ChargeForge: Gang Charging System For Physiological Sensors

BME 200/300
University of Wisconsin-Madison
Department of Biomedical Engineering

Team Members:
Allison Rausch (Team Leader)
Jake Maisel (Communicator)
Luke Blaska (BPAG)
Yeanne Hwang (BSAC)
Kenan Sarlioglu (BWIG)

Clients: Isabel Erickson Kevin Durkee
Advisor: Dr. Chris Brace

13 December 2024

Abstract

Aptima Inc. and their partner VigiLife Inc. are developing a device that monitors the physiology of Marines, such as their heart rate and respiration, in order to prevent heat illnesses or other related afflictions during training. There is currently no way to transport and charge these devices on a large scale. Pelican Cases, which are hard-shelled carrying cases, are now being used to transport devices. Still, there is nothing within the cases to organize the devices, nor is there a way to connect the devices to a charger during transit. To combat this, a tray is being designed that will be able to be inserted into a Pelican Case where the devices can be inserted into slots on the tray and be connected to their respective charger. Ideally, It will accommodate 10-20 devices and withstand extensive travel, high and low temperatures, and other harsh conditions. The material chosen for this tray is ABS, which is impact-resistant, durable, and simple to manufacture and prototype. Ultraviolet radiation may also be used to disinfect the tray and devices. The tray will be tested in its device attachment and protection as well as durability through a drop test, the simplicity of the design will be tested through an ease of use test, and the charging characteristic will be tested by using a digital multimeter to observe voltage and current flow across pogo pins. The results will illustrate the tray’s effectiveness in accomplishing client requirements.

Table of Contents

Introduction

Motivation and Global Impact

Developing a wearable physiological monitoring device addresses critical safety concerns in high-risk occupational environments, such as those involving heat stress or confined spaces. Workers in these conditions face significant health risks, and real-time monitoring of physiological data can help prevent accidents, reduce illness, and ensure timely intervention. The lack of an efficient charging and transport system for multiple sensors hinders consistent and reliable usage. This project aims to design a gang-charging system to address the practical need for sensor charging, transport, and disinfection, improving workplace safety on a global scale.

Existing Devices/Current Methods

Only some gang-charging systems currently exist for medical and physiological devices; however, many systems are designed to charge other devices efficiently. Masimo Corp developed a gang-charging system for their physiological monitoring devices. This system allows for multiple devices to be charged at the same time. Each device's power source comes from a single centralized charging unit, an aspect of this design that will be integrated into the final prototype. However, a significant drawback of this design is that it is massive and weighs significantly more than the targeted weight for this project's design. The large size makes the Masimo Corp design very difficult to transport, which is an essential aspect of the requirements set on us by the client.[1]

The MSTJRY USB charging station is a 5-port USB charging station designed for consumer devices like phones and tablets. While it offers multiple charging slots, it lacks durability. This charging station is only compatible with USB-A charging cords. USB-A is incompatible with the client's physiological devices and cannot deliver the required 2.4 Amps. Additionally, it does not support large-scale sensor charging or backup power for consistent use.[2]

Figure 1: *MSTJRY USB Charging Station for multiple devices[2]*

Brentford, a company specializing in charging stations, created the Power Sync Pro Smart Hub 20S, which allows 20 devices to be charged simultaneously using USB charging. This product comes with individual trays designed to hold iPhones. However, it is only compatible with USB-C charging, which limits its ability to supply any device with more than 1.2 amps. Additionally, this product weighs 15 lbs, adding extra weight to the charging system and making transportation more difficult. Another aspect of this system is a durable holder for the charging hub to be kept when not in use. A drawback of this holder is that it weighs 65 pounds, which alone is too heavy for the requirements set by the client.[3]

Figure 2: *Power Sync Pro Smart Hub Case[3]*

Figure 3: *Power Sync Pro Smart Hub[3]*

Problem Statement

Due to several factors, such as rising temperatures at military training sites and decreasing fitness levels among recruits, a need has developed for physiological monitoring to protect the safety of service members. Thus, a new wearable device, specifically designed for occupational safety in environments like heat stress and confined spaces, is currently being developed for use in the Marine Corps. While still in development, there is currently no way to efficiently consolidate, transport, charge, or protect the devices. These tasks are currently accomplished using a hard-shelled carrying case, which provides protection but lacks any way to organize the devices or connect them with charging cables. Thus, the team is tasked to design and fabricate a gang-charging system that allows neat organization of the devices, charging for every device in the case, and an easy-to-use design.

The design should consist of a tray to house the client's physiological sensors (refer to Figure 4) paired with a charging system to ensure a constant power supply to the sensors. Overall, the design should be able to transport, charge, and recuperate 10-20 sensors. The charging system should ideally indicate charge and UV levels. The final design should balance cost, durability, and manufacturability.

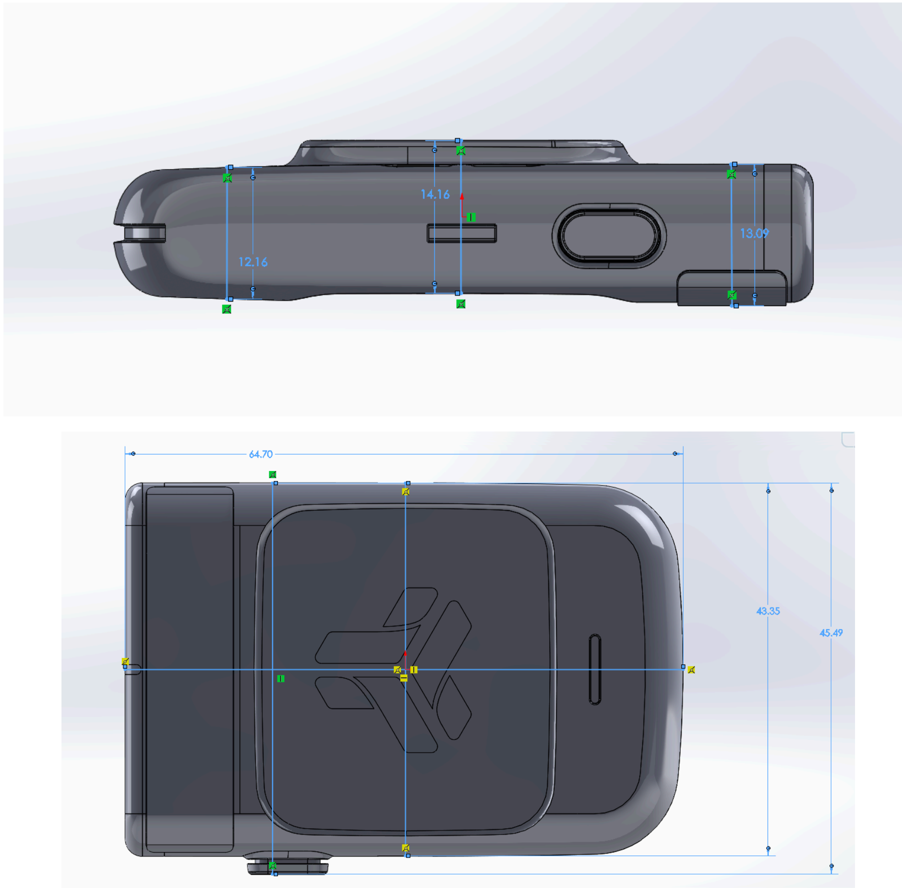


Figure 4: *CAD Model of Client's Current Prototype Sensor (Dimensions in mm)*

Background

Relevant Physiology and Biology

The Marine Corps predominantly uses the device to monitor the heat stress that a soldier experiences in training and combat. This is because high temperatures and the physical activity that soldiers are subjected to daily put them at a higher risk of heat stroke and other heat-related illnesses. In extreme conditions of high heat, elevated humidity, and energy-intensive activity under the scorching sun, Marines operating on the ocean face an increased risk of heat stroke. These environmental factors, combined with intense physical exertion, significantly heighten the potential for the body's systems to fail in regulating temperature, making them more vulnerable to heat-related illnesses [4].

In 2021, there were 1,864 incidents of heat-related illness and 488 cases of heat stroke in the US military[5]. Heat-related illnesses are due to heat stress that elevates a person's core and skin temperatures[6]. The symptoms of heat-related illnesses can vary significantly based on how severe the conditions that someone is subjected to. The least severe symptoms of heat illness are cramps, rash, swelling caused by heat, and fainting. Increasing the severity of the heat illness leads to heat exhaustion, which causes headaches, vomiting, and muscle weakness. Finally, if the severity increases more, it can lead to heat stroke, which causes a person to have an altered mental state, slurred speech, seizures, and even death [7]. The symptoms of heat-related injuries can drastically affect each soldier's alertness and ability to focus on the mission at hand. This situation can be extremely dangerous, as soldiers are often placed in high-stress environments where their actions directly impact their survival, the safety of their units, and the well-being of civilians. The added physical and mental strain in life-threatening scenarios further increases the risks associated with heat-related illnesses, potentially compromising mission success and endangering lives. Ultimately, the physiological devices will be able to monitor soldiers' core and skin temperatures to prevent heat stress-related illnesses from impacting a soldier in the field.

The physiological device will be predominantly kept at the US Marine Corps bases. The world has 39 US Marine Corps bases with very different climates and conditions that could damage the charging station and the devices inside [8]. These conditions include wind, sand, snow, rain, and a high fluctuation of temperatures. If not adequately protected, the charging station and devices could very easily be damaged. The Pelican Case solves this concern by providing a durable, waterproof housing unit for the charging station and devices.

Prototype Design and Build Research

Designing and constructing a gang-charging system prototype necessitates a comprehensive research effort encompassing multiple domains. Material science research proved pivotal in identifying durable, lightweight materials capable of withstanding extreme temperatures, frequent use, and cost-effective fabrication. Acrylonitrile butadiene styrene (ABS), a sturdy thermoplastic, was selected for the housing due to its high melting point [9], shock absorption properties [10], and compatibility with 3D printing and injection molding[11], meeting both durability and manufacturability requirements.

Ergonomic and mechanical design considerations were critical to ensure a user-friendly tray system that fits within a Pelican case. The tray is equipped with real-time charge indicators linked to sensors. Rigorous testing, including degradation, security, electricity, and ease-of-use tests, was conducted to verify the system's safety and suitability for harsh working environments.

Power system investigation was essential for developing efficient charging solutions supporting 10-20 sensors, incorporating backup power and UV sterilization technologies. The charging mechanism employs dedicated slots with specified POGO pins for each sensor, enabling simultaneous charging of 10-20 sensors and ensuring stable contact with the charging source. The system leverages USB-C power distribution methods connected to POGO pin chargers. USB charging research focused on selecting appropriate connectors, integrating USB-C charger wires with POGO pin chargers, balancing power distribution across multiple sensors, and implementing efficient voltage regulation to prevent overcharging or overheating.

Client Information

The clients are Isabel Erickson and Kevin Durkee from Aptima Inc. as well as Vigilife and the Marine Corps. They seek a gang charging tray to support physiological monitoring devices used by Marines. The primary objective is to enable these devices to be securely transported and charged within a durable, hard-shelled Pelican case. By ensuring the system's transportability and protection, the charging tray will allow the sensors to function effectively in dynamic environments and endure harsh travel conditions.

Product Design Specification

The goal of the charging tray for physiological monitoring sensors is to securely hold the sensors while enabling a gang-charging system capable of charging 10-20 sensors simultaneously. The client requires the design to prioritize durability, functionality, and simplicity. To meet durability requirements, the tray must fit within Pelican cases ranging from 12"x9"x5" to 30"x16"x10" and weigh no more than 30 pounds. The materials used must be shock-resistant and durable, ensuring the tray can withstand harsh environments, including extreme temperatures, high humidity, and rough handling, while maintaining functionality over a lifespan of 10 years. Additionally, the system must be operable by individuals without engineering expertise, ensuring ease of use in diverse operational settings. Additional requests by the client include a charge display, a UV disinfection system, and internal backup power. Refer to Appendix I for a more detailed explanation of the Product Design Specifications.

Preliminary Designs and Materials

Refer to Appendix II for budget analysis.

