mechanism behind the IR heart rate measurement, photoplethysmography. This knowledge with an understanding of the IR sensor data sheet will enable the team to optimize the IR sensor measurements. Also, to pot the electronics there must be a way to transfer data without the use of a removable SD card. This will require knowledge of electronics to make the necessary modifications to the hardware and knowledge of arduino code to modify the program. Knowledge of mechanics and materials will be necessary to make sure that the epoxy will not fracture or degrade under the harsh conditions of the sea floor.

The simplest way to test the IR sensor is isolating the sensor and empirically testing on humans before moving to live lobsters. The design will be validated before the packaging is created by micking up suction cups with clay and measuring human heart rate. The measurements will be compared to an echocardiogram heat rate measurement to check accuracy. Then, once the prototype is ready the team will send the device to the sponsors for testing with live lobsters. To test the packaging design, empirical and analytical methods will be used. To test if the packaging and mounting interferes with lobster movement the C-HAT will be placed onto a model lobster as shown in Figure 13, pg. 19, with velcro straps and the leg range of motion will be measured. The epoxy potting will be analytically verified using hand calculations to ensure that the epoxy will not crush or fracture under pressure.

PROBLEM DOMAIN ANALYSIS

In light of the requested improvements to the C-HAT's design, we first verified the infrared sensor's readings with our selected sensor attachment method, before then redesigning the packaging of the C-HAT to be more compact. In this section we will discuss our methods for sensor verification, as well as the challenges associated with it, before discussing the challenges of reducing the packaging volume.

Sensor Readings

To first verify our ability to measure heart rate with an IR sensor using photoplethysmography, we first attempted to measure our own heart rates with the IR sensor and compare this data to our heart rate found with other methods, including a medical oximeter and electrocardiogram. We used a design similar to the "lobster leash" (see Appendix C, pg. 45) to test this sensor.

Next, we implemented our new updated mounting design of foam with velcro straps (see Appendix D, pg. 52) and once again tested this sensor on ourselves with the lobster leash. The goal of this test was to observe an increase in the signal to noise ratio of our sensor, suggesting improved readings from our IR sensor. We faced numerous challenges in this test, particularly in ensuring that the sensor is aligned directly over the tested blood vessel and that no ambient light reaches this location.

Packaging

After verifying these sensor measurements, we then worked to reduce the overall packaging volume of the C-HAT. This presented numerous challenges, most notably ensuring that the C-HAT's electronics are properly waterproofed while still providing access to the C-HAT's battery and recorded data. Our team solved the waterproofing challenge by encapsulating the electronics in resin, allowing no water to ingress. However, the recorded data was difficult to retrieve because the SD card in the feather microcontroller will be encapsulated in resin. Therefore, the data was retrieved via the USB connection using 5 pins exposed to the water that will act as a USB connection that can communicate with the feather microcontroller. The battery also cannot be removed to charge, however, small flat pack lithium-ion batteries with a built in battery management system are available for purchase that are compatible with the feather microcontroller.

Required Engineering Skills

The required engineering skills we used during this project were mechatronics, design and manufacturing, circuits, and sensor integration. This project focused on mechatronics, in this case the creation of an electronic system and mechanical packaging that allows the sensors to function and protects it from the environment. The packaging solution was designed and manufactured. Knowledge from design classes was used to model the solution using computer aided design and then manufactured using 3D printing. The team also used their knowledge of circuits to swap parts and modify the C-HAT electronics to better suit the application such as using a different battery and the addition of the USB data connection. Lastly, the team used knowledge of sensors to optimize the packing design to produce the best measurements from the IR sensor responsible for photoplethysmography in the C-HAT. This included using first principles of the IR sensor function and real world testing to design a packaging concept with high quality measurements.

ENGINEERING ANALYSIS

Heart Rate Sensing

To assess if using our current sensor is feasible to use for measuring actual lobsters heart rate, we decided to compare its reading to an EKG. An EKG (electrocardiogram) uses electrodes attached to the different points in the body to measure the electrical activity throughout the heart which can be used to determine heart rate. An example of an EKG is shown below in Figure 14.

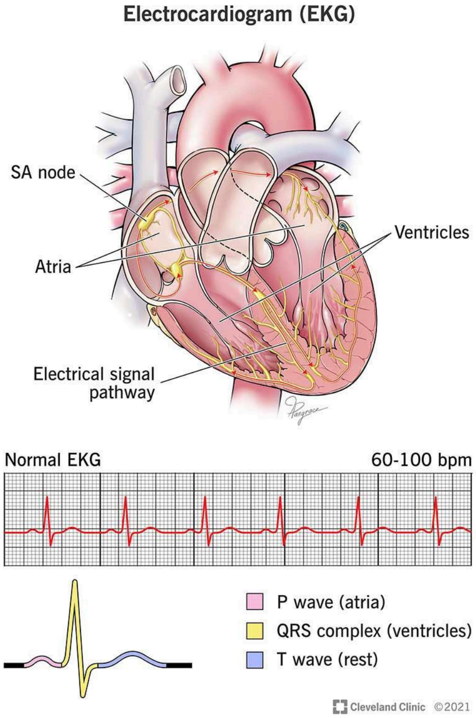


Figure 14: Example diagram of a normal EKG heart rate. Electricity is measured as the heart pumps blood through the upper atria (P wave), lower ventricles (QRS complex) and then returns to rest (T wave). [32]

An EKG was chosen to compare against the sensor for accuracy for two reasons. EKG is a proven method of measuring heart rate widely used in medical procedures. It measures heart rate using electricity, which is a different method than IR light which our sensor uses. The results from our IR sensor should be similar to EKG if it measures heart rate accurately.

To test if our IR sensor readings match the EKG we simultaneously attached an EKG to a team member and measured their heart rate by securing the IR sensor up to the radial artery in their wrist. The circuit diagram in Figure 15 shows the setup for both devices in more detail.

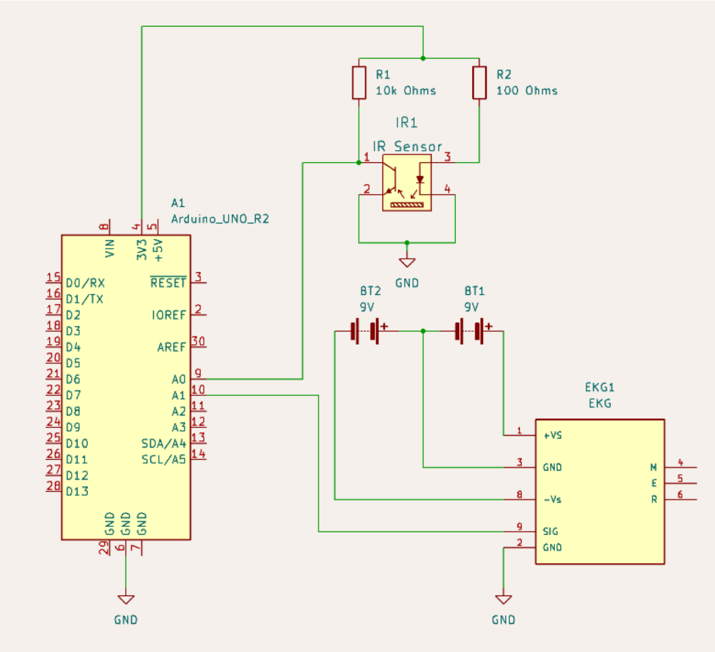


Figure 15: Circuit used to measure and compare heart rates using an IR sensor with photoplethysmography and an EKG.

Three trials of heart rate readings were done over 50-80 seconds. In Figure 16, pg. 23, the raw unscaled measurements are shown for the voltage output of both the IR sensor and EKG.

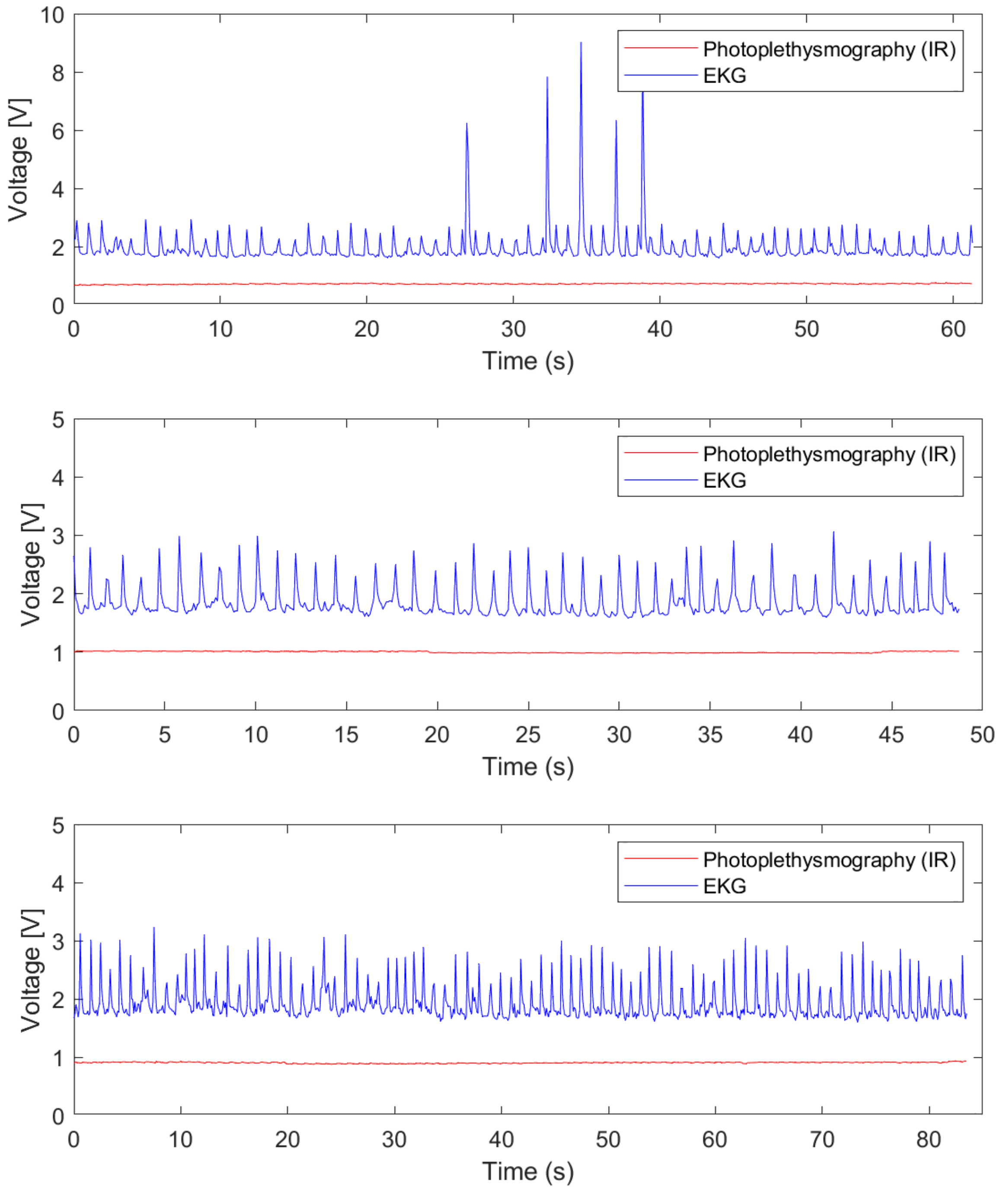


Figure 16: Output voltages for EKG and IR sensor for the three test trials.

The IR sensor outputs significantly smaller voltage magnitudes compared to the EKG so the readings were rescaled to better see if there was a pattern between the two. This rescaled graph is shown in Figure 17, pg. 24 and shows that there is a similar pattern in both readings suggesting that the IR sensor is accurately measuring the heart rate of the team member.

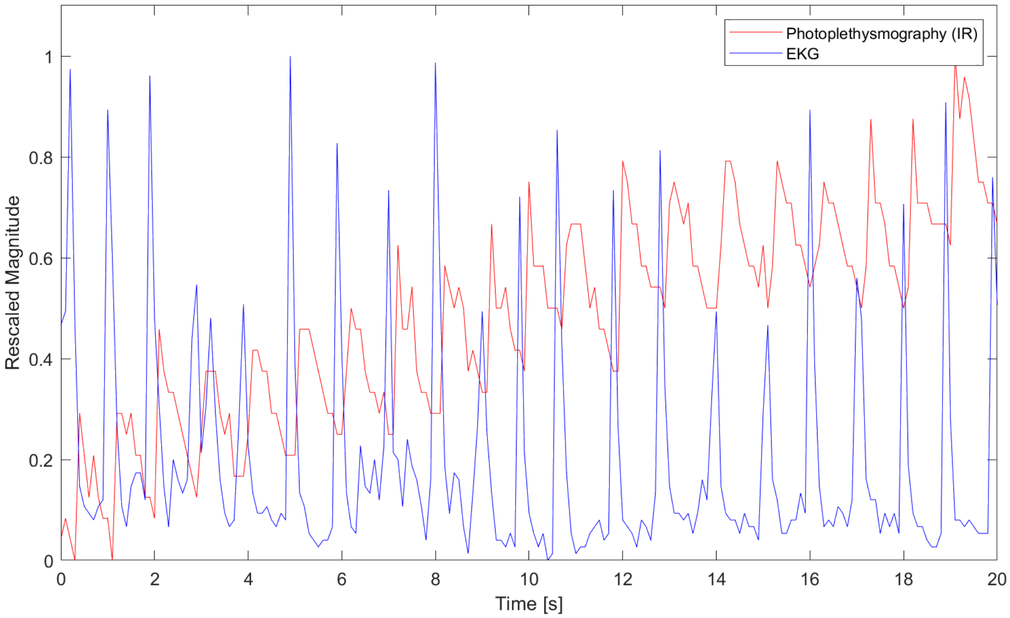


Figure 17: Rescaled outputs for IR sensor and EKG. Note the similar patterns in the two signals, suggesting that the IR sensor is indeed measuring heart rate.

Figure 17 shows that the pattern of the signal received from both the IR sensor and EKG are about the same, showing that the IR sensor is successfully detecting a heart beat through photoplethysmography. There is a slight offset between the peaks of the EKG and IR data, but this is due to the time it takes the pulse to travel from the heart (EKG) to the wrist (IR).