Tray Biomaterial

Acrylonitrile butadiene styrene

Acrylonitrile Butadiene Styrene (ABS) is a popular thermoplastic polymer used as a 3D printing filament due to its strength, durability, and ease of post-processing. ABS exhibits excellent mechanical properties, including high impact resistance, toughness, and good dimensional stability, making it suitable for a tray design. It has a Young's Modulus between 1.9 and 2.5 gigapascals (GPa) [12] and a tensile strength of 45 MPa [13], making it an excellent shock and vibration absorber while resisting cracking and fracturing under loading. ABS has approximately 12.6 kJ/m^2 of impact resistance [14] and a melting point of 473.15 - 513.15 K [15], which allows it to withstand moderate temperatures before deforming. However, ABS releases potentially harmful fumes, including styrene, when heated during the printing process, which necessitates adequate ventilation or the use of an enclosed printer with proper filtration. It is also slightly hygroscopic, meaning it should be stored properly to avoid moisture absorption, which can impact printing quality [16]. ABS's toughness and thermal stability make it ideal for printing functional prototypes and end-use parts, but safety precautions should be taken during use.

High-Density Polyethylene

High-Density Polyethylene (HDPE) is a versatile and lightweight thermoplastic commonly used as a 3D printing filament due to its excellent chemical resistance, durability, and flexibility. HDPE offers good mechanical properties, such as a Young's Modulus that ranges from 600 to 1500 MPa [17] and a tensile strength of approximately 35 - 40 MPa. [18] HDPE also has a low density of approximately 930 to 970 kg/m^3 [19], contributing to its strength-to-weight ratio. It also exhibits high impact resistance and flexibility, making it useful for applications requiring durability under mechanical stress. HDPE has a relatively low melting point of 390 - 410 K [20], giving it good thermal stability for cold environments. HDPE is chemically inert and resists moisture, but due to its warping tendencies during 3D printing, careful attention to bed adhesion and temperature control is necessary. From a safety standpoint, HDPE does not emit toxic fumes during printing, making it a safer option than filaments like ABS.

Polyethylene Terephthalate Glycol

Polyethylene Terephthalate Glycol (PETG) is a popular 3D printing filament that combines strength and durability with the ease of printing. PETG is known for its excellent mechanical properties, including high tensile strength of 31.3 Mpa[21], Young's modulus of 2.01-2.11 GPa [22], good flexibility, and impact resistance, making it ideal for functional parts that need to withstand mechanical stress. It also has excellent chemical resistance and is less prone to warping compared to other 3D printing filaments. PETG's thermal properties include a melting point between 538.5 K [23], allowing it to maintain stability at higher temperatures. PETG prints well without needing a heated enclosure and has good bed adhesion, reducing the risk of warping. Regarding safety, PETG is a relatively safe filament to print, as it produces minimal odors and no toxic fumes. Its strength, flexibility, and ease of use make PETG a popular choice for prototyping and functional parts.

Proposed Tray Design

Design 1

This tray is designed with a rectangular profile, tailored to fit within a Pelican Case with dimensions 838 mm x 457.2 mm x 279.4 mm. It features 40 recessed divots, each specifically designed to securely hold physiological sensors with dimensions 64.7mm x 43.35 mm x 13.09 mm. Integrated magnetic mechanisms within each divot ensure stable positioning of the sensors, maintaining continuous contact with the underlying charging system. The charging system is designed to be wireless, utilizing inductive charging technology, and will be seamlessly incorporated beneath the tray housed within the Pelican Case. This ensures that the sensors remain charged and operational while securely stored, offering a streamlined and efficient solution for both transport and recharging.

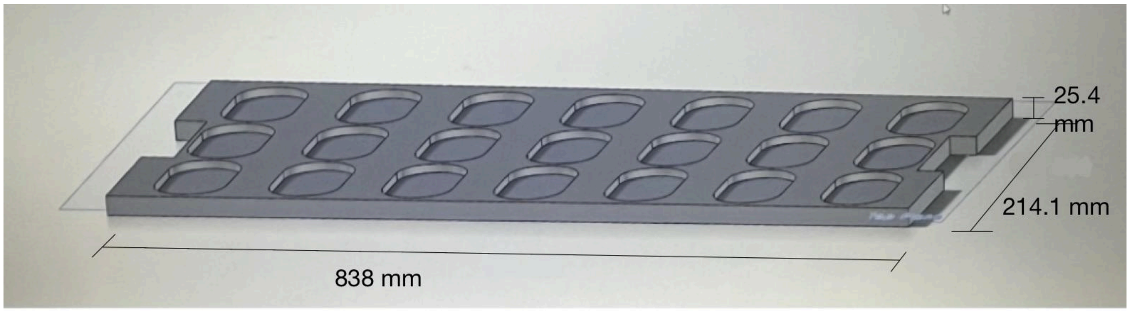


Figure 5: *Half of Full-Scale Design 1*

Design 2

This design features a compact charging dock intended for use within a Pelican Case, as requested by the client. The dock is designed to hold and charge multiple physiological sensors in individual charging slots. The final design would have thirty-two sensors within a 305 mm x 228.6 mm x 127 mm Pelican Case. Each slot is crafted to securely fit the sensor and ensure proper alignment for an efficient charging process. The sensors are positioned 45° from the vertical, allowing for security within the slots as well as an increased number of sensors available to charge at a time.

Charging is facilitated via a USB-C cable connected at the front of the dock, distributing power to the sensors through direct contact points within each slot. The streamlined design eliminates the need for magnetic mechanisms or complex connections, instead relying on a durable and straightforward charging system. This ergonomic and space-efficient solution provides a reliable, portable, and organized charging system.

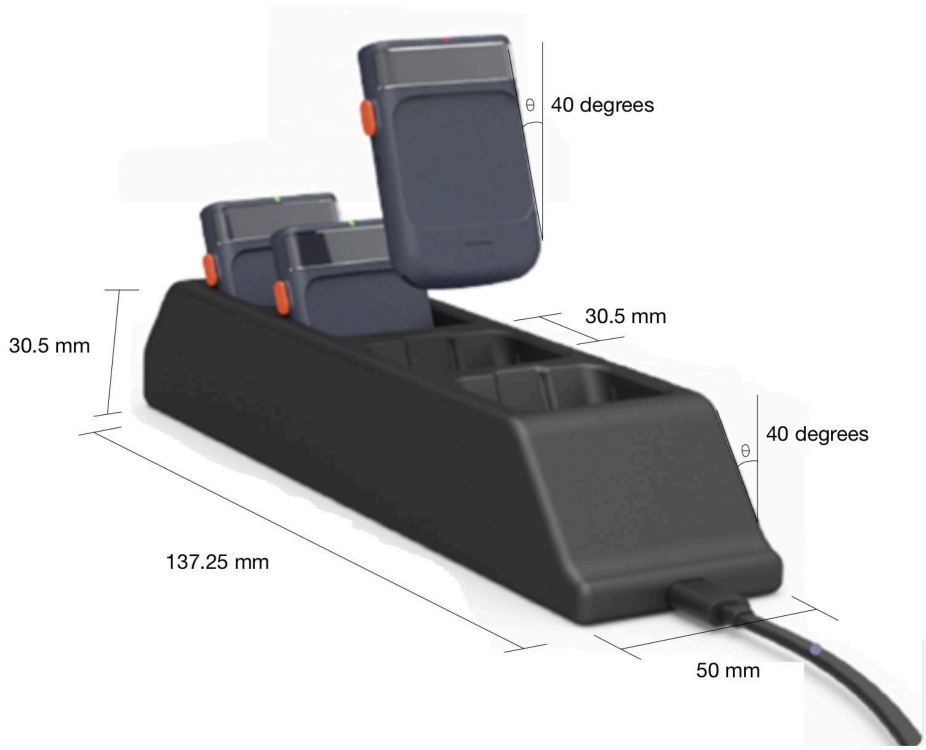


Figure 6: *A Small Scale Model of Design 2 Which Houses 4 Sensors*

Design 3

This tray features a modular gang charging system for efficient charging and storing twenty-one physiological sensors. The tray is designed to accommodate these devices in an organized, flat arrangement, with each device fitting securely into an individual slot. A tooth in each slot is inserted into the side of the sensor, holding the devices in place and ensuring proper alignment during the charging process.

Charging is achieved via pogo pins located in each slot. These pins are connected via USB to a mass charging port underneath the tray, enabling simultaneous charging of all devices. The system uses USB wires soldered to connect the charging port to the pogo pins.

This compact and ergonomic design allows easy device insertion and removal. Its robust construction makes it suitable for integration within portable cases like Pelican Cases, ensuring a stable and protected environment for transport and use. The layout optimizes space while maintaining clear organization, enabling quick access and streamlined operation.

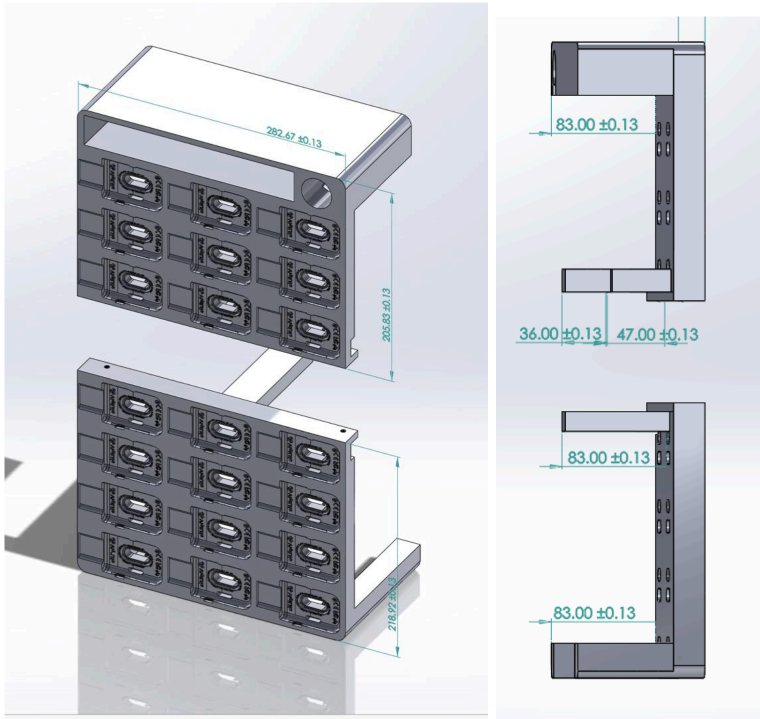
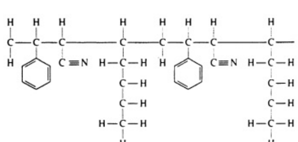
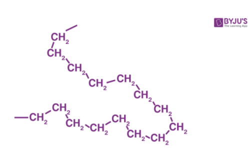
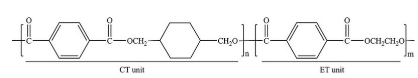


Figure 7: *CAD Model of Design 3*

Preliminary Design Evaluation

Tray Material Matrix

Materials Design				
Material		ABS	HDPE	PETG
Pictures		 *Figure 1: Chemical Composition of Acrylonitrile-Butadiene-Styrene [1]*	 Figure *2: Chemical Composition of High-density Polyethylene [2]*	 Figure *3: Chemical Composition of Polyethylene Terephthalate Glycol [3]*

Criteria	Weight	Score (max 5)	Weighted Score	Score (max 5)	Weighted Score	Score (max 5)	Weighted Score
Durability	30	5	30	4	24	4	24
Manufacturability	20	5	20	4	16	5	20
Weight	20	4	16	5	20	3	12
Safety	15	3	9	3	9	5	15
Cost	10	4	8	5	10	4	8
UV Resistance	5	4	4	2	2	3	3
Sum	**100**	**Sum**	87	**Sum**	81	**Sum**	82

Figure 8: *The Design Matrix ranks the three designs based on durability, manufacturability, weight, safety, cost, and UV resistance with criteria weighted by importance. The final ranking shows that the ABS won.*

Proposed final design

After evaluating the design matrix, the proposed final design was to use Acrylic Butadiene Styrene (ABS) as a 3D printing filament to 3D print the tray. ABS possesses mechanical and thermal properties that meet the client's requirements for the final product. The density of the material makes it slightly heavier than HDPE, but it is much stronger. The manufacturability also allows for the straightforward and repeatable creation of the tray using machines readily available at the University of Wisconsin-Madison.

See Appendix III for an in-depth analysis and criteria explanations for the Tray Material Design Matrix.

Preliminary Prototype Matrix

Proposed Tray Design			
Design	Design 1	Design 2	Design 3

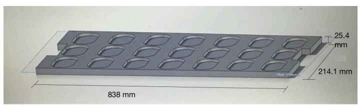
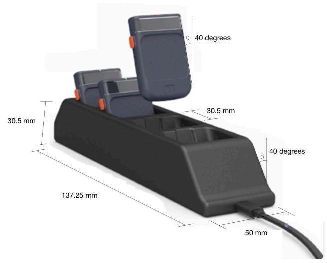
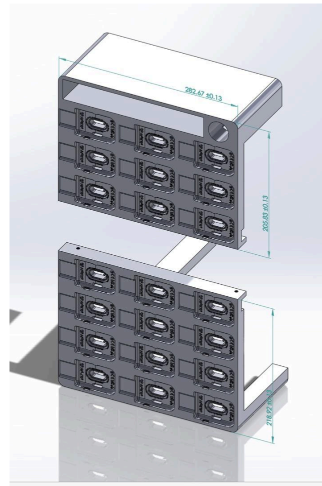
Pictures	 *Figure 1: Design 1*		 *Figure 2: Small Scale Representation of Design 2*		 *Figure 3: CAD Model of Design 3*	
Criteria	**Weight**	**Score (max 5)**	**Weighted Score**	**Score (max 5)**	**Weighted Score**	**Score (max 5)**	**Weighted Score**
Accuracy of Connection	40	2	16	4	32	5	40
Ease of Use	25	5	25	3	15	4	20
Manufacturability	15	5	15	3	9	5	15
Safety	15	2	6	5	15	4	12
Cost	5	5	5	4	4	5	5
Sum	**100**	**Sum**	67	**Sum**	75	**Sum**	**92**

Figure 9: *Preliminary Prototype Design Matrix - ranking three designs based on accuracy of connection, ease of use, manufacturability, safety, and cost with criteria weighted by importance. The final ranking shows that Design 3 won.*

Proposed final design

After evaluating the design matrix, the proposed final design was Design 3. This design ensures reliable connectivity of the sensors within their respective slots as well as the connection of the power supply to the sensor's charging port. It is an intuitive design that can be easily navigated without an engineering background. Design 3 ensures sensor safety and poses little to no safety concerns during use or manufacturing. Additionally, it has a modular design, so it can be taken apart easily and modified to fit specific client needs.

See Appendix IV for an in-depth analysis and criteria explanations for the Preliminary Prototype Design Matrix.

Prototype Fabrication and Development Process

Materials

For the case that holds the sensors, tray, and electrical components, a Pelican 1500 case was chosen because of its durability and quality. Pelican cases are designed to withstand harsh conditions and are waterproof, protecting the components and sensors from the conditions in which they will be used and stored. The 1500 model was chosen because of its sizeable interior area, allowing a single tray to hold twenty-one sensors and fit into the case. The case also has a foam insert that is removable and adjustable to fit the tray.

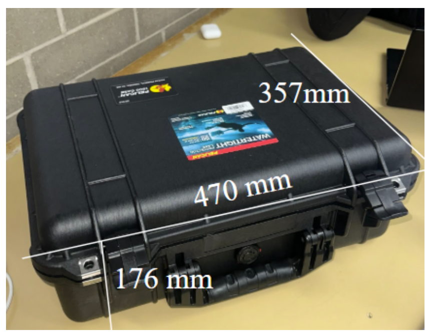


Figure 10: *Closed Pelican 1500 Case*

The tray prototype was printed in PLA, although this material was not in the material design matrix above. The tray was initially designed to be printed in ABS; however, this material was unavailable on the 3D printer. The 3D that was used was the Ultimaker S5. This printer had to be used because the size of the tray prototype was too large to be printed on any other printers available, and the only available filament for this specific printer was PLA. The pogo pin holder and prototype sensors were printed in ABS because they were much smaller prints, allowing other printers to be used. Additionally, from the material specifications sheets the client gave, the primary material used in the exterior of the sensor is ABS.

The charging system's electrical components are a USB-C charging hub, wires, and pogo pins. The hub chosen was the 24-Port 100W (20A) charging station. It was selected because it was very cheap compared to the other USB-C charging hubs and because it had a high number of ports that the USB-C could be inserted into. The wires chosen were a USB-C to USB-C Braided Charge-and-Sync Cable because it was the most cost-effective cable on the market. The client's company is currently making specialized pogo pins for the sensor, so commercial pogo pins with the same dimension were used. AdamTech manufactured the closest commercial Pogo pins found with the part number PH-MVS-5370. These were chosen because they are designed to be soldered and have the same diameter of 1.83mm as the client's Pogo pins.

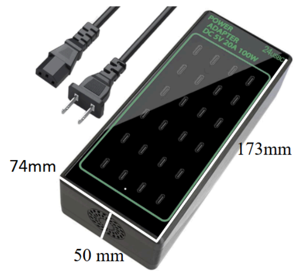


Figure 11: 24-Port 100W (20A) Charging Hub

Figure 12: *USB-C to USB-C* Cable

Figure 13: *Pogo Pins*

Methods

The development of the tray prototype began with creating a unit cell for a single sensor. All 3D prints were created using the SolidWorks application. The process of making the unit cell started with a SolidWorks file of the physiological sensor provided by the client. The next step was sketching a rectangle on the bottom of the sensor, with each side extending 6mm from each side of the sensor to create the walls. The next step was extruding the rectangle to the top of the indentations on the sides of the sensor and cutting the sensor out of the extruded box. Finally, two extruded cuts were made to create a space for the pogo pin holder to be inserted and another to keep the sensor on the bottom, not in contact with rigid material. Using the extruded cut for the pogo pin holder and the pogo pin file given by the client, the pogo pin holder was created. This holder fits tightly into the tray and separates each Pogo pin by 4mm. Finally, an extruded cut was made on the top of the unit cell so that a finger could be used to remove the device. After printing the unit cell, any additional changes or misprints were sanded out to fit the sensor.

Figure 14: *Unit Cell Design with Pogo Pin Holder*

The unit cell was used as a proof of concept to confirm that the sensor would fit and be secured in the cell. After this confirmation, the unit cell was multiplied in Solidworks to create a tray that could hold 12 units. This design featured three rows of units and four columns of units. Then, this tray was multiplied to develop two separate trays. The next step was to remove a column from one of the trays and add a hole for the plug-in to fit through so that it could be pulled out of the case. Finally, legs with a height of 83mm from the bottom of the tray were added. Also, holes with a diameter of 5mm were extruded adjacent to each other on two parts of each side of the tray. These holes were created with a

0.8mm thread as seen in Figure 15. After printing both sides of the tray, insert an M5 x 0.8 bolt and nut into thread holes to connect the two trays together.

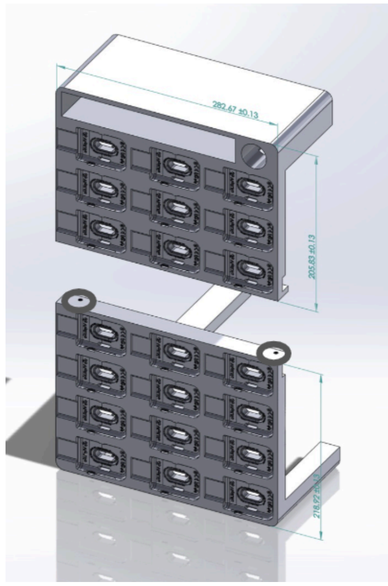


Figure 15: *Final Tray with Threaded Bolt Holes Indicated*

The first step in connecting the Pogo pins and USB-C chargers is to cut the USB-C. The length of the cut charger depends on which unit of the tray the pogo pins will be used in, ranging from 75mm to 250mm. After cutting the wire, strip the white wire using a wire cutter. Use the 12 STRD or 10 SOLID holes on the wire cutter (see Figure 16**)** so that the inside components do not get cut. After stripping the primary wire, there will be five visible wires and an outer shell. Isolate the outer shell, red wire, white wire, and green wire. The other two wires are present as support wires for the charger. (Reference Figure 17)

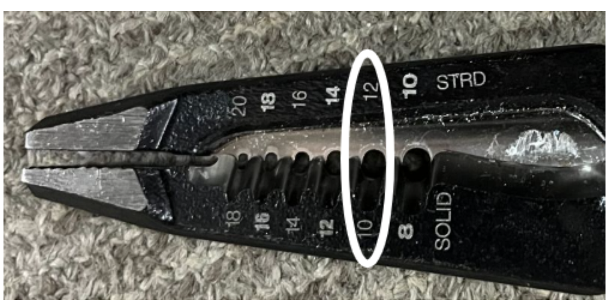


Figure 16: *Wire Cutter with Correct Hole Size*

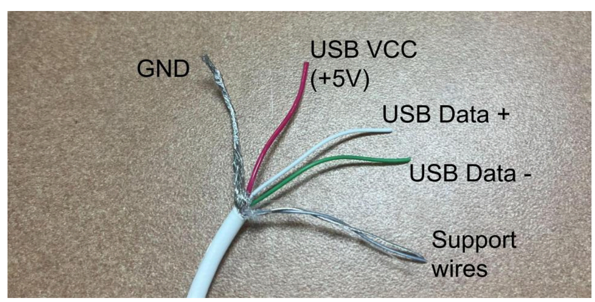


Figure 17: *Internal Wiring of the USB-C Labeled With the Function of Each*

Each isolated wire must then be stripped using a thermal wire cutter. The thermal wire cutter is used because the wires are tiny, and a standard wire cutter often cuts parts of the internal wiring. After these wires are stripped, twist the ends and gently dip each one into a lead-free solder pot refer to Figure 18. Soldering each wire is very important before attempting to solder the wires to the pogo pins because the internal wiring is stranded, not solid.

Figure 18: *Lead-Free Soldering Pot*

Finally, each of the four Pogo pins is inserted into the holes of the Pogo pin holder. Then, from either left to right or right to left, solder the red, white, green, and outer shell in that order to each Pogo pin refer to Figure 19. This process requires two people or a holder for the wire. After the Pogo pins are soldered, insert the holder into the slot in the tray. Repeat this process for each unit of the tray.

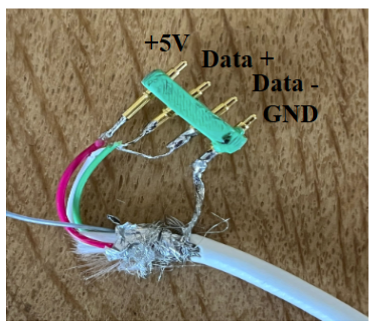


Figure 19: *USB-C Soldered to Pogo Pins*

Final Prototype

Figure 20: *Final Prototype*

The final prototype consists of half of the tray design because the other side failed during printing. The final prototype can hold up to nine physiological sensors, while the whole tray design can hold up to twenty-one sensors.

Figure 21: *Top and Side View of Tray Prototype*

The current charging hub can charge up to eight sensors at 5 volts and 2.4 Amps. Although the charging hub has 24 ports, the total amps that can be distributed is only 20A. Anything over eight sensors charged at once will distribute each sensor with less than the client's required 2.4A per sensor. The current prototype has one fully functioning USB-C to Pogo pin connection.

Figure 22: *Charging System with USB-C to Pogo Pins Connection*

The final prototype is integrated into the Pelican case using the foam inserts that come with the case. The charging hub is located at the bottom of the case, and the bottom of the foam is cut out to fit the hub securely. Additionally, the top of the foam is cut to expose eight ports that a USB-C can be plugged into. The charging hub's wall plug and wire are threaded through the circular hole in the tray and stored in the rectangular extruded cut of the tray when in transport or if the case is closed. The tray sits on top of the foam insert. The tray fits securely in the Pelican case by inserting the legs of the tray in cuts of the foam created. These cuts are the exact dimensions of the legs so that the tray can be securely placed inside the case and not move during transportation. The last aspect of the final prototype is the foam insert at the top of the case. This foam puts downward pressure on the sensors and tray. This strengthens the connection between the sensors and the tray and between the tray and the case.