Infrared Light Permeability

In order to produce clean, interpretable heart rate data from the infrared sensor, noise from ambient light must be blocked out. As a reminder, the C-HAT uses infrared light to measure the change in volume in blood vessels to measure the heart rate, which is done through a process called photoplethysmography. Ambient infrared light, which is caused by sunlight reaching the ocean floor, can create great shifts in the data and even diminish the ability to detect a heartbeat. Therefore, our team designed our project to cover the IR sensor in some material. To help inform our design decision on what material we should use to shroud the infrared sensor in, we performed engineering analysis on different materials.

To do this, our team bought an infrared flashlight that emitted 940 nanometer infrared light. Our team then assembled our IR sensor to our circuit as previously done in the IR versus EKG analysis. Then, we placed the IR sensor 4 centimeters from a wooden block, which acts as our controlled variable for our IR readings. Then, we held our IR flashlight 5 centimeters above the sensor, before turning the flashlight on and off for 3 seconds each. This pattern was repeated using different materials to cover the IR sensor from the flashlight. The experimental configuration can be seen in Figure 18, pg. 25.

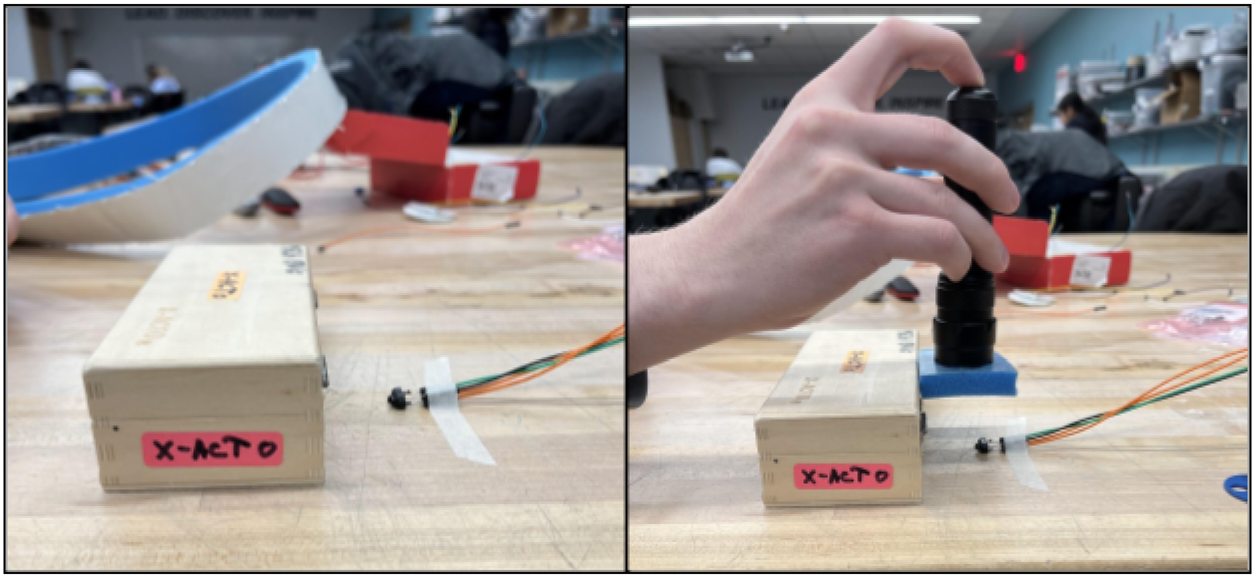
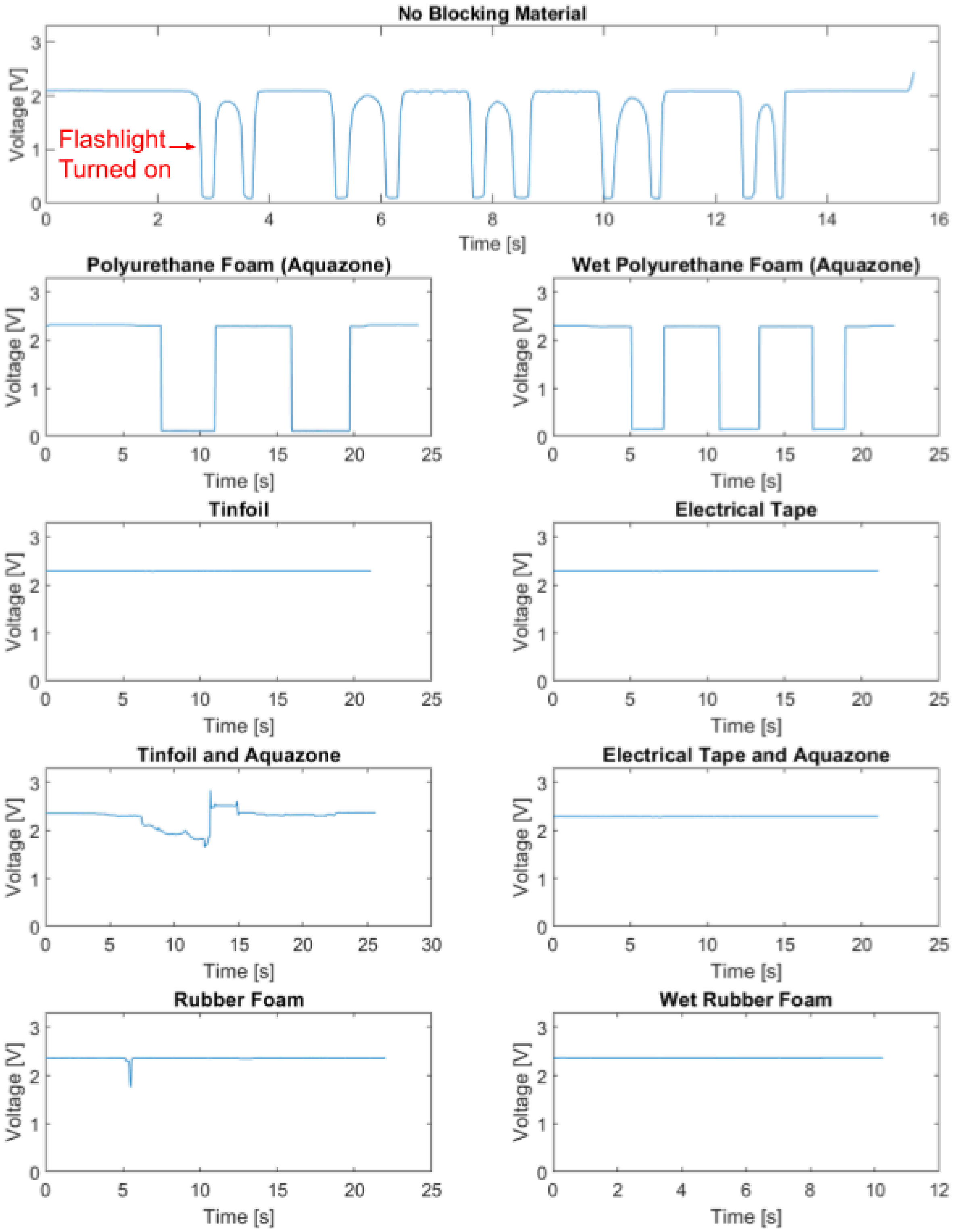


Figure 18: Experimental Set-up for our Infrared Permeability Analysis. On the left, the test is shown with no flashlight. On the right, the flashlight and a potential foam solution is shown blocking the flashlight from the IR sensor.

This experiment was performed with an array of potential solutions. Our initial design used Polyurethane Foam, shown above in Figure 18 in blue. This foam was used because it was hydrophilic, which meant it is waterproof and would not affect the neutral buoyancy. We tested this foam both dry and wet to determine if the water in the foam would refract the IR light at all. However, after testing, this foam proved to not stop the infrared light. We then continued with other potential solutions, including tinfoil, electrical tape, rubber foam, and combinations of these solutions. The results of these experiments can be seen in Figure 19, pg. 26, which shows the effectiveness of the IR light blocking properties of the materials. Our data shows that tinfoil, electrical tape, and rubber foam all work very well to block infrared light. This can be seen in the voltage drops in the graphs, as when the infrared sensor receives more infrared light, the sensor outputs a lower voltage. This is why when there was no material blocking the flashlight in our control test, the graph quickly rises and falls, similar to a step response.



No Blocking Material

Polyurethane Foam (Aquazone)

Wet Polyurethane Foam (Aquazone)

Tinfoil

Electrical Tape

Tinfoil and Aquazone

Electrical Tape and Aquazone

Rubber Foam

Wet Rubber Foam

Flashlight Turned on

Figure 19: Series of graphs representing the data collected from our infrared permeability testing, illustrating the effectiveness of different materials for blocking infrared light.

After analyzing our results, our team decided to move forward with rubber foam for our design. We choose rubber foam because it is easily purchased, cost-effective, does not require multiple materials, and can still act as a cushion for the packaging. These features allow us to continue with our previous build design's method of mounting the packaging, and will also provide the IR sensor with protection from ambient infrared light.

CONCEPT GENERATION AND SELECTION

In order to consider as many designs as possible, we first broke up our design into the two major tasks we have been asked to accomplish: improving sensor readings and reducing packaging size. We then did an individual and group brainstorming session to create as many solutions to the subproblems as possible. Then we used morphological matrices to combine these ideas. The design concepts were then compared using two pugh charts for packaging and sensor mounting. The final concepts were chosen to be foam mounting and potted electronics. Further information about the concepts generated in this session can be found in Appendix C.

FINAL DESIGN AND PROTOTYPE

The final design of the C-HAT utilizes the foam mounting and potted packaging identified in the concept generation to meet the engineering requirements and specifications set. First the electronics design will be introduced. The electronics are common between all C-HAT designs. There are three models of the C-HAT: final design, Lobster Leash, and an alternative redesign. The Final C-HAT design is fully self contained and potted. A C-HAT variation called the Lobster Leash for testing and tank research is also introduced. In response to problems occurring during verification and testing, an alternative redesign was created to meet these challenges.

Final C-HAT Electronics Design

The electronics of the C-HAT are composed of two subsystems: sensor and datalogger. The sensors included are an IR sensor, photosensor, temperature sensor, and an IMU. The data logger includes an arduino feather adalogger, real time clock, and a battery. The IR sensor is mounted on the carapace above the heart to get a clear measurement. The Photosensor will extend outside the packaging towards the head of the lobster to monitor ambient light. The temperature sensor will be mounted to the sidewall of the C-HAT to read the ocean temperature. The IMU is placed centrally on the carapace to get accurate motion readings. A cross section showing the location of the electronic components is in Figure 20.

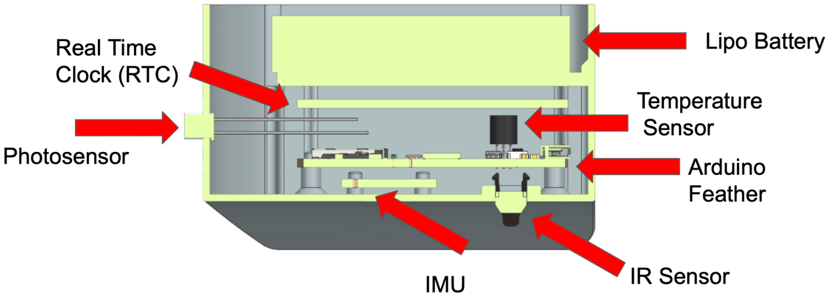


Figure 20. Cross section view of C-HAT electronics with callouts for components.

Final C-HAT Design

The final design of the C-HAT is fully self-contained using potted electronics. The battery, arduino, and sensors are fully encased in a waterproof IR opaque resin. The final design can be seen in Figure 21. The internal electronics design is unchanged from the alpha design. The final design features a more sleek overall design with a rounded front and low profile velcro mounting straps. The velcro straps have also been reduced in width to reduce the impact of the C-HAT to the lobster. The rounded front allows for the integration of the data retrieval system.

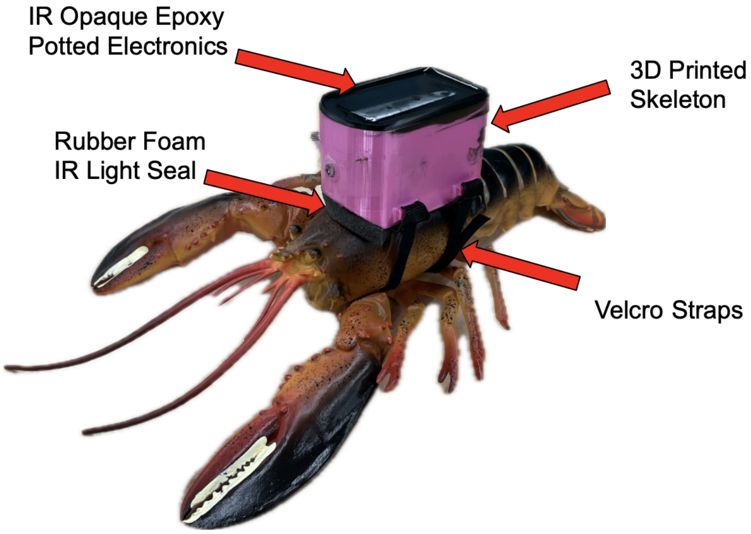


Figure 21. Final C-HAT mounting design utilizing epoxy potted electronics, velcro mounting straps, and an rubber foam IR light seal

To retrieve data on the fully potted C-HAT a 5 pin USB connector was installed on the C-HAT as shown in Figure 22, pg. 29. The 5 pin connector connects to a matching custom USB cable. This allows the user to fully access the arduino through the usb port. To retrieve the data after collection, a separate program is uploaded to the C-HAT that reads the SD card data then outputs it to the serial monitor. The serial monitor data can be exported to a csv either by copying and pasting the built in arduino serial monitor or by using the free program PUTTY. To delete the data on the SD card, another program is uploaded to the arduino that deletes all data on the SD card. To get the C-HAT ready for the next test, the C-HAT code is reuploaded to the arduino. The code used can be found in appendix F.

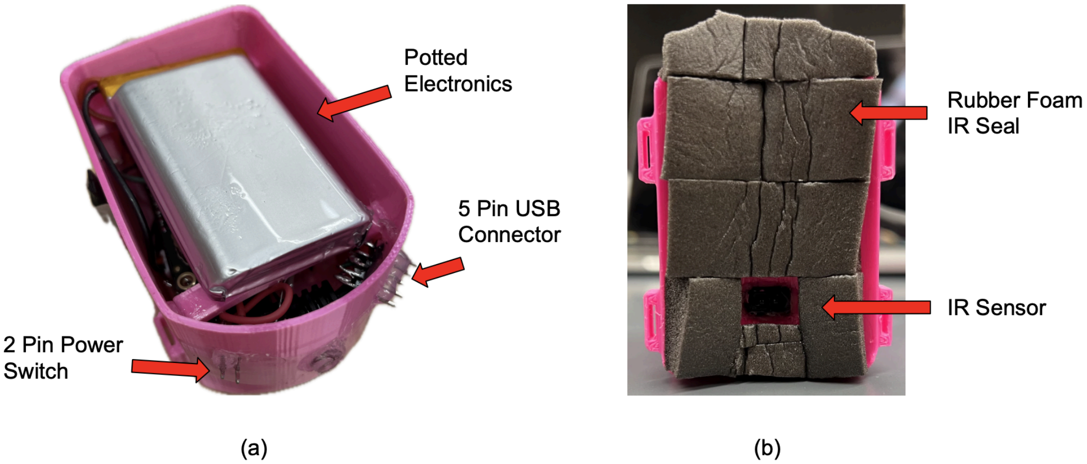


Figure 22. a) Final C-HAT mounting design electronics design with 5 pin USB connector and 2 pin power switch. b) Bottom of C-HAT showing rubber foam IR seal and IR sensor location

C-HAT Lobster Leash Design

For tank testing and validation of the mounting system, a version of the final C-HAT design was prototyped where only the sensors are potted in the 3D printed skeleton. This lobster leash can be seen below in Figure 23. The potted sensors include the IR sensor, temperature sensor, photosensor, and accelerometer. A cable connects the potted sensors to the arduino, real time clock, and battery.

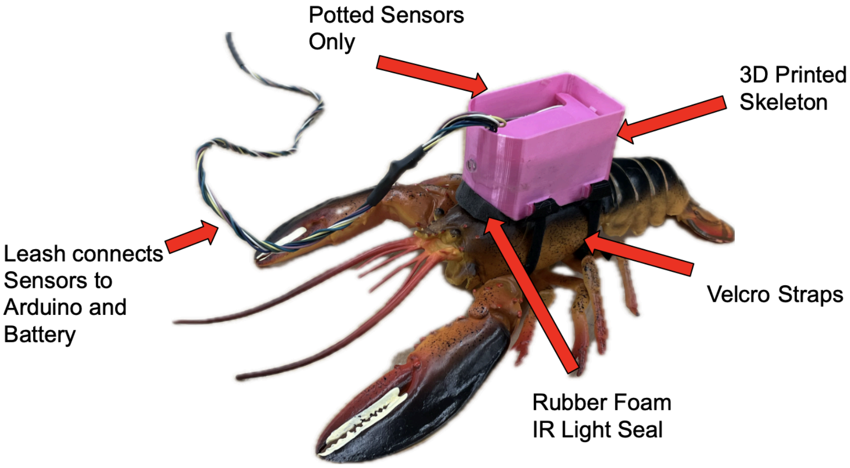


Figure 23. Lobster leash C-HAT design on model lobster

To test, the C-HAT body is placed on the lobster and put into the tank. The leash is attached to the arduino, real time clock, and battery. To retrieve data, the SD card is taken out of the arduino and read using a computer.

Alternate Design

After difficulty with potting and validation discussed below, an alternative redesign was created to address challenges of the previous design. The alternate design utilized the validated mounting system of the final fully self contained design and combined it with the previous Go-Pro case packaging. This design can be seen in Figure 24 pg.31 .

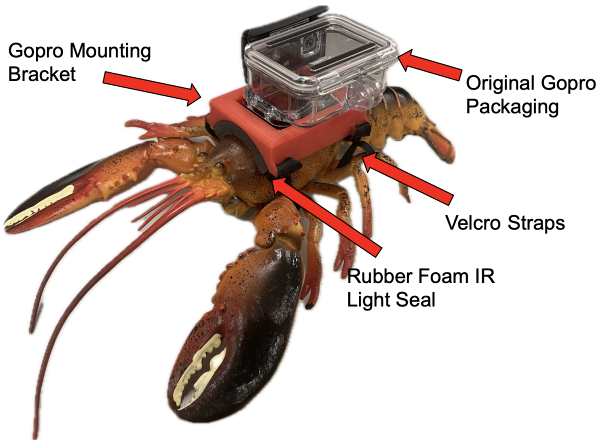


Figure 24. Alternate C-HAT mounting design utilizing validated mounting system and existing gopro waterproof packaging design.

This design does not use potting to waterproof the electronics. Instead, an off the shelf Go-Pro case with a gasket is used. This is more bulky than the potting design, however it also allows for easy access to the electronics inside for servicing, modification, and data retrieval. Data retrieval is fast and easy through the micro SD card. The mounting system is identical to the potted design with thin velcro straps and an IR blocking rubber foam light seal. While this design is more bulky than the fully potted final design, the simplicity of this solution may make it easier for the sponsor to validate the team's mounting design and implement it into real world research.

VERIFICATION AND VALIDATION PLANS

Heart Rate Verification

The first specification that must be verified is the IR sensor's ability to accurately measure heart rate within ±5% of the heart rate. To do so, we compared the heart rates measured by the EKG and IR sensor from our heart rate sensing engineering analysis data. The process in which this data was obtained can be found on pg. 23. After collecting this data, *Matlab* was to measure the time between the peaks of the IR and EKG sensor data, which was then used to determine an instantaneous heart rate using Equation 1.

$$Heart\ Rate\ =\ \frac{60}{t_{peak\ to\ peak}} \tag{1}$$

A plot of the instantaneous heart rates over the course of each of the three trials can be seen in Figure 25.

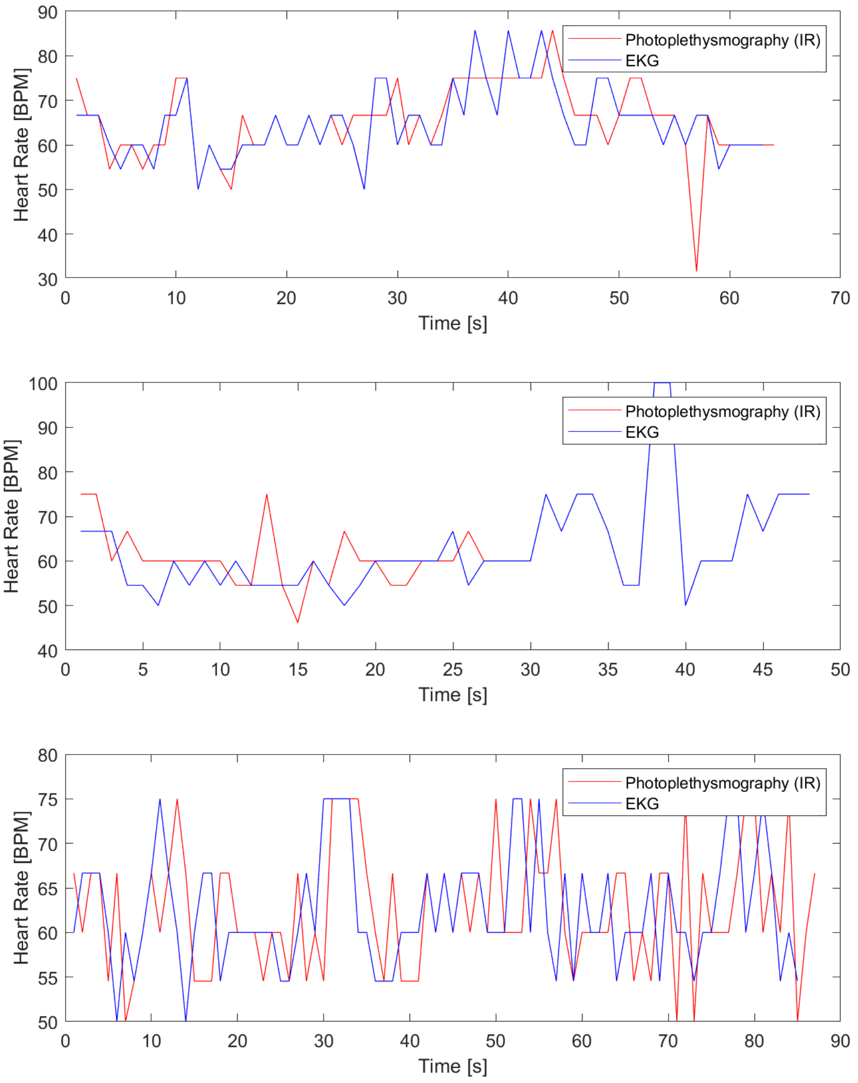


Figure 25: A plot of the instantaneous heart rates of the human test subject measured using photoplethysmography (IR sensor) and an EKG over the trial duration for three trials. Note that the IR sensor's attachment loosened in trial three, resulting in the additional noise seen in the plot.

An average of the instantaneous heart rates in each trial was then taken, and along a two-sample, two tailed, t test at a 95% confidence interval was used to assess if there was any significant difference between the IR and EKG readings. These results can be seen in Table 6, pg 32.

Table 6: Calculated average heart rates and p-value for EKG and IR measurements t-test for all three trials.

Heart Rates			
Trial	**EKG [BPM]**	**IR [BPM]**	**P-value**
1	65.1 ± 3.3	65.2 ± 4.3	0.92
2	62.7 ± 4.5	62.6 ± 3.4	0.89
3	62.5 ± 6.6	60.7 ± 6.7	0.31

As shown in the table, the heart rate found with an EKG and an IR sensor was nearly identical, with a maximum difference of 2.9% in trial 3. This shows that our infrared sensor can meet the specification of accurately measuring a heart rate within ± 5%. Furthermore, the p-value for every trial except 3 is around 0.90, This means that there is about a 90% chance there's less than a 5% difference between heart rates if we repeat these tests. Trial 3 has a lower p-value due to the noise created from the IR sensor shifting. It should be noted that the large error in the average heart rates reflect the change in our subject's heart rate over the course of the trial.

After fully potting the C-HAT, we once again attempted to verify our ability to measure heart rate with the IR sensor, but we ultimately failed to observe a heart beat in the packaging. We believe that this is simply due to the anatomical differences between ourselves and the intended wearer (lobsters). The orientation of the IR sensor was placed to measure the expansion and contraction of the lobster's heart, which is offset 90° from the ideal orientation to measure the expansion of our own blood vessels at our wrist. However, we did also encounter some difficulties potting that resulted in epoxy coating some of the IR sensor's lens. This could have impacted the accuracy of the sensor, but we still wish to test this design on a lobster.

Due to these difficulties with potting, we also redesigned our mounting interface to fit the previously used GoPro case.

Waterproofing Verification

In order for our packaging solution for the redesigned C-HAT to be considered a success, it must be IP68 rated at 20 meters and 48 hours, meaning that it has total protection against water and solid ingress at a depth of 20 meters and for a duration of 48 hours. This will ensure that the C-HAT will continue to function in a typical lobster habitat without short circuiting the electronics and jeopardizing both the data and the lobster's safety. To ensure our packaging solution is waterproof without potentially damaging any electronics, we placed a strip of cobalt chloride test paper in the locations occupied by the Adafruit Feather, the RTC, the IMU, and the LIPO battery. These test papers detect the presence of water or moisture, turning from blue to a light pink. The papers will then be potted in clear epoxy in place of our circuit. This potted packaging was then placed in a pot of saltwater (salinity of 35%) for 36 hours, as can be seen in Figure 26, pg. 33.

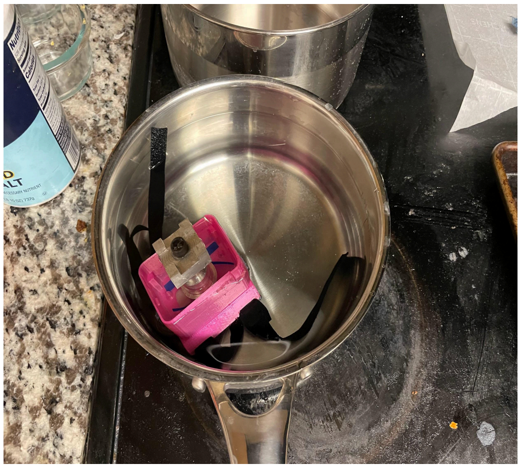


Figure 26: Cobalt chloride papers potted in C-HAT packaging and submerged in saltwater. Note that C-HAT is weighed down by the Machine Shop Training Rook as the packaging was buoyant without the electronics and full epoxy.

The packaging was then removed from the water and the cobalt chloride strips were closely examined for a change in color indicating the presence of moisture. As can be seen below in Figure 27, there was no change in the color of these strips, indicating that our packing is waterproof.

Figure 27: The potted blue cobalt chloride strips after waterproof testing. Note that the color of each strip remained blue, indicating no moisture within the potted packaging and thus verifying that this packaging method is waterproof.

After verifying this packaging method would be waterproof, we fully potted the C-HAT electronics, including the LiPo battery, temperature sensor, photoresistor, RTC, IMU, IR sensor, and the Adafruit Feather 32u4 Adalogger in the C-HAT packaging, as can be seen in Figure 22, pg. 29. To verify that the sensors and other electronics still worked within the epoxy, we first submerged the C-HAT in water and held an IR flashlight 6 cm above the surface of the water, as can be seen in Figure 28, pg. 34. The flashlight was then turned on and off for intervals of 5 seconds over a 60 second trial in order to confirm the IR sensor's function.

Figure 28: The fully encased C-HAT submerged in water to confirm electronic function underwater.

After the trials, we were able to confirm these sensor's function with data that can be seen in Figure 29.

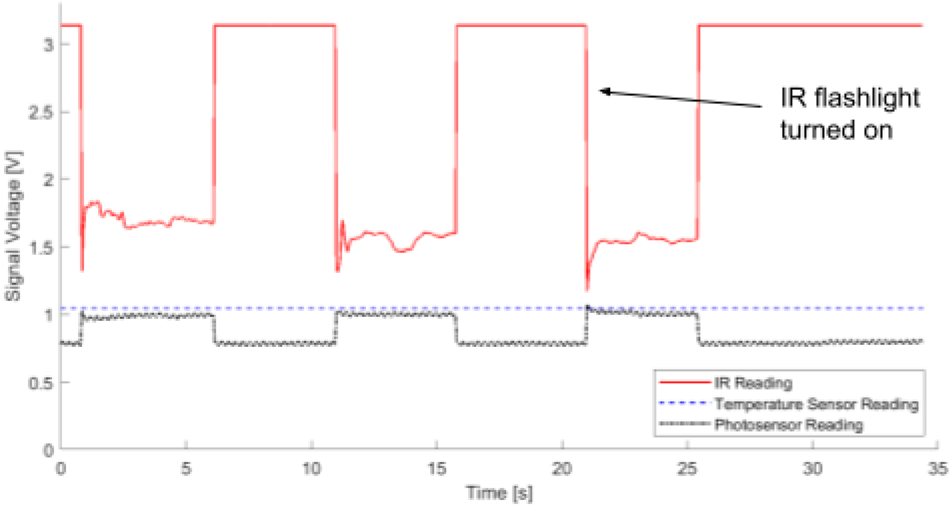


Figure 29: Infrared, temperature, and photo sensor readings from the testing of the sensors underwater. Note that the IR sensor and photo sensor both respond to the IR flashlight turning on and off, showing their continued function. The temperature sensor shows no change in reading as the temperature did not change during the trial.