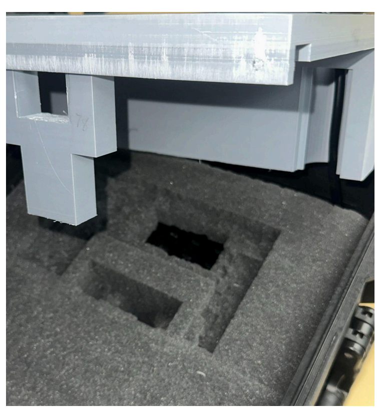


Figure 23: *Altered Foam Inserts Under the Tray*

Testing

Test 1 - Degradation Test

A degradation test was performed to evaluate the durability of the tray design through many cycles of use. The client specified that the industry minimum for the lifespan of the tray is two years, and they estimated that each slot could be expected to be used about 3 times a day per month for a total of around 100 uses per month. Extrapolated out to a year, this would equal 1,200 uses per year. This test was used to determine if the snapping mechanism is still functional and to ensure that the degradation a slot endures does not affect the sensor's connection to the tray. The 3D printed model of the sensor was inserted and taken out 1,200 times in the central slot of the tray(row 2 column 2) to simulate a year of use, and measurements of the tooth used to hold the sensor in place, as pictured in Figure 24, were taken every 200 cycles and recorded. After these trials, it would be assessed if it was necessary to continue on to do another year of simulation or if the decrease in size was negligible in the scope of the project.

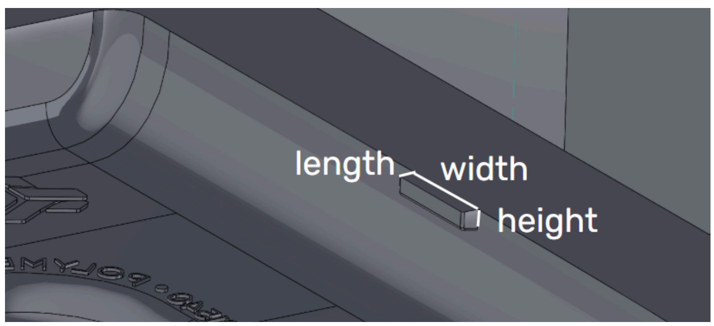


Figure 24: *Dimensions of tooth that were measured every 200 cycles*

Test 2 - Security Test

A security test was performed to validate the locking mechanism of each slot in the tray design to ensure its functionality in less careful carrying conditions. A drop test was performed in which a 3D printed sensor was placed in a slot of the tray, the tray was placed in the case, and the case was closed. Ten trials were performed of dropping the case from one meter as pictured in Figure 25 with the sensor in the chosen slot. After each drop, the case was opened to check if the sensor was still firmly in place, then closed and dropped again until ten drops. This procedure was repeated for all nine slots of the tray for a total of ninety drops. While there is no way to test if the sensor would stay charging without the actual sensor itself, ensuring a firm fit inside the tray was a high priority of the client.

The security test was also combined with the degradation test. After the degradation test on the central slot, a drop test following a similar procedure as above with 50 trials was performed. The purpose of this test was to confirm that after a year of simulated use, the tooth's wear was not substantial enough to affect the performance of the tray holding in the sensor.

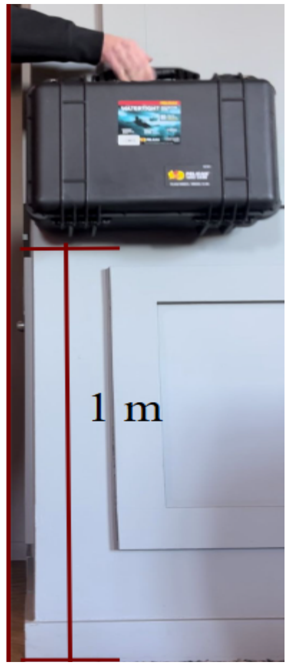


Figure 25: *Conditions of the drop test performed with Pelican Case*

Test 3 - Electricity Test

To test the effectiveness of the soldering from the wires of the USB cable to the pog0 pins, a simple electrical test was performed to examine if the design could function at the client specified 5V and 2.4 amps. Once a connection was established between the USB and pogo pins, a digital multimeter was used first to test the voltage. The USB was plugged into the USB hub which was plugged into a wall outlet, which is how the design is expected to be utilized. Then, alligator clips were connected to the multimeter and attached to the ground and power pins respectively, and the result was measured. To test for 2.4 amps, an alligator clip from the multimeter was attached to the ground pogo pin and the other alligator clip was connected to a 2 Ohm resistor to simulate the load of the sensor. The other pin of the resistor was connected to the power pogo pin to complete the circuit, and the amps were measured. The resistor also had to be held in water during measurement to reduce overheating as it was not rated for the power in the circuit.

Test 4 - Ease of Use Test

An ease of use was performed to determine if the design was intuitive to use for a wide variety of users without instruction. The unit cell and the 3D printed sensor were given to one hundred participants who were asked to place the sensor into the slot, and they were timed while performing the task. The first ten users were asked questions using System Usability Scale principles such as questions like, “How easy was it to insert the sensor into the tray? (1 = Very Difficult, 5 = Very Easy).” But, it was determined that after these tests, the timing was a more effective evaluator of the ease of use with more applicable results. The rest of those questions and detailed steps for all tests can be found in Appendix VI.

Results

Degradation Test Results

The results of the degradation test show the wear of the selected slot throughout the trials. Illustrated on the graph below in Figure 26 is the dimensions of the tooth throughout the 1,200 cycles. The length and the height stayed relatively constant, while the length was the main dimension that was affected, as it decreased from the original 1.03 mm to .9 mm, with the average decrease in length per use being 0.108 µm.

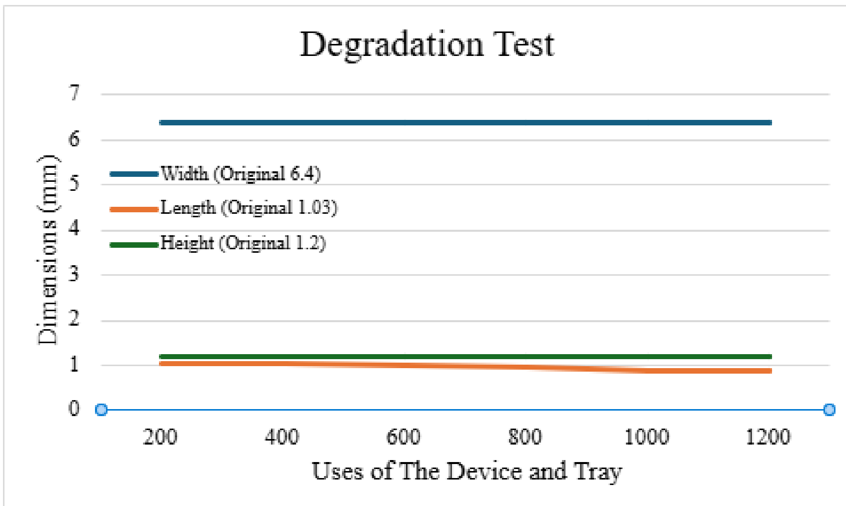


Figure 26: *Graph of the correlation between tray uses and the dimensions of the tooth that is used as the locking mechanism.*

Security Test Results

The security tests yielded consistent results. Through the ten trials in each slot for the total of 90 trials, the sensor was not dislodged at all due to the one meter drop. The combined degradation and security test also provided similar results, as after 50 drops with the one year simulated slot, the sensor still did not move at any point.

Electricity Test Results

The results of the electrical test provided confirmation that the pogo pins were functioning at 5.21 Volts and 2.5 amps. The 5.21 Volts successfully fulfills the projects requirements, and the 2.5 amps was read due to the resistor being 2 Ohms instead of 2.0833 Ohms which would have exactly replicated the load of the sensor, but it can be assumed due to the accuracy of the 2 Ohm resistor that if the resistance was raised, 2.4 amps would be read. Images of the 5.21 V reading can be seen in figure 27.

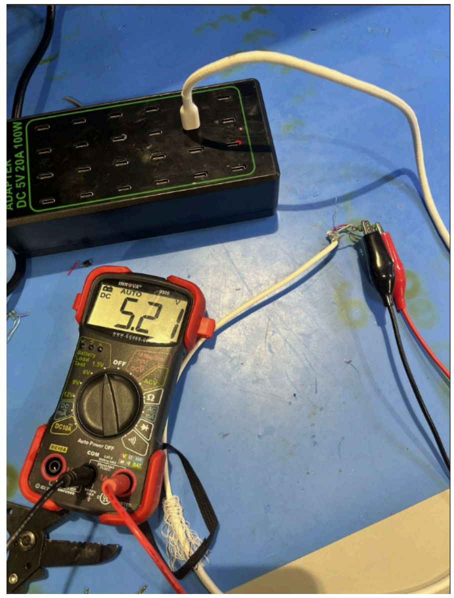


Figure 27: *Reading of 5.21 V on multimeter when connected to fully soldered pogo pins and USB*

Ease of Use Test Results

After monitoring the one hundred participants, it was determined that the average time was 4.78 seconds to insert the sensor into the tray. Out of the one hundred, 97 were able to insert the sensor into the tray before thirty seconds, and the greater than 30 seconds data entries were rather large outliers as seen by the box plot in figure 28. These outliers also largely affected the standard deviation, as with the outliers included the standard deviation was 4.89 seconds , while without the outliers the standard deviation was 1.31 seconds.

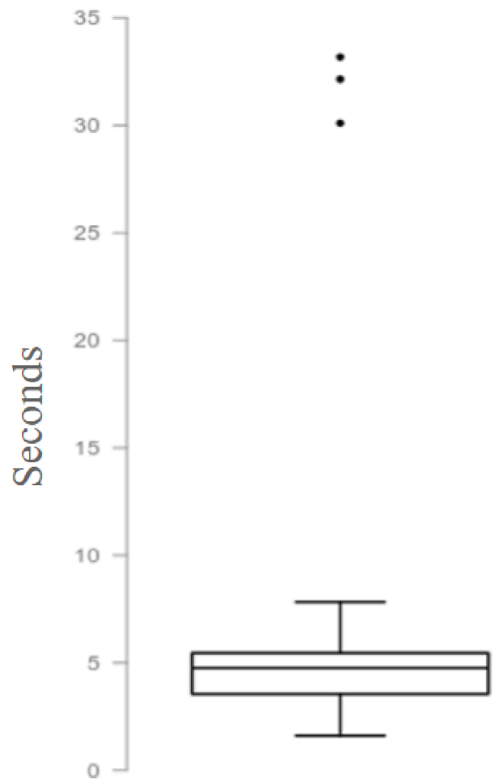


Figure 28: *A box plot generated to represent the time in seconds of the one hundred participants included in testing the ease of use of the tray design. It has a median of 4.41 seconds and a first quartile of 3.5525 seconds and third quartile of 5.455 seconds.*

Refer to Appendix VII for all raw data.

Discussion

Analysis of the degradation test data reveals that while the slot is still functional after a year of use, there is notable degradation to the length of the tooth. This was to be expected, as the front face of the tooth is what the sensor must slide by when being inserted and removed. Extrapolating the data using the calculation that the tooth loses 0.108 µm per use, it is found that the tooth would be about half of its length at .512 mm after 4,800 uses, or four years of wear. This successfully accomplishes the clients needs, but compared to the life of the Pelican case, which has a lifetime guarantee[24], it has a much shorter lifespan. This is not a large issue, as when one tray has become unusable, the whole case will not need to be replaced, but a new tray can be placed in the same case. The drop test results reveal effective and consistent results, as there was not one trial where the sensor became dislodged in the case, which ensures secure connectivity through rough transport for the client. There is no research to compare these results to, but it can be assumed that the design is as effective as any existing product with one hundred percent success. The electrical test's results show successful reaching of proper electrical specifications for one USB. With access to only four pogo pins as sent by the client, this is where the electrical testing ended. But, one thing to note is the USB hub chosen has 24 ports compared to a competitor MSTJRY USB hub which only provides six, providing lots more charging capability. Finally, the ease of use test results reveal that the average of 4.78 seconds of use ensures that the design is intuitive and quick to use. While difficult to find the time for insertion for similar devices, the client determined that under five seconds would be sufficient in validating that the tray is straightforward to use. It can also be assumed that when someone inserts the sensor once and understands the mechanism, subsequent attempts will most likely be quicker.