To then confirm our interface's ability to filter out ambient IR light, we repeated this experiment with the C-HAT mounted to the model lobster, as can be seen in Figure 30, pg. 35. Once again, the IR flashlight was turned on and off for intervals of 5 seconds for a trial of 60 seconds, but in this test the IR light was also moved around the lobster to test different angles of incoming IR light.

Figure 30: The fully encased C-HAT mounted on the model lobster and submerged in water to confirm the interface’s ability to filter out IR light underwater.

As can be seen below in Figure 31, the IR sensor recorded no change in its reading, showing that our interface is able to filter out all ambient IR light underwater.

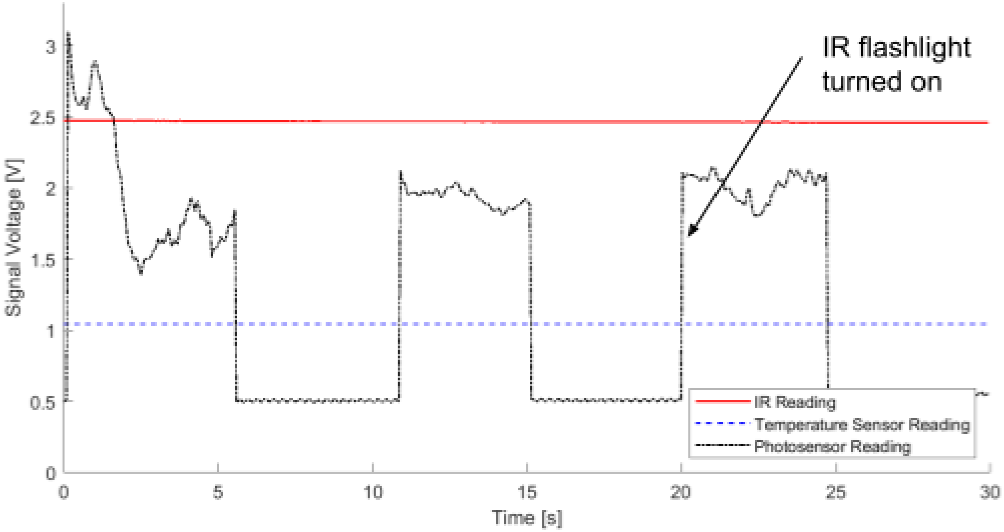


Figure 31: Infrared, temperature, and photo sensor readings from the testing of the interface underwater. Note that the photo sensor responds to the IR flashlight turning on and off, but the IR reading remains constant, showing that the interface successfully filters out all ambient infrared light to the IR sensor.

Buoyancy Verification

To ensure minimal impact on the movement of the lobster, the C-HAT must be neutrally buoyant. This ensures the C-HAT does not cause the lobster to float without adding any additional weight that the lobster must carry. To achieve this neutral buoyancy, the C-HAT must have a density near that of seawater, 1.03 g/cm^3. In order to ensure our design meets this specification, we first found the overall volume of the C-HAT using the 3D modeling software *SolidWorks* to be 117.4 cm^3, or 162.4 cm^3 with the foam. We also determined that the mass of the electronic and packaging to be 61.3 g, and the required volume of epoxy is approximately 100 cm^3. Using the known density of epoxy resin (1.2 g/cm^3), we determined that 120 g of epoxy will be needed to pot the C-HAT. Thus, the total mass of the C-HAT is 181.3 g, or 185.3 g with the foam, and the density of the potted C-HAT is 1.14 g/cm^3. This is slightly above the density of seawater and could be reduced, but it would require an increase in the C-HAT's volume. The applied load on the lobster will only be 0.04 lbs (0.175 N) though, which should not impact the lobster's movement.

The Go-Pro case with our adjusted mounting interface is likely to float, but its weight can easily be adjusted using lead pellets until neutral buoyancy is achieved.

Validation Plans

To validate that our redesign of the C-HAT is capable of actively measuring the stress response of American lobsters, we will send the final design to the researchers at WHOI for testing on live lobsters within a tank. Here, a pod of ten lobsters should be split into a control group and an experimental group. The initial stress level of each lobster should be measured through the heat shock protein levels in the lobsters' cells. C-HATs will then be secured to the experimental group before placing them back into their tank.

Over the course of four days, observe the lobster's behavior using live monitoring and video cameras. Note any difficulties moving or burrowing in the experimental group caused by the C-HAT. Also note any differences in the interactions between the experimental and control groups to ensure the C-HAT has no social effect on the lobsters. Introduce occasional stressors to the environment (noise, movement, or light) and note when they are introduced.

After the fourth trial day, remove the C-HATs from the experimental group. Then measure the final stress level of each lobster via heat shock protein levels. After processing the heart rate data from the C-HAT, seek to make the following three observations. First, check for the expected change in heart rate at the times stressors are introduced. Second, compare the stress levels measured through heat shock proteins and the C-HAT in the experimental group. Third, compare the changes in stress levels between the experimental and control group to ensure the C-HAT is not detrimental to the health of the lobster. If the C-HAT is able to accurately detect these stressors and stress levels without causing harm to the lobster, the design is successful.

DISCUSSION

Our redesign of the C-HAT was split into two main focuses: a new packaging solution for the electronics to reduce the overall volume and impact on the lobster, and a new mounting interface to improve sensor readings by increasing the attachment strength and filtering out ambient IR light. We were able to successfully design and test an interface that reduces the noise to the IR sensor and IMU by creating a secure, form-fitting attachment that filters out ambient light. This interface is also easily manufactured with widely available materials.

Our packaging solution was not as successful, though. While we were able to reduce the volume of the C-HAT slightly, we failed to achieve neutral buoyancy in this iteration. The potted design also prevents access to the micro SD card for data retrieval and battery for recharging, but we implemented a 5-pin interface to interact with the Adafruit Feather via USB. The C-HAT can be charged from these pins, and the data can be offloaded using an Arduino sketch we created. We also experienced difficulties with epoxy leading onto the IR sensor during potting, but this could be avoided by reducing the tolerance around the sensor and not curing the epoxy in a vacuum oven. We were able to remove much of the epoxy from the fully encased C-HAT, but the epoxy created too much noise in the leash's sensor. Unfortunately due to the epoxy, the electronics in the C-HAT can not be removed or repaired. Due to these difficulties, we also adapted our mounting interface to fit the Go-Pro case packaging currently used by our sponsor, but we have not been able to test this yet.

Given more time, we would like to repot both the fully encased C-HAT and lobster leash with reduced tolerances around the sensor for additional testing. We would also like to attempt to further reduce the height of the C-HAT by expanding its width slightly. Finally, we would like to reexamine the electronics of the C-HAT for potential smaller alternatives. If no major reductions in the volume can be achieved, we would then test our interface adapted to fit the Go-Pro case.

REFLECTION

Health and Ethics

The only ethical dilemma faced within this project is the treatment of the American lobsters that must wear the C-HAT for studies on their physiology and movement. As such, our redesign of the C-HAT sought to prioritize the health, safety, and welfare of these users. While the presence of the C-HAT on the lobster will almost certainly impact the lobster's physiology and movement, we sought to minimize these effects while also improving sensor readings. The C-HAT will also be used to monitor the potentially detrimental effects of ocean noise on lobster physiology, which could lead to regulations on offshore construction that benefit the greater lobster population. Testing with invertebrates does not typically require oversight from The Institutional Animal Care & Use Committee (IACUC), but the health and wellbeing of the lobsters must still be prioritized.

For our design, we did not prioritize sustainability. Due to the scale of our project, we do not expect our design to be mass produced with a maximum of 15 units being produced. Additionally, our design is removable and is expected to be collected before the end of its lifetime and reused. The C-HAT will likely be disposed of in a landfill after the batteries fail or the unit becomes obsolete. In the future, if this design was to be used for a wide-spread research, we would advise that our design be iterated to put higher focus on sustainability. C-HAT is an open-source project, therefore intellectual property does not play a role in this project.

Global Impact

The redesign of the C-HAT will likely have no direct impact on the global marketplace as we do not expect these to be mass produced. We expect a maximum of 15 C-HAT's to be manufactured and used by our sponsors at WHOI for their research, but this design is open source and available for use by other marine biologists. As such, we did not prioritize sustainability. Our design is easily removable and rechargeable, allowing it to be used for numerous trials, but it will likely end up in a landfill after its batteries fail. Thus, if future iterations are produced at a larger scale, we recommend a greater emphasis on sustainability.

Despite the low marketability of the C-HAT, the results of the research conducted with it could have a far greater societal and economic impact. Research linking the increase in ocean noise from offshore wind farms to detrimental effects on lobster physiology could lead to greater restrictions on the construction and operation of these wind farms, especially with the previous research with other marine life. This may negatively impact the transition to clean energy, but it will protect marine life and the large lobster fishery industry of New England.

Team Dynamics

Despite varying backgrounds, our team experienced no difficulties in communicating and working with our sponsor or between ourselves. Varying backgrounds in computer science, electronics, and modeling allowed our team to seamlessly approach the various aspects of the C-HAT design to quickly decompose where we may find improvements. Most design decisions were unanimous, but any difference in opinion was quickly settled with a vote. Our sponsor's background in marine biology also provided invaluable insight and recommendations as we iterated our design.

In our design, we sought to prioritize the revisions requested by our sponsor, namely improving sensor readings through an improved mounting interface. Due to this focus, we did avoid reexamining the electronics and sensors used in the C-HAT, which could have also offered an improved performance. Due to our desire to achieve more with our redesign, we were also heavily motivated to pot our circuit for its potential volume reduction, but this created new challenges in manufacturing with few advantages. Luckily we were able to also replicate our interface design to fit the more manufacturable Go-Pro case assembly.

There were little cultural influences on our design, apart from an appreciation for lobsters and the agreement that the hot pink filament provided the most fashionable C-HAT.

RECOMMENDATIONS

After reflection on our design and its ability to address the requirements of the project, our team has some recommendations. First, we recommend the use of the Go-Pro case for the packaging design. We feel that the time, money, and effort of potting the electronic components in epoxy is not worth the slight decrease in packaging size. Our own experience with potting led to epoxy spilling through small holes between the 3D printed packaging and the infrared sensor, which covered the sensor in epoxy and jeopardized the entire design. Potting the electronics in epoxy also created a problem in off-loading the data from the micro-SD card, in which we needed to design the circuit so that we could connect to an external computer after retrieval of the C-HAT. This process could be bypassed using the Go-Pro case, as data retrieval would be as easy as removing the micro-SD card. The main advantage the potted design has is the size is smaller than the Go-Pro case, however, future development into the design of the Go-Pro case can be done to determine a better solution that decreases the size of the packaging while maintaining the waterproof qualities of the 2-part O-ring design. If you wish to further explore the potted design, also avoid placing the potted circuit in a vacuum oven during the curing process. This will speed up the process, but we experienced epoxy leaks due to our seals melting in this oven.

Additionally, we also recommend the use of rubber foam as done in our design. This foam, when placed along the bottom of the C-HAT, has many benefits. First, it blocks infrared light, which will greatly improve the accuracy of the infrared sensor reading by reducing the noise from ambient infrared light. This, in turn, will improve the quality of the heart rate measurements and provide a better idea of the lobster’s stress level. Secondly, the foam secures the packaging to the lobster’s carapace. The friction the foam provides is enough such that the C-HAT does not slide on the back of the lobster. Keeping the C-HAT still and the infrared sensor in one place also helps to reduce noise in the infrared sensor measurements and provides a better reading for the lobster’s heart rate. Finally, the foam allows the C-HAT to fit a range of lobster sizes, as the packaging will mold to the carapace of the lobster.

Ultimately, the combination of infrared blocking material, such as the rubber foam, and a two-part O-Ring case, such as the Go-Pro case, could provide the best results while also being the cheapest and easiest design to manufacture. If our team had more time, we would iterate our design to an alternate design, such as that in Figure 21, and work to verify it’s effectiveness.

CONCLUSION

In conclusion, our project objective is to help researchers and scientists understand the relationship between under-sea ocean noise and the stress the noise causes in marine life by redesigning the C-HAT biologger to improve measurements and reduce impact to the lobsters. The highest priority design requirements relate to the optimal operation of the IR heart rate sensor. The next highest priority requirements relate to the packaging and mounting solution creating the least disturbance to the lobster. Through background research the team found that measuring heart rate though photoplethysmography using IR sensors was the best method to measure stress non-invasively. Next, concept generation was split though functional decomposition into two sections: sensing and packaging. For each section the team generated ideas collaboratively. A Pugh chart was made to find a final solution. The final design for sensing was chosen to be a suction cup that secures the sensor to the lobster and blocks ambient light. The design for packaging was chosen to be a 3D printed skeleton holding the electronics that is potted in epoxy resin with velcro straps to mount onto the lobsters.

Initial testing of the IR sensor was conducted and showed that a human pulse can be measured and used to accurately measure heart rate. After testing the infrared absorptivity of multiple different interface materials, rubber foam was chosen for the interface. This foam is form fitting and blocks out ambient infrared light, in addition to providing a firm attachment when paired with the velcro straps.

Two prototypes of the final design were created. One is fully self contained and the other utilizes a tether called the Lobster Leash. The fully self contained design will be used for ocean testing and the leash will be used for testing and in tank research.

From verification testing, we learned that the potting waterproofs the electronics and the mounting block IR light. We also learned that potting the sensor can cause issues in manufacturing. Epoxy can leak onto the sensor, making the reading have noise and unable to pick up a pulse. The epoxy potting also makes data retrieval difficult and time consuming when offloading large amounts of data. A full redesign of the packaging and potting may be necessary to solve these problems. To address some of the problems, the team made a gopro mounting system using the verified mounting system.