Ethical considerations were a priority to the research and development process. Ensuring the safety of users was critical, leading us to select materials like ABS that are non-toxic in their final form and suitable for prolonged human interaction. ABS also keeps open the opportunity of later inclusion of a UV disinfection system, which mitigates the risk of disease transmission among users, a critical feature in shared equipment scenarios common in military or industrial settings. Working to improve the overall use of the sensor system itself also has ethical implications. By facilitating real-time physiological monitoring, the sensor contributes to the well-being and safety of workers, aligning with ethical imperatives to protect human health in hazardous environments.

The evaluation process identified a few notable areas for improvement. While the tray was determined to pass the degradation test, the design's total lifespan was not determined. Further testing to determine this like filing down the tooth dimensions until the tray no longer held the sensor could be used to find the approximate time of use before failure. Using this final dimension with the wear per use of each insertion could give us a very rough estimate of this life span. Depending on these results could result in the change of the unit cell of the tray design to create a more wear resistant mechanism. One idea would be to still use the tooth, but utilize the bending and flexibility properties of the material by adding open space behind the tooth where it could flex into before snapping back into place once the sensor was inserted. This would create a more forgiving mechanism and put less stress on the tooth itself from repeated use.

While the electrical test yielded results that were satisfactory to the client’s needs, some changes would still need to be made for this prototype to be functional on a larger scale. The USB hub that the USB’s would need to be plugged into has a maximum Wattage of 100W, which only allows eight USB’s to function at 2.4 amps and 5V at a time before reducing the current. Thus, if using the same concept a 252 Watt hub would be needed to ensure the 21 slots of the tray are able to get the proper power. There would also need to be considerations for heat generation inside the case and how to ensure the safety of the users and the design.

Due to the sensor still being prototyped and testing being performed with a 3D model, there is error that needs to be accounted for in the testing. Since the sensor is still in development, the weight has yet to be determined and cannot be accurately simulated. This lack of weight would likely impact the wear of the tray slightly throughout the degradation test, but would be more of a consideration for the drop test. Adding weight and momentum could affect how well the sensor would stay attached to the tray when dropped from one meter. An additional factor affecting the security test includes that the test was performed in a controlled, standard condition environment where environmental factors such as extreme temperatures, humidity, or exposure to dust could not be tested for, as the expanding or contraction of the tray due to temperatures and wetness or dryness of conditions could have impacted the snapping mechanism.

Using PLA to prototype the tray could also cause errors in the assessment of the design. While it was determined that ABS would be the most effective material choice for fulfilling the clients needs, PLA was easier to prototype as the large printers required for the tray-sized prints could only use PLA. While fairly similar, the slight differences in material properties could have a large impact on the wear of the tray especially over many trials, as it could promote different material interactions and would cause inconsistencies in the wear compared to the testing performed and calculations obtained originally in the degradation test. The difference in flexibility also has implications for the snapping mechanism of the design. ABS has a Young's Modulus of 1.9-2.5 Gpa[25], making it more flexible than PLA with a modulus of around 4 Gpa[26] , making PLA less flexible as a higher Young's Modulus indicates a more rigid material by resisting strain more effectively at higher stresses. This could have changed the design's overall evaluation, especially in the degradation and security tests.

It is important to note once again that since the sensor is still in a prototyping phase, much of the design was to be utilized as a proof of concept for the client and an idea to build off when they create their final design of the gang charging system. This heavily influenced the approach to the project, as the team and client collectively decided that the proof of the electrical functionality would only need to be represented in one unit cell. This is partly due to the fact that it would not be able to be tested with a real sensor, but also that the soldering of the USB's to pogo pins is tedious and unrealistic for how the client plans to manufacture their chargers at a large scale. The tray itself also followed this proof of concept trend, and while another half of the tray would have been desirable, it did not change how the prototype was evaluated.

Conclusions

The goal of this project was to design and fabricate a gang charging system that can effectively address the Marine Corps need for a secure, transportable, and efficient method to charge and configure the physiological monitoring devices. The final design incorporates a tray system that allows for charging multiple sensors and proper organizational capabilities while ensuring users' safety and ease of use. This specific design allowed for the client objectives to be met, including durability, transportation, electrical functionality, ruggedness, and useability. Though, certain areas for development and improvement in the project can be implemented in the future.

Overall, the degradation test showed promising results demonstrating that the tray design remains functional over significant use. However, the tooth wear indicates a limited lifespan when compared to other parts of the final design such as the pelican case. The security tests were able to prove that the sensor stayed firmly in place during drops, which provided confidence in its reliability during rough handling. Additionally, the electrical tests met the required specifications for both voltage and current, further proving their credibility with the prototype's performance under current constraints. The prototype lacked scalability due to the USB hub's power limitations but a higher quality USB hub could allow more devices to be charged within the Pelican case[27]. Furthermore, the ease of use testing proved that the tray design was intuitive and efficient as almost all users were successful in inserting the device into the tray within the expected time.

While the design was able to meet key requirements and performance metrics, a few challenges and limitations were encountered and documented. To improve the durability of the tray future iterations should be focused on creating an injection molded tray with device specifications retesting, for durability and heat resistance[28]. Next, receiving the final device and pogo pins from the client would be essential to test their specific product with the tray design and test for chargeability. Additionally, using a higher quality USB hub would mitigate the limited amount of power which would help expand charging to the whole tray. Incorporating a UV disinfection system is also a key addition in future iterations as this would enhance the health and sanitation aspect of the design and was a client requested feature. These improvements would refine the system and ensure its long term functionality in military conditions.

References

[1]“U.S. Patent and Trademark Office Publishes Masimo Corporation’s Patent Application for Charging Station for Physiological Monitoring Device - Articles - UW-Madison Libraries,” Wisc.edu, 2020. https://search.library.wisc.edu/article/cdi_proquest_wirefeeds_2449416013 (accessed Dec. 12, 2024).
[2]“PowerSync Pro Gen. 2 Smart Hub - Mobile Device Provisioning - Bretford,” Bretford, Dec. 10, 2024. https://www.bretford.com/solutions/charging-stations-and-smart-hubs/powersync-pro-2nd-gen/#features (accessed Dec. 12, 2024).
[3]“PowerSync Pro Gen. 2 Smart Hub - Mobile Device Provisioning - Bretford,” Bretford, Dec. 10, 2024. https://www.bretford.com/solutions/charging-stations-and-smart-hubs/powersync-pro-2nd-gen/ (accessed Dec. 12, 2024).
[4]“Dehydration and Heat Stroke,” Hopkinsmedicine.org, Jun. 20, 2024. https://hopkinsmedicine.org/health/conditions-and-diseases/dehydration-and-heat-stroke (accessed Dec. 11, 2024).
[5]“Heat Illness, Active Component, U.S. Armed Forces, 2021,” Military Health System, Apr. 01, 2022. https://health.mil/News/Articles/2022/04/01/Update-Ht-MSMR (accessed Oct. 10, 2024).
[6]Cleveland Clinic, “Hyperthermia: Symptoms, Causes, Treatment and Recovery,” Cleveland Clinic, 2021. https://my.clevelandclinic.org/health/diseases/22111-hyperthermia (accessed Oct. 10, 2024).’
[7] Mayo Clinic, “Heatstroke - Symptoms and causes,” Mayo Clinic, Jun. 25, 2022. https://www.mayoclinic.org/diseases-conditions/heat-stroke/symptoms-causes/syc-20353581 (accessed Oct. 10, 2024).
[8]“Marine Corps Base Guide List,” Military.com, 2019. https://www.military.com /base-guide/browse-by-service/marines
[9]Protolabs, “ABS Plastic: Advantages, Disadvantages, and Applications,” www.protolabs.com. https://www.protolabs.com/materials/abs/
[10]“Thermoplastic Acrylonitrile-Butadiene-Styrene (ABS) [SubsTech],” Substech.com, Dec. 14, 2023. https://www.substech.com/dokuwiki/doku.php?id=thermoplastic_acrylonitrile-butadiene-styrene_abs#google_vignette (accessed Sep. 26, 2024).
[11]Team Xometry, “ABS Injection Molding: Definition, Applications, Process, and Techniques,” www.xometry.com, Oct. 24, 2022. https://www.xometry.com/resources/ injection-molding/abs-injection-molding/
[12]“ABS material - Properties and common applications,” EuroPlas. https://europlas.com.vn/en-US/blog-1/abs-material-properties-and-common-applications
[13]“Thermoplastic Acrylonitrile-Butadiene-Styrene (ABS) [SubsTech],” Substech.com, Dec. 14, 2023. https://www.substech.com/dokuwiki/doku.php?id=thermoplastic_acrylonitrile-butadiene-styrene_abs#google_vignette (accessed Sep. 26, 2024).
[14]“ABS - Incept 3D,” Incept3d.com, 2024. https://incept3d.com/materials/ABS (accessed Sep. 26, 2024).
[15]Protolabs, “ABS Plastic: Advantages, Disadvantages, and Applications,” www.protolabs.com. https://www.protolabs.com/materials/abs/
[16]B. O’Neill, “ABS printing speed limits and other considerations,” Wevolver, Oct. 19, 2022. https://www.wevolver.com/article/abs-print-speed (accessed Sep. 26, 2024).

[17]“High density Polyetheen | Designerdata,” Designerdata.nl, 2024. https://designerdata.nl/materials/plastics/thermo-plastics/high-density-polyetheen#google_vignette (accessed Sep. 26, 2024).
[18]“MatWeb - The Online Materials Information Resource,” www.matweb.com. https://www.matweb.com/search/DataSheet.aspx?MatGUID=f9470672aa5549cb9c7b157677d02062&ckck=1
[19]Plastics Europe, “Polyolefins • Plastics Europe,” Plastics Europe. https://plasticseurope.org/plastics-explained/a-large-family/polyolefins/#:~:text=The%20density%20of%20HDPE%20can
[20]“Polymer Degradation and Stability | Journal | ScienceDirect.com,” Sciencedirect.com, 2019. https://www.sciencedirect.com/journal/polymer-degradation-and-stability
[21]“Material Properties of Thermoplastic PETG - Exceptionally Durable,” Dielectric Manufacturing. https://dielectricmfg.com/resources/knowledge-base/petg/
[22] M. Davies, “What Is the Density of PETG & How Does It Affect 3D Printing? - 3D Print Beast.” Accessed: Sep. 26, 2024. [Online]. Available: https://www.3dprintbeast.com/petg-density/
[23]unionfab, “Melting Point of PETG: Properties and Applications,” Unionfab, Apr. 24, 2024. https://www.unionfab.com/blog/2024/04/melting-point-of-petg
[24]“Pelican Case Differences | The Case Store,” The Case Store, 2017. https://www.thecasestore.com/learning-the-difference-between-pelican-cases (accessed Dec. 10, 2024).
[25]“ABS material - Properties and common applications,” EuroPlas. https://europlas.com.vn/en-US/blog-1/abs-material-properties-and-common-applications
[26]MatWeb, “MatWeb - The Online Materials Information Resource,” www.matweb.com.
[27]Cadence, “What are the maximum power output and data transfer rates for the USB standards?,” What are the Maximum Power Output and Data Transfer Rates for the USB Standards?, https://resources.pcb.cadence.com/blog/2020-what-are-the-maximum-power-output-and-data-transfer-rates-for-the-usb-standards (accessed Dec. 11, 2024).
[28]K. de Noaum and M. Conniff, “Understanding ABS Injection Molding,” Xometry, https://www.xometry.com/resources/injection-molding/abs-injection-molding/ (accessed Dec. 11, 2024).