The team’s next step is to send our C-HAT design to our sponsor. We will explain the issues we encountered with potting. The redesigned GoPro design will also be given for immediate use. The GoPro design will be used for testing by WHOI on a live pod of lobsters to validate its ability to collect accurate data.

ACKNOWLEDGEMENTS

We would like to offer a special thank you to Dr. Andria Salas and Dr. T. Aran Mooney with the Woods Hole Oceanographic Institute (WHOI) for providing us with the opportunity to work on the redesign of the Crustacean Heart and Activity Tracker (C-HAT), as well as for the time and insights they dedicated to our design process.

We would also like to extend our gratitude to Professor Alex Shorter, Anika Satish, and Adi Scharf at the University of Michigan for their invaluable guidance within our design.

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APPENDIX A: C-HAT Circuit Diagram

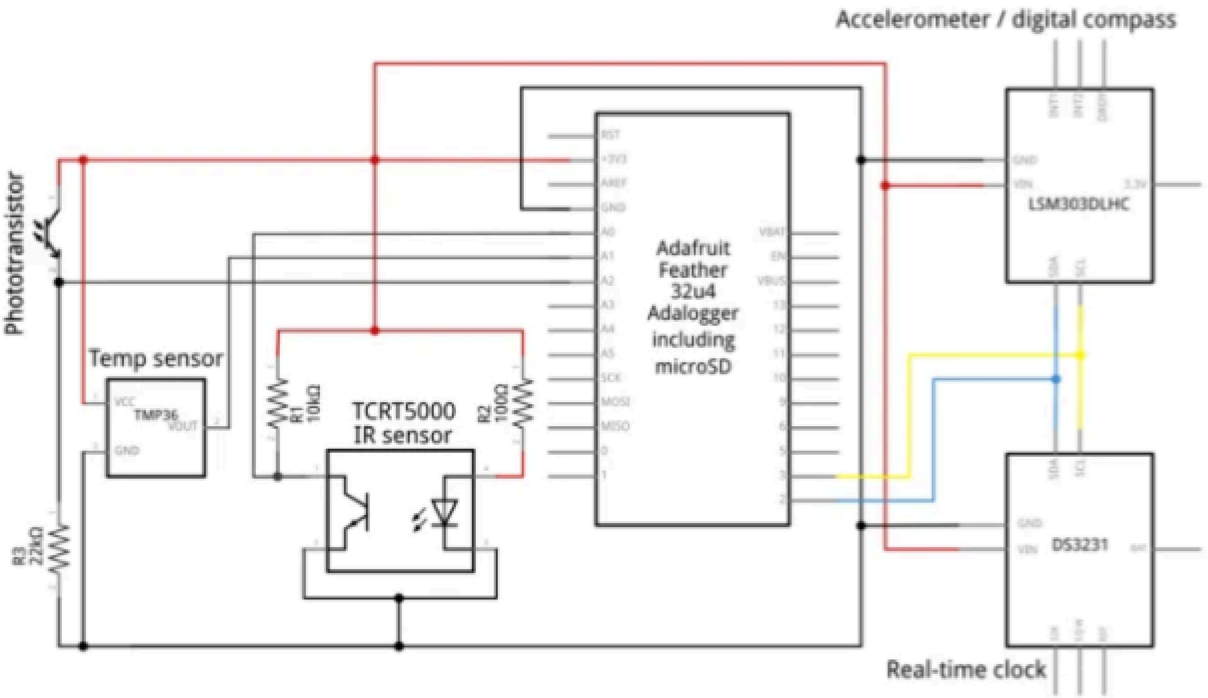


Figure A1: Circuit diagram of the current C-HAT biologger, consisting of a photoresistor, temperature sensor, infrared sensor, accelerometer/digital compass, real time clock, and Adafruit Feather 32u4 Adalogger with a microSD.

APPENDIX B: Design Processes

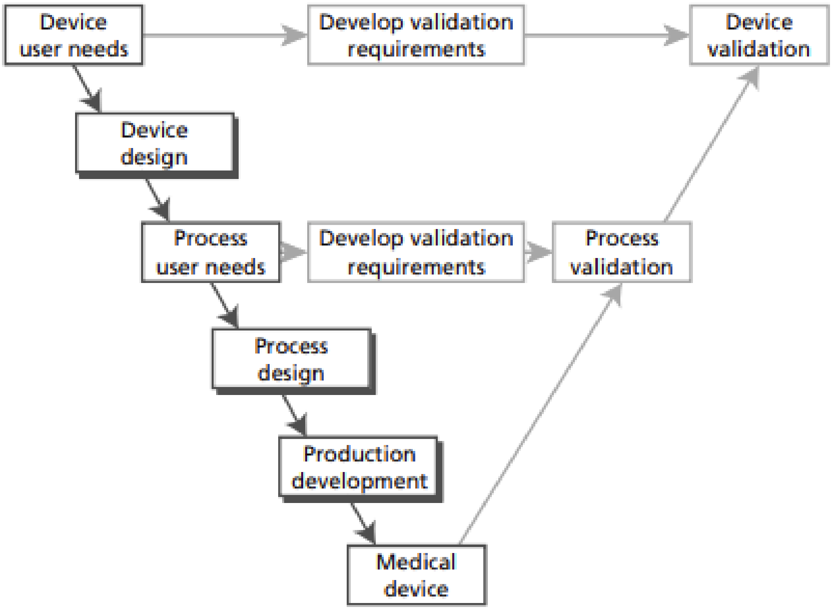


Figure B1: This graphic shows the Alexander and Clarkson (“V”) Model [24]

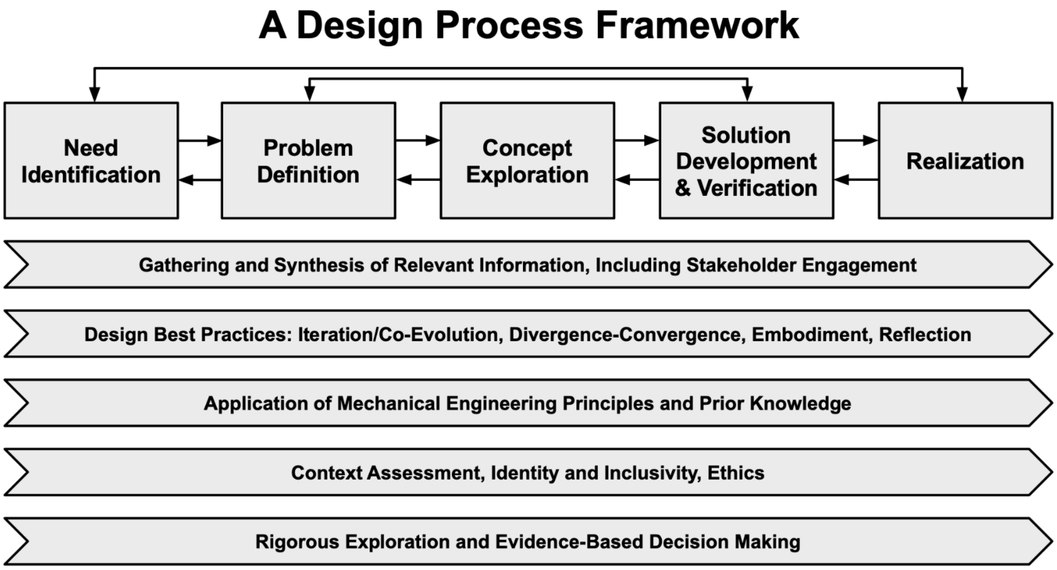


Figure B2: This graphic shows the ME 450 Design Process. [25]

APPENDIX C: Concept Generation

Sensor Readings

To improve the sensor readings, we first considered a different type of sensor (including a microphone, stress ball, and thermometer), but from previous benchmarking, we concluded that using an IR sensor with photoplethysmography would provide the best heart rate measurements. We next thought to attach the infrared sensor more securely. To do so, we considered using cyanoacrylate glue at the interface between the lobster carapace. We also considered the idea of using multiple velcro straps to secure the sensor and housing, as shown in Figure C1.

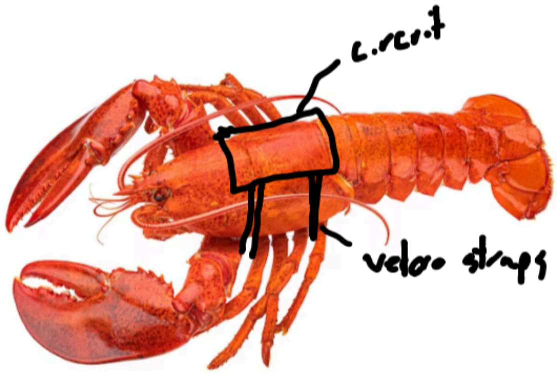


Figure C1: Initial sketch of C-HAT attached using velcro straps.

Our next idea was to reduce the signal to noise ratio of the sensor by blocking out ambient light. One idea to accomplish this was to create a foam interface in between the electronics packaging and the lobster, as shown in Figure C2. The opaque foam would allow the C-HAT to be more form fitting on the lobster, while also blocking ambient light to the IR sensor. This design would also require the use of velcro straps to ensure the foam is compressed onto the lobster's back.

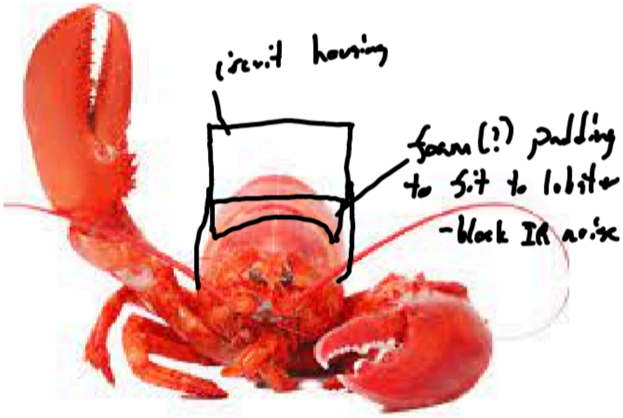


Figure C2: Initial sketch of the foam interface in between the C-HAT circuit housing and the lobster.

We also considered embedding the infrared sensor into a suction cup, as shown in Figure C3, to both improve the sensor's securement and block out ambient light. This will however significantly increase the height of the C-HAT and still require the use of velcro straps.

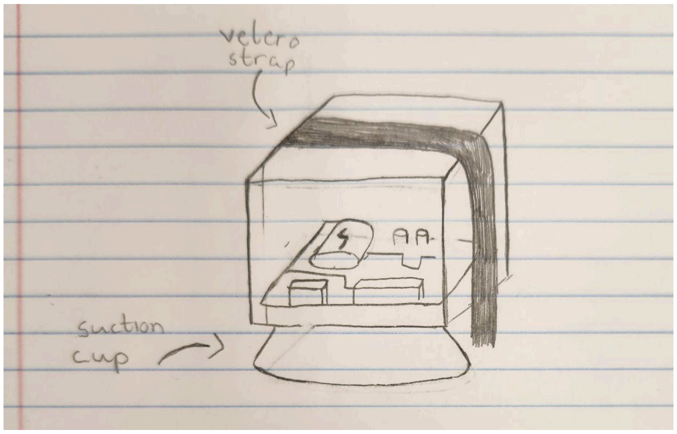


Figure C3: Initial sketch of using a suction cup and velcro straps to attach the C-HAT. Note the infrared sensor is within the center of the suction cup.

To select a method of attaching the sensor and improving its readings, we used the pugh chart shown in Table C1.

Table C1. Pugh chart comparing the methods of attaching the IR sensor to the lobster based on the strength of the sensor attachment, the impact of the attachment on the lobster, the design's ability to reduce ambient light to the IR sensor, the manufacturability of the attachment method, and its cost.

Criteria:	**Weight**	**Velcro Straps**	**CA Glue**	**Foam**	**Suction Cup**
Attachment Strength	5	-1	1	0	1
Low Impact on Lobster	4	0	-1	0	1
Manufacturability	3	1	1	1	-1
Cost	2	1	1	1	0
Reduction Ambient Light	5	-1	-1	1	1
TOTAL:	**19**	**5**	**-1**	**10**	**11**

As shown in the chart, we decided that embedding the infrared sensor within a suction cup and securing this attachment with velcro straps would provide the best sensor attachment and readings. Velcro straps alone fail to provide a strong enough attachment to the lobster, making the sensor prone to shifting that will produce noise in our readings. The use of cyanoacrylate glue will increase this attachment strength, but this will greatly increase the impact of the sensor on the lobster as this is a far more permanent attachment. Both the velcro straps and CA glue also fail to reduce the ambient light, which will result in more noise to the sensor reading. The foam interface and suction cup both offer a solution to the ambient light problem, but the attachment strength of the suction cup is significantly stronger.

Packaging

In order to run and store the C-HAT, we next thought out ideas to improve its current packaging. Our first idea was similar to the current solution of a gopro case, in which we would create an air-tight box with an o-ring seal to keep the electronics dry. A sketch of this concept is shown in Figure C4.

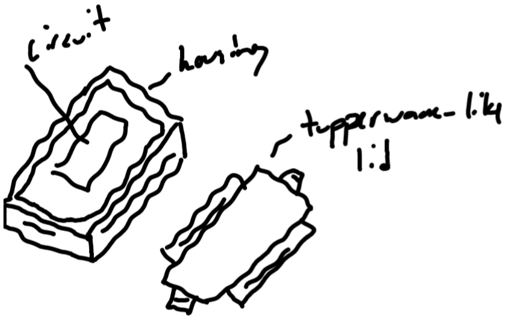


Figure C4: Initial sketch of a 2-part case with an O-ring. The circuit is contained in the housing seen on the left, which can be sealed with the lid on the right.

Our next idea was to separate the sensors from the other electronics with a long cable, allowing the majority of the circuit to lie in a stationary point while just the sensors remain on the lobster. A sketch of this concept, dubbed the “lobster leash”, is shown in Figure C5.

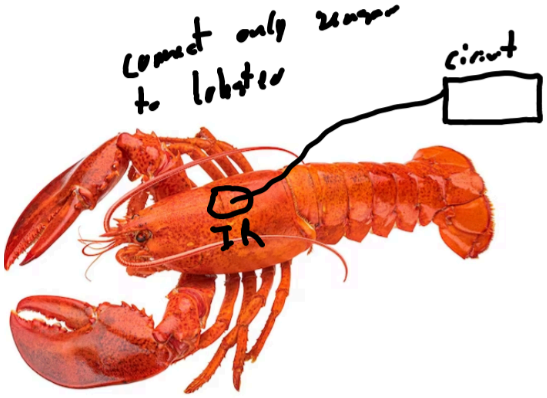


Figure C5: Initial sketch of the “lobster leash” on an American lobster. Here, only the sensors are attached to the lobster and a cable connects the sensors to the rest of the C-HAT circuit.

We also thought of potting the electronics in epoxy in the design shown in Figure C6, which would allow us to greatly reduce the overall volume of the C-HAT while ensuring the electronics are waterproofed.

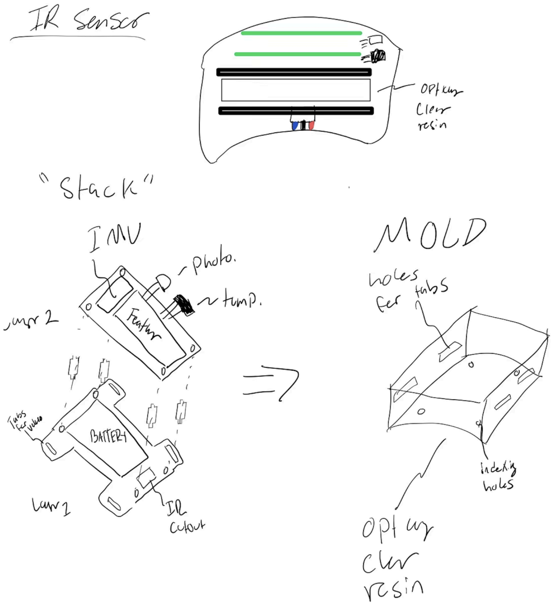


Figure C6: Initial design of the C-HAT circuit potted in epoxy.

To decide on the packaging method that we would employ, we utilized the pugh chart shown in Table C2.

Table C2. Pugh chart comparing the possible packaging methods for the C-HAT based on the criteria of improving the sensor attachment, retaining mobility within the lobster, reducing the overall casing size, ease of data retrieval, and feasibility of construction.

Criteria:	**Weight**	**2-Part Case (O-ring)**	**Lobster Leash**	**Epoxy Potting**
Sensor Attachment	5	0	1	0
Mobility	4	0	-1	1
Casing Size	4	-1	-1	1
Data Retrieval	3	1	1	-1
Feasibility	2	1	1	1
TOTAL:	**18**	**1**	**2**	**7**

Based on the table above, we decided to pot the electronics in epoxy. The use of a 2-part case with an o-ring seal would successfully waterproof the C-HAT's circuit, but this method would fail to reduce the overall size of the packaging. The lobster leash design would reduce the size of the interface with the lobster, allowing us to focus on improving sensor readings, but the cable attaching the sensors to the rest of the electronics will greatly increase the overall size of the C-HAT and is highly likely to restrict the lobster's movement.

The epoxy potting method will allow us to reduce the overall volume of the C-HAT biologger while ensuring that the electronics are waterproof. The epoxy can also be molded around the lobster to ensure it does not interfere with the lobster's movement. This will complicate data retrieval as the C-HAT currently uses a removable SD card which would be encased in the epoxy, but this can be solved with slight modifications to the C-HAT's electronics.

For our alpha design, we will proceed with a design that pots the C-HAT's electrical components in epoxy. We will then use a combination of a suction cup with an embedded IR sensor and velcro straps to attach this potted circuit to the lobsters.

Individual Brainstorming Sketches

Figure C7: Sketch of C-HAT redesigned to lie under the lobster.

Figure C8: Sketch of extended, flattened C-HAT

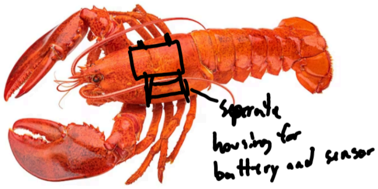


Figure C9: Sketch of C-HAT packaging separated into the power source and other electronics.

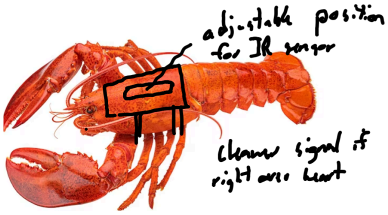


Figure C10: Sketch of C-HAT with adjustable IR sensor position

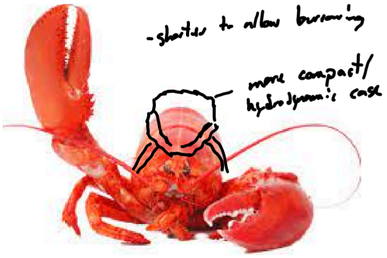


Figure C11: Sketch of streamlines C-HAT to reduce drag

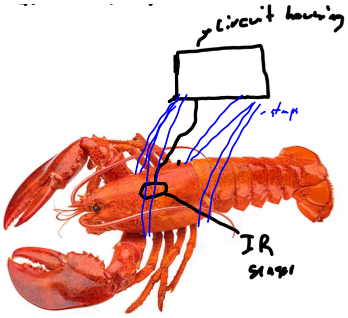


Figure C12: Sketch of "lobster kite", where the sensors are secured to the lobster and the remainder of the circuit floats slightly above.

Figure C14: Sketch of C-HAT with opaque extrusion around the IR sensor to block ambient light.

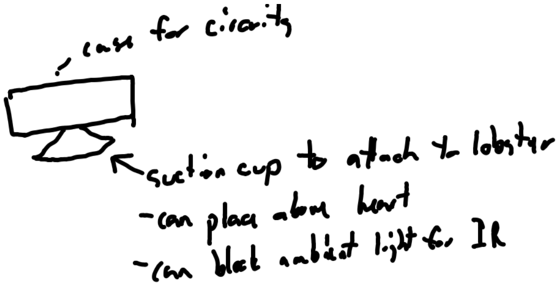
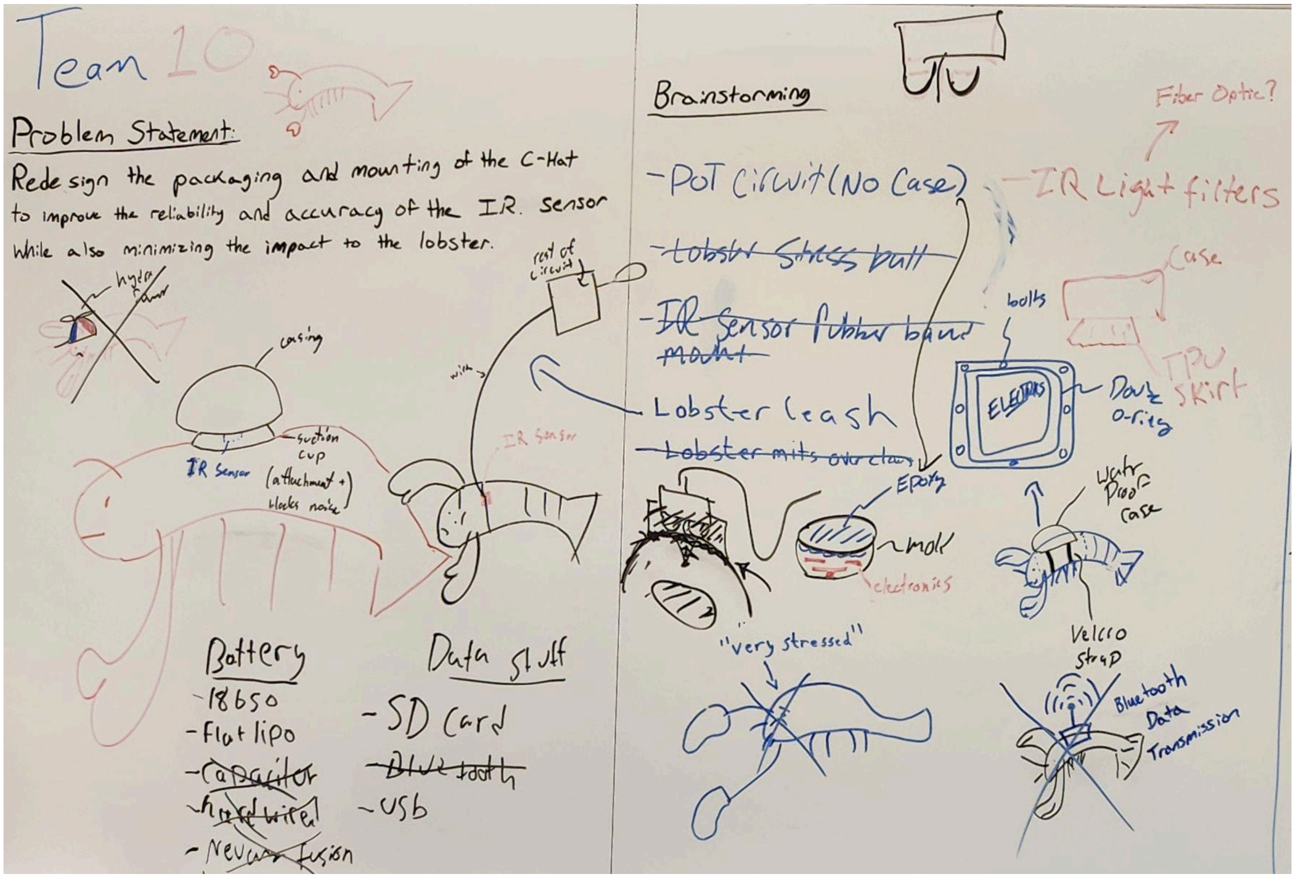


Figure C15: Initial sketch of using a suction cup to attach the C-HAT and block ambient light to the IR sensor. Note velcro straps are not used in this initial design.

Group Brainstorming Sketches



Team 10

Problem Statement:

Redesign the packaging and mounting of the C-Hat to improve the reliability and accuracy of the IR. sensor while also minimizing the impact to the lobster.

Figure C17: Group brainstorming session for generating concepts for sensing, mounting, and packaging. Ideas for sensing include, but are not limited to: a stress ball, an EKG, a microphone, and the existing IR sensor. Ideas for mounting include, but are not limited to: a suction cup, a TPU skirt, a clear epoxy interface, velcro straps, and zip ties. Ideas for packaging include, but are not limited to: a “lobster leash”, epoxy potting, and a 2-part case with an O-ring. Additional ideas for data retrieval are also included, such as an SD card, bluetooth, and direct USB connection.

APPENDIX D: Bill of Materials and Manufacturing Plan

Table D: Bill of Materials

Item	Quantity	Cost Per	Total Cost	C-HATs per Cost	Unit Cost
Foam	1	$8.57	$8.57	18	$0.48
Battery (new)	1	$11.59	$11.59	1	$11.59
Micro SD Card	1	$8.17	$8.17	1	$8.17
Battery (old)	1	$6.95	$6.95	1	$6.95
Adafruit Feather 32u4 Adalogger	1	$21.95	$21.95	1	$21.95
Adafruit DS3231 Precision RTC Feather Wing	1	$13.95	$13.95	1	$13.95
Adafruit LSM303AGR Accelerometer Magnetometer	1	$12.50	$12.50	1	$12.50
IR Sensor	1	$1.80	$1.80	1	$1.80
Temperature Sensor	1	$2.30	$2.30	1	$2.30
Phototransistor	1	$0.95	$0.95	1	$0.95
Epoxy Resin (Quart)	1	$49.97	$49.97	5.5	$9.09
Epoxy Slow Hardener (0.44 Pint)	1	$30.88	$30.88	5.5	$5.61
Switch	1	$0.95	$0.95	1	$0.95
Arduino Cable	1	$7.99	$7.99	2	$4.00
Rubber Foam	1	$15.08	$15.08	50	$0.30
C-HAT Skeleton (3D printed)	1	$0.10	$0.10	1	$0.10
C-HAT Battery Base (3D printed)	1	$0.65	$0.65	1	$0.65
Total			$193.60		$101.33

Manufacturing Plan

To manufacture the alpha design, the skeleton will first be printed from PLA using an FDM printer. The C-HAT skeleton and C-HAT battery base are the only custom parts and they will be printed using a standard FDM printer. All other parts are off the shelf and readily available. The electronic circuits will be soldered and fit into the skeleton. The code will be updated in the arduino and the functionality will be tested. Once the circuits are confirmed to work, epoxy will be poured into the skeleton cavity to permanently seal the electronics. The foam will be added to the bottom of the C-HAT using the adhesive backing. Velcro straps will be fitted onto the mounts.

APPENDIX E: Alpha and Pre-Alpha Designs

Pre-alpha design

Our pre-alpha design features a potted circuit with suction cups and velcro straps to secure and mount the sensor securely on the lobsters back. These concepts scored high on our Pugh chart so they were chosen for initial designs. The straps and suction cups will both work to reduce minor movements, which we were told directly from our sponsor affect the level of noise in the IR sensor's readings

The initial design for the packaging was modeled in Solidworks. Holes are made on the sides of the packaging to house the velcro straps discussed in ideation. A layered design as shown above in Figure E1, is used so that only the battery and circuit have to be potted. The top of the IR sensor sticks out of it since it is waterproof. This allows the sensor to be as close as possible to the lobster's carapace and thus its heart for the most accurate measurements to be taken.

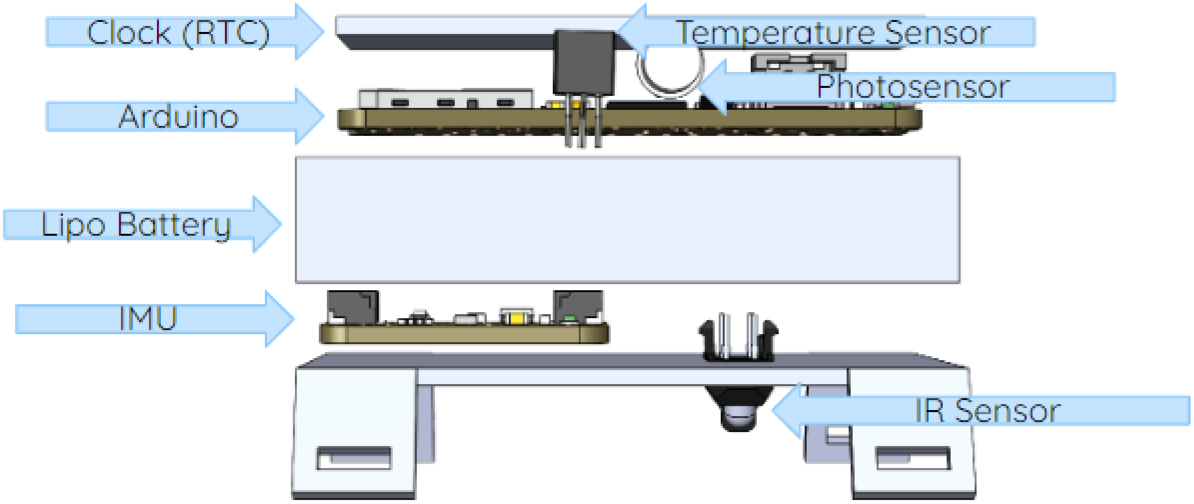


Figure E1: CAD Model side view of initial mounting and packaging design. (without epoxy potting)

For this project, two C-HAT packaging designs will be manufactured: an alpha and final design. The alpha design will consist of a packaging design with only the sensors inside with a cable connecting the arduino and battery. The alpha design will be used for verification of the sensors. The final build will be self contained with all the electronics and battery inside. This will be the final product that can be used for research. This section will focus on the alpha design.