Appendix

Appendix I - Product Design Specification (PDS)

Function

A new wearable device for physiological monitoring, specifically designed for occupational safety in environments like heat stress and confined spaces, is currently being developed. There is no system to reliably charge and house the physiological sensors during transit. Thus, the team is tasked to design and fabricate a gang-charging system to be housed within a hard shelled carrying case - providing protection and constant connectivity of the sensors. Overall, the design should be able to transport, charge, and recuperate 10-20 sensors. The charging system ideally should indicate charge and UV levels. The final design should balance cost, durability, and manufacturability.

Client requirements

- The client primarily requests a tray to be fabricated that is able to charge the devices.
- The client requests ease of removal and insertion of sensors out of the tray.
- The client requests there is a charge indicator on the device.
- The client requests a mechanism for UV disinfection within the device
- The client requests the device is simple and intuitive, easily operated by a person without an engineering background.
- The client requests the device has internal backup power.

Design requirements

1. **Physical and Operational Characteristics**
    a. **Performance requirements**
        i. It is expected that the tray can hold 10-20 sensors of 43.35 mm by 64.7 mm and allow easy removal and insertion of these sensors.
        ii. The tray must allow constant connection between the sensors and the charging system.
        iii. A UV disinfection system is preferred within the Pelican Case and should be activated when the case is closed.

iv. The model should withstand extensive travel
   1. It should degrade at a rate less than .2 µm /use as it will be used many times daily.

v. The device will be exposed to high temperatures, low temperatures, dust, and humidity.
   1. The chosen material should have a melting temperature no lower than 423 K.

vi. The device should be functional when used at Marine training sites, construction sites, and athletic training facilities.

vii. The device should be simple enough to be operated by someone without an engineering background.

b. Safety

i. Sensors should not fall out of their charging slot when dropped from a height 1 meter or when held upside down for 30 minutes.

ii. Voltage flow and current are concerns in the event of a short circuit, overload, or ground fault in the wiring system. Therefore, a maximum constant voltage of 5 volts and current of 2 amps should remain consistent at all times.

iii. Charging system must follow Intrinsic Safety Standards. [1]

iv. In the event of using UV-curable resins, the user must wear chemical-resistant gloves that are not made of latex. Nitrile and neoprene gloves are best suited for handling. Parts should also be washed after being cured using the solvent that is compatible with the chosen resin. [2]

v. Trays should not contain sharp edges or protruding pieces that are sharp enough to penetrate the user's skin.

vi. There will be no materials that will require labeling as toxic or harmful material.

vii. All corners must be rounded or filed down to prevent shearing and/or slicing injuries to handlers.

viii. Tray must clamp and attach to the Pelican Case tightly without counteracted bending moments.

c. Accuracy and Reliability

i. Charging cables must be functional for 24 hours at a time.

ii. The UV disinfection system must prevent contagion between multiple users and disinfect devices.

iii. Client requires the charge display must have a ±5% error from true charge values.

iv. The tray device must remain reliable when exposed to high temperatures, low temperatures, dust, and humidity.

1. The tray should have no observed deformation or fractures within a temperature range of 238.71 - 322.04 K.

d. Life in Service

i. The device should be able to operate for 24 hours at a time.

ii. The sensors must remain in contact with the charging system at all times during usage.

iii. The charging system should constantly supply 5 Volts and 2 Amps of current to the sensors.

iv. The tray should have a life span of approximately 10 years.

1. The tray should be easily repaired.
2. The tray should remain functional after 100s of uses.

v. The UV light within the disinfection system should have a lifespan of approximately 8,670 - 1,400 hours. [3]

e. Shelf Life

i. The storage facility where the device will be kept has a temperature range from 293.15 - 297.04 K.

ii. The device will be stored in a facility with a relative humidity level of 55-40.[4]

f. **Operating Environmen**t

i. The gang charging device should ideally operate in many different environments. The device will mainly be used on Marines training sites, construction sites, and athletic training sites.

ii. The device must withstand very high temperatures of over 310.93 K.

iii. The device should be able to withstand very low temperatures. There are US military bases in very remote areas that reach temperatures as low as 241.48 K [5]. The device must remain operable after being exposed to such a temperature.

iv. The case must be durable enough to withstand other environmental factors including sand, wind, and dust as well as impacts such as drops from up to 1 meter.

v. The case must be able to withstand heavy and long transportation times. During this process, the device has to remain intact and not break the physiological sensors.

g. Ergonomics

i. Many people will be tasked to operate the device, including engineers, trainers, military personnel, etc.
ii. The device should be easy enough to be operated by a person in any occupation.
iii. The process of using the device should be very simple allowing it to be operated by only one person.

h. Size

i. The smallest pelican case that can be used to fit 10-20 devices is a 13 in x 11 in x 6 in case with an interior dimension of at least 12 in x 9 in x 5 in. The small size of this case allows the operator to carry and move the device.
ii. The largest pelican case recommended is a 33 in x 18 in x 11 case with an interior dimension no larger than 30 in x 16 in x 10 in. This case has wheels and a handle allowing the user to transport the device.

i. Weight

i. The client prefers that the device is under 30 pounds.

j. Materials

i. Tray materials need to be shock-resistant, sturdy, elastic, and durable.
ii. It needs foam that can protect the device while charging: polyester foam will be ideal as it has great compression resistance and is lightweight. [10]
iii. Pins and latches of the Pelican Case should not rust easily, so it would be ideal to use materials like Stainless Steel.
iv. Lightweight charging ports are needed.

k. Aesthetics, Appearance, and Finish

i. The client prefers the color of the final product is black or US Marine Corps colors (Scarlet and Gold).
ii. Hard and rough texture that can absorb shock.
iii. Cube shape that is stable and resistant to tipping.

2. Production Characteristics

a. Quantity

i. A single successful working prototype is the goal of the project

ii. It would be ideal if the design is easy to repeat and implement into other Pelican Cases so it can be effectively used on a large scale for the Marine Corps

b. Target Product Cost

i. The initial budget for the project is $300, and this will be the target cost. Additional funds will be offered by the client if necessary.

ii. The Pelican Case cost will range from $120 - $406 depending on the size chosen, but the client will provide this and will not be factored into the budget.

3. Miscellaneous

a. Standards and Specifications

i. The National Electrical Code (NEC) is a set of standards for safe electrical design and installation. Much of the NEC is focused on 600V or less, which will be relevant for this design as wall outlets use around 120V [6].

ii. Some of the more applicable codes include Article 250.52, which prevents electrical shocks and hazards due to faulty or wet wiring via proper grounding. This must be factored into the design as the devices may be wet when placed into the case [6].

iii. Article 300 details the minimum allowed wire coverings for buried wires to ensure no moisture exposure [6].

iv. Article 210 specifies minimum wire size and ampacity for varying circuits[6]

v. Many further standards in the NEC can be examined for certain scenarios.

vi. In the case that UV is used in the design, there are several UV standards to be adhered to. ASTM(American Society for Testing and Materials) E2297-23 details proper sensitivity range and calibration for UV use[7]. ASTM G154-23 details the standard practice for operating UV lamps and exposure of materials, which has important implications for what material is chosen[8].

b. Customer

i. The primary customer is the U.S. Marine Corps, represented by the client, Isabel Erickson and Aptima Inc. The charging system must meet their operational needs, which involves functioning in extreme environments like marine training sites and construction fields.

ii. The Marines require a durable device capable of withstanding rough handling, varied temperatures, and dust. Additionally, the device must be simple to use, intuitive for personnel, and integrated easily into their current workflow.

iii. Color preferences have also been noted, with a strong preference for a black or scarlet and gold design, aligning with Marine Corps colors.

c. **Patient-related concerns**

i. The gang charging system must ensure that the sensors are properly disinfected between uses to prevent cross-contamination.

ii. Incorporating UV light for this purpose offers an efficient, low-maintenance method for disinfection, ensuring compliance with hygiene standards, especially when multiple users share the same sensors.

iii. The storage of personal data may be a concern, as physiological sensors might gather sensitive health data. Therefore, the device should comply with data privacy regulations, ensuring that any data stored is confidential.

d. **Competition**

i. After analyzing the competition for gang-charging systems, few are tailored specifically for tough, military-grade environments that require both charging and disinfection capabilities.

ii. Competing products usually focus on either charging or storage but lack the UV disinfection and extreme durability that this system offers.

iii. This system differentiates itself by integrating durability, ease of use, and UV disinfection in a compact, portable form, meeting the specific needs of Marines operating in challenging conditions.

iv. For example, Masimo Corp filed a patent on a physiological device charging station. This design includes a multiple-level system that holds the trays for the devices. The design has a charging port that protrudes from the bottom of the station to provide charge to the devices. However, this design is very large and not made for easy transportation [9]. One of the main requirements for the design is that it is very easy to transport.

References:

[1] C. Crouse-Hinds, "AN9003 - A Users Guide to Intrinsic Safety." [Online]. Available: https://www.mtl-inst.com/images/uploads/datasheets/App_Notes/AN9003.pdf

[2]“Safe Handling of 3D Printing Resins | RadTech.” Accessed: Sep. 19, 2024. [Online]. Available: https://radtech.org/safe-handling-of-3d-printing-resins/#:~:text=Do%20not%20touch%20the%20resin

[3] U. S. Office of Water, “Wastewater Technology Fact Sheet,” Sep. 1999. [Online]. Available: https://www3.epa.gov/npdes/pubs/uv.pdf

[4] O. of the U. S. of D. for A. and Sustainment, “DOD SUPPLY CHAIN MATERIEL MANAGEMENT PROCEDURES FOR STORAGE AND MATERIAL HANDLING.” Oct. 12, 2017. [Online]. Available: https://www3.epa.gov/npdes/pubs/uv.pdf

[5] Quartermaster Research & Engineering Command, “FREQUENCIES AND DURATIONS OF HOURLY TEMPERATURES FORT GREELY, BIG DELTA, ALASKA.” [Online]. Available: https://apps.dtic.mil/sti/tr/pdf/AD0234283.pdf#:~:text=This%20report%20presents%20in%20detail%20the%20frequency%20and

[6]National Electrical Code, NFPA 70, 2023 ed., National Fire Protection Association, Quincy, MA, 2023.https://link.nfpa.org/publications/70/2023

[7]Standard Guide for Use of UV-A and Visible Light Sources and Meters used in the Liquid Penetrant and Magnetic Particle Methods, ASTM E2297-23, ASTM International, West Conshohocken, PA, 2023.https://compass.astm.org/document/?contentCode=ASTM%7CE2297-23%7Cen-US

[8]Standard Practice for Operating Fluorescent Ultraviolet (UV) Lamp Apparatus for Exposure of Nonmetallic Materials, ASTM G154-23, ASTM International, West Conshohocken, PA, 2023.https://compass.astm.org/document/?contentCode=ASTM%7CG0154-23%7Cen-US

[9] M. Corp, “Charging Station for Physiological Monitoring Device” [Online]. Available: https://www.freepatentsonline.com/y2023/0147750.html#google_vignette

[10] Foad Rahimidehgolan and W. Altenhof, “Compressive behavior and deformation mechanisms of rigid polymeric foams: A review,” Composites Part B: Engineering, vol. 253, pp. 110513–110513, Mar. 2023, doi: https://doi.org/10.1016/j.compositesb.2023.110513.

Appendix II - Material Costs and Analysis

Item	Manufacturer	Mft Pt#	Vendor	Vendor Cat#	Date	QTY	Cost Each	Total	Link
Case/Tray									
PLA Filament			Makerspace		N/A	1743	$0.05	$87.15	ABS Material
Pelican 1500 Protector Case	Pelican	1500-000-110	Pelican		11/8/2024	1	$152.00	$152.00	Pelican Case
Charging System									
4' USB-C to USB-C Braided Charge	Best Buy	BE-MCA4CCW	Best Buy		11/8/2024	1	$8.99	$8.99	USB-C
POGO Pins	Adam Tech	PH-MVS-5371	DigiKey		11/8/2024	4	$1.80	$7.20	POGO pins
24-Port 100W (20A) USB C Charger	Dongguan Zeen Tengxiang Industrial Co.	ZE-TX24C01A	Amazon		11/8/2024	1	$36.99	$36.99	USB Hub
							TOTAL:	**$292.33**	

Figure 29: *Purchase Log for ChargeForge*

Appendix III - Tray Material Design Matrix

Criteria Descriptions:

Durability: The material must withstand handling and multiple trials without breaking apart. The material must withstand changes in temperature - between 241.48 K and 310.3 K. According to the PDS criteria, the client expects a lifespan of approximately 10 years.

Manufacturability: The design will be scored on the difficulty of manufacturing the tray and the charging system. This includes access to and effects of software necessity, machine accessibility, skill level requirements, and outside resource necessity.

Weight: The material should be lightweight enough to ensure the tray design is less than 6.8 kg.

Safety: The design will be scored on how likely the chosen material and charging system will produce any hazards during the construction process and during use afterward.

Cost: The cost of the design must fall within the budget of $300. The likelihood of excess material must be taken into account to reduce wasteful spending.

UV Resistance: The material must be able to withstand UV disinfection between uses. The effective dose for disinfection ranges from 5 to 10 mJ/cm^2 [4], but some systems can exceed 30 mJ/cm^2 for faster disinfection. The material should be fully functional after 100+ rounds of disinfection.

Ranking Analysis:

ABS:

Durability: Acrylonitrile butadiene styrene (ABS) is a sturdy thermoplastic with excellent durability. It has a Young's Modulus between 1.9 and 2.5 gigapascals (GPa) [5] and a tensile strength of 45 MPa [6], making it an excellent shock and vibration absorber while resisting cracking and fracturing under loading. These properties make it a popular choice in protective cases for electronics[5]. ABS has approximately 12.6 kJ/m^2 of impact resistance [7] and a melting point of 473.15 - 513.15 K [8], which fulfills the intended objective. As ABS exceeds the required durability goals, it scored a 5.

Manufacturability: ABS is commonly used in 3D printing and is available in the Makerspace. This allows for easy manufacturability as a design can be drawn on design software to exact measurements and specifications and then printed out. It can also be printed relatively quickly at 60 mm/s [9], which ensures there will be no warping or other imperfections during printing. As the Makerspace is easily accessible and 3D printing is relatively simple, ABS scored a 5 for manufacturability.

Weight: ABS is considered a lightweight material with a low density of 1050 kg/m³ [6]. The density of ABS is slightly higher than HDPE and lower than PETG so it scored a 4.

Cost: ABS is a relatively inexpensive material, as it is comparable in pricing to the other materials at $15-20 per kilogram[10]. This price aligns with the project's budget, as the tray design will not exceed 1-2 kilograms. Thus, it scored a 4 for cost.

Safety: ABS is a non-toxic material and there have been no known adverse health effects reported due to long-term exposure[11]. One drawback of ABS is that it has low fire resistance and can be harmful when burned, but this would not ideally need to be considered for this project. As ABS has low fire resistance, it scored a 3 for safety.

UV Resistance: ABS exhibits moderate UV resistance with its thermal expansion of 90E-6 in/in*K [6] with a maximum working temperature of 343K [6]. Some special chemicals and coatings can be applied to enhance UV stabilization which helps to prevent color from fading and surface degradation[5]. Thus, it scored a 4.

HDPE:

Durability: HDPE is highly durable, with excellent impact resistance and the ability to withstand tough environmental conditions such as temperature fluctuations, humidity, and mechanical stress. The Young's modulus, which measures a material's stiffness and how easily it can deform or stretch for (HDPE) can range from 600 to 1500 MPa. [12] HDPE has a tensile strength of approximately 35 - 40 MPa [13]. This makes it ideal for military use where the device will be transported frequently and exposed to harsh environments. HDPE has a melting point of 390 - 410 K [13], well above the desired goal. With all these criteria in mind, HDPE scored a 4 on durability as it falls within the target temperature resistance and strength but could be more durable.

Manufacturability: HDPE is easy to mold because of its low melting point of 390 - 410 K [13] which makes it easy to manufacture in bulk through processes such as injection molding, extrusion, and thermoforming. For this reason, HDPE can be constructed in any shape that is needed for the gang charging system tray. The HDPE tray would be manufactured in the Engineering Centers Building which is easily accessible yet time consuming so it scores a 4 for manufacturability.

Weight: HDPE is very lightweight because of its linear molecular structure with few side branches, making it vital for a portable charging system. The density of HDPE is 930 to 970 kg/m³. [14] As the lightest weight option, HDPE scored a 5.

Safety: HDPE is non-toxic, non-conductive, and chemically resistant, making it very safe for use in environments where it might be exposed to chemicals, moisture, or extreme conditions. However, HDPE is slightly flammable so it poses a risk if the charging mechanism overheats. With this possibility in mind HDPE scored a 3 for safety.

Cost: HDPE is cost-effective and similarly priced to other plastic filaments with HDPE, ABS, and PETG all costing around $15-$20/kg [10]. Its affordability, combined with its strength, makes HDPE a great option for large-scale manufacturing and for keeping the project within budget. Since there will be no additional 3D printing costs with HDPE, it scores a 5 for cost.

UV Resistance: HDPE does have some limitations when it comes to UV exposure. As a material, HDPE is not naturally UV resistant, meaning prolonged exposure to UV light, including UV-C light used for sterilization, can lead to degradation over time.A quantification of UV exposure for disinfecting the monitoring devices is 5 to 10 mJ/cm^2 [15] at 200-280 nm wavelength. Unmodified HDPE can degrade significantly after exposure to UV-C light for around 100–500 hours. Thus, HDPE scores a 2 on UV resistance.

PETG:

Durability: PETG has a high tensile strength of 31.3 Mpa and a Young's modulus of 2.01-2.11 GPa [16]. This allows PETG to sustain repeated impacts while keeping its overall shape and function. This is important because it will be subjected to harsh conditions that are found on military bases. The melting point of PETG is 538.5 K [17]. This is a very high melting point that makes the material ideal for sustained heat of the outdoors. Although PETG has a high melting point and a similar Young's Modulus to the other options, it has a lower tensile strength than ABS so PETG scored a 4 for durability.

Manufacturability: PETG is a very easy material to manufacture because PETG is a 3D printable material. This allows the material to be shaped into any design concept for the charging tray. However, PETG prints at around 40-60 mm/s which can be slightly slower than the other materials.[18] As access to 3D printers is readily available, PETG scored a 5 on manufacturability.

Weight: This material is denser than some of the other materials that are being considered. PETG has a density of 1,260 - 1,280 kg/m^3 [19]. So it scored a 3.

Safety: PETG is a very safe and nontoxic material. This material does not pose a risk to the customer. The fumes that are emitted are nontoxic making it a safer material than ABS[]. Thus, PETG scores a 5 for safety.

Cost: PETG is cost-effective and has the same price as other plastic filaments with HDPE and ABS all costing around $15-$20/kg.[20] These are all very cost-effective materials. As a cost is associated with 3D printing, PETG scored a 4 on cost.

UV Resistance: PETG is a UV-resistant material, however, prolonged exposure to UV causes wear on the material. This degradation of the material can lead to a reduced mechanical properties by 30% [21]. This is very important because the tray will be exposed to UV. This could lead to rupture of the material due to photolysis. Thus, PETG scored a 3 for UV resistance.

References

[1]Omnexus, “Acrylonitrile Butadiene Styrene (ABS Plastic): Uses, Properties & Structure,” Omnexus, 2019. https://omnexus.specialchem.com/selection-guide/acrylonitrile-butadiene-styrene-abs-plastic

[2]Byju's, “High-density Polyethylene,” BYJUS, Feb. 28, 2019.https://byjus.com/chemistry/high-density-polyethylene/

[3]“PETG 3D Printing Guide | Top 3D Shop,” Digital Manufacturing Store Top 3D Shop. https://top3dshop.com/blog/petg-3d-printing-guide

[4]“Polymer Degradation and Stability | Journal | ScienceDirect.com,” Sciencedirect.com, 2019. https://www.sciencedirect.com/journal/polymer-degradation-and-stability

[5]“ABS material - Properties and common applications,” EuroPlas. https://europlas.com.vn/en-US/blog-1/abs-material-properties-and-common-applications

[6]“Thermoplastic Acrylonitrile-Butadiene-Styrene (ABS) [SubsTech],” Substech.com, Dec. 14, 2023. https://www.substech.com/dokuwiki/doku.php?id=thermoplastic_acrylonitrile-butadiene-styrene_abs#google_vignette (accessed Sep. 26, 2024).

[7]“ABS - Incept 3D,” Incept3d.com, 2024. https://incept3d.com/materials/ABS (accessed Sep. 26, 2024).

[8]Protolabs, “ABS Plastic: Advantages, Disadvantages, and Applications,” www.protolabs.com. https://www.protolabs.com/materials/abs/

[9]B. O’Neill, “ABS printing speed limits and other considerations,” Wevolver, Oct. 19, 2022. https://www.wevolver.com/article/abs-print-speed (accessed Sep. 26, 2024).

[10]3D Printing, “3D Printing,” Shops, 2024. https://shops.chem.wisc.edu/3d-printing/ (accessed Sep. 26, 2024).

[11]“Facts You May Not Have Known About Acrylonitrile Butadiene Styrene,” Nov. 15, 2023. https://adrecoplastics.co.uk/key-facts-you-may-not-have-known-about-acrylonitrile-butadiene-styrene-abs/#:~:text=Acrylonitrile%20Butadiene%20Styrene%20(ABS)%20is%20considered%20to%20be%20a%20safe

[12]“High density Polyetheen | Designerdata,” Designerdata.nl, 2024. https://designerdata.nl/materials/plastics/thermo-plastics/high-density-polyetheen#google_vignette (accessed Sep. 26, 2024).

[13]“MatWeb - The Online Materials Information Resource,” www.matweb.com. https://www.matweb.com/search/DataSheet.aspx?MatGUID=f9470672aa5549cb9c7b157677d02062&ckck=1

[14]Plastics Europe, “Polyolefins • Plastics Europe,” Plastics Europe. https://plasticseurope.org/plastics-explained/a-large-family/polyolefins/#:~:text=The%20density%20of%20HDPE%20can

[15]“Polymer Degradation and Stability | Journal | ScienceDirect.com,” Sciencedirect.com, 2019. https://www.sciencedirect.com/journal/polymer-degradation-and-stability

[16]“Material Properties of Thermoplastic PETG - Exceptionally Durable,” Dielectric Manufacturing. https://dielectricmfg.com/resources/knowledge-base/petg/

[17]unionfab, “Melting Point of PETG: Properties and Applications,” Unionfab, Apr. 24, 2024. https://www.unionfab.com/blog/2024/04/melting-point-of-petg

[18] M. Davies, “What Is the Optimal Print Speed for PETG? (Detailed Guide) - 3D Print Beast.” Accessed: Sep. 26, 2024. [Online]. Available: https://www.3dprintbeast.com/petg-print-speed/

[19] M. Davies, “What Is the Density of PETG & How Does It Affect 3D Printing? - 3D Print Beast.” Accessed: Sep. 26, 2024. [Online]. Available: https://www.3dprintbeast.com/petg-density/

[20] “3D Printing,” Shops. Accessed: Sep. 26, 2024. [Online]. Available: https://shops.chem.wisc.edu/3d-printing/

[21] C. G. Amza, A. Zapciu, F. Baciu, M. I. Vasile, and D. Popescu, “Aging of 3D Printed Polymers under Sterilizing UV-C Radiation,” *Polymers (Basel)*, vol. 13, no. 24, p. 4467, Dec. 2021, doi: 10.3390/polym13244467.

Appendix IV - Preliminary Prototype Design Matrix

Criteria Descriptions:

Accuracy of Connection: The design must provide accurate and reliable connectivity between the sensors and their respective chargers. The sensors must be constantly connected to the charging source within the case. The tray should be able keep sensors in their respective slots even upon impact or various arrangements in space.