Alpha Packaging and Mounting Design

The alpha packaging and mounting design consists of a 3D printed skeleton, velcro straps, and a rubber foam light seal potted with epoxy. These parts can be seen in Figure E2, pg 54. The 3D printed skeleton acts as a mount for the electronics and a mold for the epoxy potting. 3D printed standoffs are integrated into the design to allow for fastener free assembly. After snapping into place, the components will be potted in epoxy, permanently securing and waterproofing them. The two velcro straps attach to the skeleton using loops and secure the C-HAT to the lobster. The thin velcro straps pass between the lobster legs allowing for full range of motion. The rubber foam creates a barrier between the IR sensor and the ambient IR light leading to higher quality readings. The rubber foam has been tested to block all IR light. The rubber foam also creates friction on the lobster carapace keeping the sensor in the correct position. The Alpha prototype has a 24 percent decrease in height and a 74 percent decrease in volume when compared to the current standard gopro case packaging.

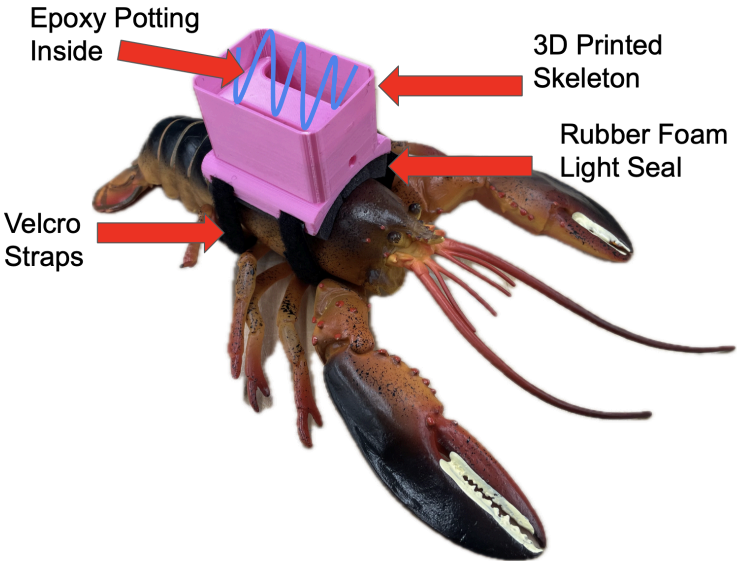


Figure E2: 3-D printed alpha design on lobster model

Alpha Electronics Design

The alpha design electronics will have two sections: the sensors and the microcontroller /battery. The sensors will be secured and potted into the packaging design. A long cable will connect the sensors to the arduino microcontroller and battery. In use, the packaging will be mounted on the lobster and data can be taken from the microcontroller outside the tank. This makes data transfer and battery management easier for testing purposes on a live lobster. The sensors included are an IR sensor, photosensor, temperature sensor, and an IMU. The IR sensor will be mounted on the bottom of the skeleton with the lead half potted in epoxy and the receiver and transmitter open outside of the case. The Photosensor will extend outside the packaging towards the head of the lobster. The temperature sensor will be mounted to the skeleton sidewall to read the ocean temperature. The IMU is placed centrally in the carapace on the bottom of the skeleton to get accurate readings. Outside of the packaging, the arduino and battery will be mounted on a board to be placed outside the testing area connected with a cable to the sensors. While the alpha prototype will not have the battery and arduino in the packaging, the skeleton will have mounting locations for future integration. A cross section showing the location of the electronic components is in Figure E3, pg 55.

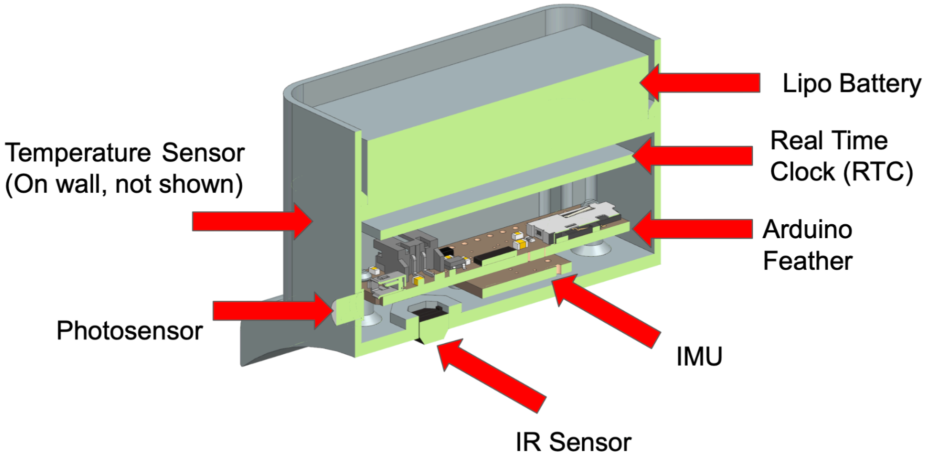


Figure E3: Isometric section view of packaging with callouts for components

APPENDIX F: Arduino Sketches

In order to record and retrieve data with the C-HAT, four different Arduino sketches are needed, all of which are uploaded to the Feather using the 5-pin interface. First is the *C-HAT Operation* sketch, which is used to record data with the sensors and store it on the micro SD card. This sketch will run as long as power is supplied to the C-HAT and should be used during C-HAT testing.

Next is the *Retrieve Filename* sketch (pg. 67), which, as the name suggests, prints the file names stored on the micro SD card to Arduino’s serial monitor.

Next is the *Retrieve Data* sketch (pg. 68), which prints the data from a given file name on the micro SD card to the serial monitor. This allows the data to be easily transferred to a spreadsheet or data processing program.

Finally is the *Remove Files* sketch (pg. 69), which deletes all the files from the micro SD card, clearing the C-HAT’s data and readying it for another trial. We decided to keep these last three sketches separate in case there are any errors in the initial attempt to retrieve data. This way, no data is deleted until it is all safely retrieved. All four sketches can be seen in the following pages.

C-HAT Operation

```
/*Crustacean HAT Datalogger
 * (Heart and Activity Tracker)
 * v2.4 2021-10-7
 * Ben Gutzler bgutzler@gmail.com
 * Uses Adafruit Feather Adalogger, Adafruit DS3231 Precision RTC and LSM303
compass/accelerometer
 * along with TMP36 temp sensor, and HW5P phototransistor
 * Much code borrowed shamelessly from Adafruit examples
 * Tilt compensation now included on compass, based on Pololu and ST Microelectronics
guides
 * Outputs a shedload of raw-ish data of pitch and roll to help decode heading later, maybe,
if we ever figure out the tilt issues

*/

/*USAGE: connect power, then hit RESET button to ensure everything is starting at same
time
 * If solid LED: something is not right
 * LED should flash every 4 seconds to indicate writing to SD card
 * Check this BEFORE starting trial!
 * Not a bad idea to check RTC is set either
 */

#include <Wire.h>
```

```
#include <SD.h>
#include <Adafruit_Sensor.h>
#include <Adafruit_LIS2MDL.h>
#include <Adafruit_LSM303_Accel.h>
#include "RTClib.h"


// LOGGING STUFF
// how many milliseconds between grabbing data and logging it. 1000 ms is once a second
  #define LOG_INTERVAL 200 // mills between entries (reduce to take more/faster data)

// how many milliseconds before writing the logged data permanently to disk
// set it to the LOG_INTERVAL to write each time (safest)
// set it to 10*LOG_INTERVAL to write all data every 10 datareads, you could lose up to
// the last 10 reads if power is lost but it uses less power and is much faster!
  #define SYNC_INTERVAL 4000 // mills between calls to flush() - to write data to the card
  uint32_t syncTime = 0; // time of last sync()

#define ECHO_TO_SERIAL   1 // echo data to serial port

#define IRPin 0    //IR transceiver signal to A0
#define TempPin 1 // thermistor signal to A1
#define LightPin 2 // phototransistor signal to A2
#define statusPin 13 //D13 is red LED
#define errorPin 8 //D13 is green LED

RTC_DS3231 RTC;
  const int chipSelect = 4; //SS pin on Featherlogger
  File logfile; // the logging file

 //defining how to read the uncalibrated data
  int IRReading;
  int TempReading;
  int LightReading;
  float accelX = 0.00;
  float accelY = 0.00;
  float accelZ = 0.00;
  float TempV;
  float TempC;

  // this should let me take more than one measurement per second and keep them straight
  unsigned long millis_now;
  unsigned long millis_prev = 0;
  int millis_diff;
```

```
  uint16_t seconds_now;
  uint16_t seconds_prev = 0;

/* Assign a unique ID to this sensor at the same time */
Adafruit_LIS2MDL mag = Adafruit_LIS2MDL(12345);
Adafruit_LSM303_Accel_Unified accel = Adafruit_LSM303_Accel_Unified(54321);

  sensors_event_t a, m;

void error(char const *str)
{
  Serial.print("error: ");
  Serial.println(str);
  digitalWrite(errorPin, HIGH);
  digitalWrite(statusPin, HIGH);
   while (1){ //This loops to make the lights blink on and off to make it clear there's an issue
    delay(200);
    digitalWrite(errorPin, LOW);
    digitalWrite(statusPin, LOW);
    delay(200);
    digitalWrite(errorPin, HIGH);
    digitalWrite(statusPin, HIGH);
   }
}


void setup(void)
{
  Serial.begin(9600);
 Serial.println();

  pinMode(IRPin, INPUT);
  pinMode(TempPin, INPUT);
  pinMode(LightPin, INPUT);

  // initialize the SD card
  pinMode(10, OUTPUT);

  // let it know the light pins are output only
  pinMode(8, OUTPUT);
  //pinMode(13, OUTPUT);
  /*pin 13 blinks most often, and setting to OUTPUT allows it to
   * dump a lot more current into lighting up the LED - it's fine without
   * and saves us some power!
```

```
 */

// see if the card is present and can be initialized:
if (!SD.begin(chipSelect)) {
  error("Card failed, or not present");
}
Serial.println("card initialized.");

// create a new file
char filename[] = "HATLOG00.CSV";
for (uint8_t i = 0; i < 100; i++) {
  filename[6] = i/10 + '0';
  filename[7] = i%10 + '0';
  if (! SD.exists(filename)) {
    // only open a new file if it doesn't exist
    logfile = SD.open(filename, FILE_WRITE);
    break;  // leave the loop!
  }
}

if (! logfile) {
  error("couldn't create file");
  digitalWrite(errorPin, HIGH);
}

// connect to RTC
Wire.begin();
if (!RTC.begin()) {
  error("RTC failed");
  digitalWrite(errorPin, HIGH);
}

if(!mag.begin())
{
  /* There was a problem detecting the LIS2MDL ... check your connections */
  error("Ooops, no LIS2MDL detected ... Check your wiring!");
  while(1);
}
if (!accel.begin()) {
  /* There was a problem detecting the LSM303 ... check your connections */
  error("Ooops, no LSM303 Accelerometer detected ... Check your wiring!");
  while (1)
    ;
}
```

```
  //THIS IS WHAT GETS LOGGED

logfile.println("datetime,heartIR,accelX,accelY,accelZ,hdg_uncomp,hdgcompensated,temp,l
ight,roll,pitch,magX,magY,magZ");
#if ECHO_TO_SERIAL

Serial.println("datetime,heartIR,accelX,accelY,accelZ,hdg_uncomp,hdgcompensated,temp,li
ght,roll,pitch,magX,magY,magZ");
#endif //ECHO_TO_SERIAL

}

// ACTUALLY RUNNING THIS
void loop(void)
{
  DateTime now;

  // delay for the amount of time we want between readings
  delay((LOG_INTERVAL -1) - (millis() % LOG_INTERVAL));

  digitalWrite(statusPin, LOW); //making LED blink when writing to SD
    //easier to see if it's still running or the battery is dead

  // fetch the time
  now = RTC.now();

  seconds_now = now.second();
  millis_now = millis();
  millis_diff = millis_now - millis_prev;
  if (millis_diff > 900) {
    millis_diff = 0;
  }
  if (seconds_prev != seconds_now) {
    seconds_prev = seconds_now;
    millis_prev = millis_now;
   }

  //Get analog sensor readings
  IRReading = analogRead(IRPin);
  TempReading = analogRead(TempPin);
  LightReading = analogRead(LightPin);

  //Convert analog temp input to degrees C
```

```
  //The next block of code is an expansion of this: TempC = ((TempReading*3.3)*100)-50;
    TempV = TempReading*3.3;
    TempC=TempV/1024; //equivalent to saying "TempC = previous value of TempC * 100"
    TempC-=.5;
    TempC*=100;

  /* Get new sensor events */
 // sensors_event_t a, m;
  accel.getEvent(&a);
  mag.getEvent(&m);

   accelX = a.acceleration.x;
   accelY = a.acceleration.y;
   accelZ = a.acceleration.z;

/*
 * This big chunk of code does the tilt compensation.
 * It works together with a couple functions at the bottom to calculate pitch and roll.
 * I got the math from a post on the Pololu forums:
https://forum.pololu.com/t/lsm303d-tilt-compensation-problem/11611
 * Kevin at Pololu wrote Heading2.ino which formed the base of the math.
 * I adapted some of the pitch and roll equations from ST Microelectronics app note DT0058
"Computing tilt measurement and tilt-compensated e-compass"
 *
https://www.st.com/content/ccc/resource/technical/document/design_tip/group0/56/9a/e4/04
/4b/6c/44/ef/DM00269987/files/DM00269987.pdf/jcr:content/translations/en.DM00269987.p
df
 * I could've used an existing Pololu library with the LSM303DLHC, but I'm trying to
futureproof.
 */

  int32_t temp_mx = mag.raw.x;
  int32_t temp_my = mag.raw.y;
  int32_t temp_mz = mag.raw.z;

 //Uncomment this next section if you want to calibrate each LSM303 chip - leaving it
commented sticks with factory calibration
  // doing math for offsets from empirical calibration values - these values are from the
testbed version at Wells 2020/2/6
     /*    min   max   avg
      * x  -407  177   -115
      * y  -405  271   -67
      * z  -540  134   -203
     */
```

```
  /*
  int32_t temp_mx -= (-115);
  int32_t temp_my -=  (-67);
  int32_t temp_mz -= (-203);
 */

/*Heading calculations*/
//h1 = uncompensated Adafruit code
float h1 = (atan2(mag.raw.y,mag.raw.x) * 180) / PI;
 if (h1 < 0) h1 += 360;

//hcomp = from https://www.instructables.com/id/Tilt-Compensated-Compass/
float Mag_roll = (atan2(a.acceleration.y, a.acceleration.z)*(180/PI));
float Mag_pitch = (atan(-a.acceleration.x/((a.acceleration.y * sin(atan2(a.acceleration.y,
a.acceleration.z)) + a.acceleration.z * cos(atan2(a.acceleration.y,
a.acceleration.z))))))*(180/PI);
float Xhorizontal = accelX*cos(Mag_pitch) + accelY*sin(Mag_roll)*sin(Mag_pitch) -
accelZ*cos(Mag_roll)*sin(Mag_pitch);
float Yhorizontal = accelY*cos(Mag_roll) + accelZ*sin(Mag_roll);
float hcomp = atan2(Yhorizontal,Xhorizontal) * 180 / PI;
  if (hcomp < 0) hcomp += 360;

//end of the tilt compensation and heading calculation bit


// log time and data
  logfile.print("");
  logfile.print(now.year(), DEC);
  logfile.print("/");
  logfile.print(now.month(), DEC);
  logfile.print("/");
  logfile.print(now.day(), DEC);
  logfile.print(" ");
  logfile.print(now.hour(), DEC);
  logfile.print(":");
  logfile.print(now.minute(), DEC);
  logfile.print(":");
  logfile.print(now.second(), DEC);
  logfile.print(".");
  logfile.print(millis_diff);
  logfile.print("");
  logfile.print(", ");
  logfile.print(IRReading); //to get from IR reading to voltage: IRreading*3.3/1024
```

```
  logfile.print(", ");
  logfile.print(accelX);
  logfile.print(", ");
  logfile.print(accelY);
  logfile.print(", ");
  logfile.print(accelZ);
  logfile.print(", ");
  logfile.print(h1);
  logfile.print(", ");
  logfile.print(hcomp); //this is VERY noisy - will want to smooth afterwards
  logfile.print(", ");
  logfile.print(TempC); //TMP36 outputs straight to ºC
  logfile.print(", ");
  logfile.print(LightReading); //to get from reading to voltage: reading*3.3/1024
  logfile.print(", ");
  logfile.print(Mag_roll);
  logfile.print(", ");
  logfile.print(Mag_pitch);
  logfile.print(", ");
  logfile.print(temp_mx);
  logfile.print(", ");
  logfile.print(temp_my);
  logfile.print(", ");
  logfile.print(temp_mz);
  logfile.println();
#if ECHO_TO_SERIAL
  Serial.print("");
  Serial.print(now.year(), DEC);
  Serial.print("/");
  Serial.print(now.month(), DEC);
  Serial.print("/");
  Serial.print(now.day(), DEC);
  Serial.print(" ");
  Serial.print(now.hour(), DEC);
  Serial.print(":");
  Serial.print(now.minute(), DEC);
  Serial.print(":");
  Serial.print(now.second(), DEC);
  Serial.print(".");
  Serial.print(millis_diff);
  Serial.print("");
  Serial.print(", ");
  Serial.print(IRReading);
  Serial.print(", ");
```

```
  Serial.print(accelX,4);
  Serial.print(", ");
  Serial.print(accelY,4);
  Serial.print(", ");
  Serial.print(accelZ,4);
  Serial.print(", ");
  Serial.print(h1);
  Serial.print(", ");
  Serial.print(hcomp);
  Serial.print(", ");
  Serial.print(TempC);
  Serial.print(", ");
  Serial.print(LightReading);
  Serial.print(", ");
  Serial.print(Mag_roll);
  Serial.print(", ");
  Serial.print(Mag_pitch);
  Serial.print(", ");
  Serial.print(temp_mx);
  Serial.print(", ");
  Serial.print(temp_my);
  Serial.print(", ");
  Serial.print(temp_mz);
 Serial.println();
#endif //ECHO_TO_SERIAL


// Now we write data to disk! Don't sync too often - requires 2048 bytes of I/O to SD card
  // which uses a bunch of power and takes time
  if ((millis() - syncTime) < SYNC_INTERVAL) return;
  syncTime = millis();
  logfile.flush();
  digitalWrite(statusPin, HIGH);
}
```

Retrieve Filename

```
// This code can be used to get a list of all files on the C-HAT SD card.

#include <SPI.h>
#include <SD.h>
```

```
const int chipSelect = 4; //  pin for SD card reader

void setup() {
  // Open serial
  Serial.begin(9600);
  while (!Serial) {
  }

  Serial.print("Initializing SD card");

  if (!SD.begin(chipSelect)) {
    Serial.println("Initialization failed");
    return;
  }
  Serial.println("Initialization done");

  // List all files on the SD card
  listFiles();
}

void loop() {

}

void listFiles() {
  // Open the root directory
  File root = SD.open("/");

  // print the name of each file
  while (true) {
    File entry = root.openNextFile();
    if (!entry) {
      // No more files
      break;
    }
    if (entry.isDirectory()) {
      // Skip directories
      continue;
    }
    Serial.println(entry.name());
    entry.close();
  }
```

```
  root.close();
}
```

Retrieve Data

```
// This code can be used to offload data from the C-HAT SD card onto the serial monior. To collect data,
// the arduino serial monitor can be used and the data copyand pased into a spreadsheet. Alternatively,
// the program PUTTY can be used to automatically record the serial monitor and export a CSV file.


#include <SD.h>

const int chipSelect = 4; // pin for SD card
File dataFile;

void setup() {
  // Initialize serial communication
  Serial.begin(9600);

  // Initialize SD card
  if (!SD.begin(chipSelect)) {
    Serial.println("Initialization failed");
    return;
  }

  Serial.println("Initialization done");

  ////////////////////////////////////

  // Edit name to desired file to offload

  dataFile = SD.open("HATLOG01.csv");


  ////////////////////////////////////


  // Check if the file opened
  if (!dataFile) {
    Serial.println("Error opening data file");
    return;
  }
```

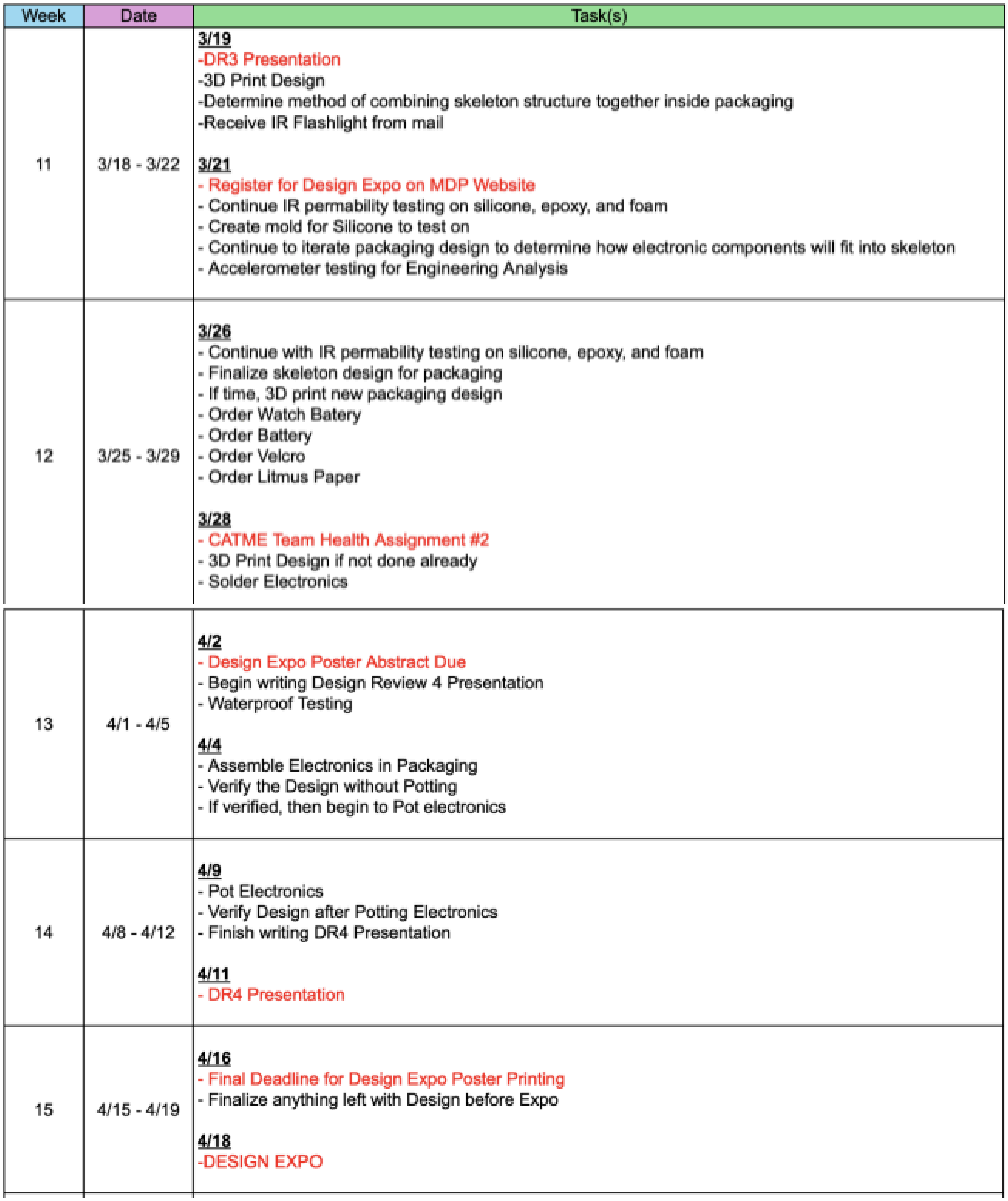
```
  Serial.println("Reading data from file:");

  // Read data from file and print to serial monitor

  while (dataFile.available()) {
    Serial.write(dataFile.read());
  }

  dataFile.close();
}

void loop() {

}
```

Remove Files

```
// This code can be uploaded to the C-HAT to delete all files on the C-HAT SD card.

#include <SPI.h>
#include <SD.h>

const int chipSelect = 4; // pin for SD card reader

void setup() {
  // Open serial communications and wait for port to open
  Serial.begin(9600);
  while (!Serial) {
    ;
  }

  Serial.print("Initializing SD card");

  if (!SD.begin(chipSelect)) {
    Serial.println("Initialization failed");
    return;
  }
  Serial.println("Initialization done");

  // Delete all files on the SD card
  deleteAllFiles();
}

void loop() {
```

```
}

void deleteAllFiles() {
  File root = SD.open("/");

  // Delete all files
  while (true) {
    File entry = root.openNextFile();
    if (!entry) {
      // No more files
      break;
    }
    if (entry.isDirectory()) {
      // Skip directories
      continue;
    }
    Serial.print("Deleting file: ");
    Serial.println(entry.name());
    entry.close();
    SD.remove(entry.name());
  }
  root.close();
}
```

APPENDIX G: Project Plan



Week	Date	Task(s)
11	3/18 - 3/22	**3/19** -DR3 Presentation -3D Print Design -Determine method of combining skeleton structure together inside packaging -Receive IR Flashlight from mail **3/21** - Register for Design Expo on MDP Website - Continue IR permability testing on silicone, epoxy, and foam - Create mold for Silicone to test on - Continue to iterate packaging design to determine how electronic components will fit into skeleton - Accelerometer testing for Engineering Analysis
12	3/25 - 3/29	**3/26** - Continue with IR permability testing on silicone, epoxy, and foam - Finalize skeleton design for packaging - If time, 3D print new packaging design - Order Watch Batery - Order Battery - Order Velcro - Order Litmus Paper **3/28** - CATME Team Health Assignment #2 - 3D Print Design if not done already - Solder Electronics
13	4/1 - 4/5	**4/2** - Design Expo Poster Abstract Due - Begin writing Design Review 4 Presentation - Waterproof Testing **4/4** - Assemble Electronics in Packaging - Verify the Design without Potting - If verified, then begin to Pot electronics
14	4/8 - 4/12	**4/9** - Pot Electronics - Verify Design after Potting Electronics - Finish writing DR4 Presentation **4/11** - DR4 Presentation
15	4/15 - 4/19	**4/16** - Final Deadline for Design Expo Poster Printing - Finalize anything left with Design before Expo **4/18** -DESIGN EXPO

Figure G: Project Plan for the weeks up to the Design Expo

Jayson Terry

I am a senior in BSE mechanical engineering. I am passionate about animals and the environment so I was very excited to be a part of this project. I love my dog, Kobe who is a black double doodle. My previous work includes redesigning multiple parts with FEA for the Umich Solar Car team in 2022.

Nick Boesch

I am a senior student in Mechanical Engineering at the University of Michigan. I plan to graduate at the end of this semester in May of 2024. I chose Mechanical Engineering because I wanted to use my degree to address a range of problems. I was born and raised in Michigan and am searching for employment opportunities locally.

Lukas Fenske

I am a mechanical engineering student at University of Michigan graduating fall of 2024. I have an interest in the extremes of aerospace and deep ocean. I have had internships at NASA's Jet Propulsion Laboratory where I worked on the Mars Sample Retrieval Helicopter. I also interned at WHOI in highschool with the AUV Sentry. When not engineering, I enjoy Skiing and hiking.

Jack Winiarski

I'm a senior at the University of Michigan pursuing a BSE in mechanical Engineering with a concentration in robotics. I have a great interest in prosthetic design, biomechanical systems, and designing wearable sensors, and have gained much experience in these areas as the electrical team lead of Michigan Neuroprosthetics. I have also raised 6 rescue animals and work in animal care at the local nature center, so conservation issues are always close to heart.