Ease of Use: The design must be simple enough that people who lack an engineering background can operate it properly without explanation. The design should also allow easy removal and insertion of the sensors as the design will be utilized in a fast paced environment.

Manufacturability: The design will be scored on the difficulty of manufacturing the tray and the charging system. This includes access to and effects of software necessity, machine accessibility, skill level requirements, and outside resource necessity.

Cost: The cost of the design must fall within the budget of $300. The likelihood of excess material must be taken into account to reduce wasteful spending.

Safety: The design will be scored on how likely the chosen material and charging system will produce any hazards during the construction process and during use afterward.

Ranking Analysis:

Design 1:

Accuracy of Connection: The flat, hollow tray design allows seamless integration of inductive charging technology, enabling efficient energy transfer to the sensors. Design 1 employs a magnetic mechanism to hold the chargers in their respective divots. The magnets are not strong enough to fully ensure the chargers will not fall out if the case experiences impact or gets turned over. Due to the inconsistency of connection and firm hold of the sensors, Design 1 received a rating of 2 in terms of accuracy of connection.

Ease of Use: Design 1 is very simple to operate. The user only needs to place the sensors onto the tray, allowing for an intuitive and frictionless process. With no physical barriers to remove the sensors, they can be retrieved effortlessly. Thus, Design 1 scored a 5 for ease of use.

Manufacturability: Design 1 is extremely simple to manufacture as the design itself is relatively simple and the team has easy access to 3D printers. Thus, Design 1 scored a 5 for manufacturability.

Cost: Design 1 will be cost effective as it will be made using 3D printers in the Makerspace. ABS plastic, the filament the team will use, is $15-20 per kilogram[1]. This price aligns with the project's budget, as the tray design will not exceed 1-2 kilograms. Thus, it scored a 5 for cost.

Safety: Design 1 is overall a safe design as it has no sharp edges and poses no health risks during 3D printing. In terms of sensor safety, the sensors could fall out of the tray depending on the depth of the divots and the lack of strength of the magnets. In terms of the charging system being housed within the tray, there is a risk of overheating. However, this is not too large of a concern as ABS has a high melting point of 473.15 - 513.15 K. [2] Due to the lack of guarantee for sensor safety, which is a large priority, Design 1 scored a 2 for safety.

Design 2:

Accuracy of Connection: Design 2 utilizes magnetic mechanisms within each slot as well as a form fitting slot design to ensure a constant and reliable connection between the sensors and their respective charging points. The tray efficiently distributes power to each sensor port, ensuring constant charging. However, with the design relying on sensors being placed perfectly onto the USB charger, it is likely that chargers will not be placed consistently with accuracy. Thus, this design received a rating of 4 for accuracy of connection.

Ease of Use: Although Design 2 allows for easy insertion of the sensors into their dedicated ports, the more intricate design of the slots makes sensor removal slightly more complex compared to Designs 1 and 2. Despite this, it remains user friendly, with the sliding mechanism providing reliable docking. As a result, Design 2 offers a relatively simple direction of usage but falls short of the simplicity seen in Designs 1 and 2 and thus it scores a 3 for ease of use.

Manufacturability: The complexity of Design 2 presents more challenges in manufacturing compared to other options. The detailed CAD modeling and extended 3D printing time required for this design increase production effort. Consequently, Design 2 earned a score of 3 for manufacturability, acknowledging the additional time and effort needed to create this design.

Cost: Design 2 will be relatively cost effective as it will be made using 3D printers in the Makerspace. ABS plastic, the filament the team will use, is $15-20 per kilogram[1]. This price aligns with the project's budget, as the tray design will not exceed 1-2 kilograms. However, design 2 has a larger volume than its competing designs so it will be slightly more costly. Thus, it scored a 4 for cost.

Safety: Safety is a primary focus of Design 2, as it features walls surrounding the sensors, ensuring they remain securely in place. This added protection reduces the risk of accidental dislodging, making the design inherently safer for users and the sensors alike. The secure housing of the sensors and lack of sharp edges highlight its commitment to safety. As a result, Design 2 scored a 5 for safety.

Design 3:

Accuracy of Connection: Design 3 consists of a tooth within each slot that is specifically fit to the VigiLife sensors. It also has specifically designed pogo pins that were fabricated to fit the exact connections on the sensors. With this locking mechanism and the specified pins, Design 3 ensures the sensors will remain within their charging ports and will remain charging. Thus, Design 3 scored a 5 for accuracy of connection.

Ease of Use: Design 3 is quite simple to operate. The user needs to place the sensors into the divot and snap it into place. With a little practice, they can be retrieved effortlessly. However, the removal and insertion of devices from Design 3 is not as simple as Design 1. Thus, Design 3 scored a 4 for ease of use.

Manufacturability: Design 3 is simple to manufacture as the design itself is relatively simple and the team has easy access to 3D printers. In order to mass produce this design, it may be more difficult to 3D print but for the purposes of the prototype it is easy. Thus, Design 3 scored a 5 for manufacturability.

Cost: Design 3 will be cost effective as it will be made using 3D printers in the Makerspace. ABS plastic, the filament the team will use, is $15-20 per kilogram[1]. This price aligns with the project's budget, as the tray design will not exceed 1-2 kilograms. Thus, it scored a 5 for cost.

Safety: Design 3 is overall a very safe design as it has no sharp edges and poses no health risks during 3D printing. Additionally, it holds the sensors very securely - ensuring sensor safety. In terms of the charging system being housed within the tray, there is a risk of overheating. Even though this is not too large of a concern as ABS has a high melting point of 473.15 - 513.15 K [2], Design 3 scored a 4 for safety.

References

[1]3D Printing, “3D Printing,” Shops, 2024. https://shops.chem.wisc.edu/3d-printing/ (accessed Sep. 26, 2024).

[2]Protolabs, “ABS Plastic: Advantages, Disadvantages, and Applications,” www.protolabs.com. https://www.protolabs.com/materials/abs/

Appendix V - Material Fabrication Protocols

ABS Plastic

1. **Process:** ABS is a thermoplastic filament that is melted and extruded through a heated nozzle onto a build platform. The layers of said filament soften and fuse together to create the final object [1]
2. **Temperature:** The ideal bed temperature for ABS is between 95–110°C. The extruder temperature is usually between 220–250°C, but can vary depending on the printer and brand. [2]
3. **Enclosure:** An enclosure or heated build chamber is recommended to maintain a consistent temperature and reduce warping. [1]
4. **Ventilation:** Use an open space with good ventilation.
5. **Build surface:** Kapton tape can be used as a build surface. To improve adhesion, you can also coat the print surface with ABS juice, which is a mixture of acetone and a small amount of ABS filament. Other options include glue stick or hairspray. [3]
6. **Warpage control:** Use brims and rafts to control warping.
7. **Fan:** Leave the fan off for the first layer, and set it to no more than 30% of its maximum speed for subsequent layers. [3]
8. **Smoothing:** To smooth ABS parts, you can brush liquid acetone onto the surface. Use a fine-tipped brush for small details and a flat brush for larger areas. After applying acetone, let the parts dry before use. [3]

References

[1]Xometry, "All About ABS 3D Printing Filament: Materials, Properties, Definition," www.xometry.com, Sep. 19, 2022. https://www.xometry.com/resources/3d-printing/abs-3d-printing-filament/

[2]"Ultimate Materials Guide - Tips for 3D Printing with ABS." https://www.simplify3d.com/resources/materials-guide/abs/

[3]"Ultimate Materials Guide - Tips for 3D Printing with ABS." https://www.simplify3d.com/resources/materials-guide/abs/

Appendix VI - All Testing Protocols

Test 1 - Degradation Test

To ensure the durability and reliability of the tray material, Acrylonitrile butadiene styrene, it was necessary to calculate the wear per use. This evaluation was critical to verify that the sensors would remain securely positioned in their designated slots even after hundreds of insertions and removals each day. Following thorough testing, it was determined that the degradation rate of the tray is 0.108 µm/use, an exceptionally small value that can be deemed negligible for the purposes of this project.

Equipment and Materials:

1. Test setup with the tray made of PLA plastic.
2. Utilize ABS printed 3D sensors.
3. Precision measurement tools (micrometer or caliper).
4. Use camera for wear observation.
5. Data logging system to record the number of cycles.

Procedure:

1. Initial Setup:

- 1.1 Ensure the tray and sensors are clean and free from contaminants.
- 1.2 Measure and record the dimensions of the tray's charging port openings to establish baseline data.
- 1.3 Inspect the tray's surface for any pre-existing wear or irregularities, documenting with images.

2. Calibration of Testing Equipment:

- 2.1 Configure the mechanical apparatus (if available) to perform controlled sensor insertions and removals.
- 2.2 If manual testing is used, ensure consistent force and alignment during each cycle.

3. Insertion and Removal Cycles:

- 3.1 Insert the sensor into the tray's charging port and remove it, completing one cycle.
- 3.2 Repeat the process for a predefined number of cycles
- 3.3 Log the number of cycles completed at regular intervals (every 200 cycles).

4. Interim Wear Measurements:

- 4.1 At every 200 cycles, measure the dimensions of the tray's tooth mechanism to detect changes.
- 4.2 Use a microscope or camera to capture images of wear patterns.
- 4.3 Record observations, including material loss, deformation, or cracking.

5. Final Wear Assessment:

- 5.1 After completing the full test (1,200 cycles), perform a detailed measurement and analysis of the tray's dimensions.
- 5.2 Compare the final dimensions with the baseline to calculate the wear rate per cycle.

6. Data Analysis and Reporting:

- 6.1 Analyze the data to determine the average wear per cycle.
- 6.2 Extrapolate the data to estimate wear after expected daily use.
- 6.3 Document findings, including wear rate, images of degradation, and any notable observations.

Test 2 - Security Test

To validate the reliability of the tray design, a test was conducted to ensure that the sensors remain securely positioned within their designated charging ports under varying forces and orientations. This assessment was critical to confirm the tray's functionality in real-world scenarios where unexpected movements or vibrations may occur. The results demonstrated that the tray provides adequate retention for the sensors when dropped from a height of 1 meter, meeting project requirements.

Procedure for just drop test:

1. **Preparation:**
    - Place the 3D-printed sensor in one slot of the tray.
    - Insert the tray into the carrying case and close the case securely.
2. **Drop Test:**
    - Hold the case at a height of one meter.
    - Drop the case from 1 meter.
3. **Post-Drop Inspection:**
    - Open the case to check if the sensor remains firmly in place within the slot.
    - Close the case and repeat the drop.
4. **Repetition:**
    - Perform 10 drop trials for the same slot.
    - Repeat the procedure for all nine slots for a total of 90 drops.

Procedure for combined drop test and degradation test

1. **Simulated Degradation:**
    - Perform a year-long simulated degradation test on the central slot (details of the degradation test setup are specified separately).
2. **Post-Degradation Drop Test:**
    - Place the 3D-printed sensor in the degraded central slot.

- Insert the tray into the carrying case and close the case securely.
- Hold the case at a height of one meter.
- Drop the case from one meter.

3. **Repetition:**
    - Perform 50 drop trials.

Test 3 - Electricity Test

A test was conducted to verify the functionality of the pogo pins in supplying consistent charge to the sensors. Using a digital multimeter, the voltage and current across the pogo pins were measured to ensure proper electrical contact and charging capability. The results confirmed that the pogo pins maintained a steady voltage of 5 - 5.21 Volts and a current of 2.4 amps, validating their performance for this project.

Equipment and Materials:

1. Tray with installed pogo pins.
2. Sensors designed to connect with the pogo pins.
3. Digital multimeter (DMM) capable of measuring voltage and current..
4. Load resistor or device capable of simulating the sensor's power draw

---

Procedure:

1. Initial Setup:

- 1.1 Inspect the pogo pins for physical damage or misalignment.
- 1.2 Ensure the sensors are clean and free of debris at the contact points.
- 1.3 Insert the sensors securely into the tray, ensuring proper contact with the pogo pins.

2. Multimeter Calibration and Configuration:

- 2.1 Set the digital multimeter (DMM) to voltage measurement mode.
- 2.2 Verify that the DMM is properly calibrated for accurate readings.

3. Voltage Measurement:

- 3.1 Power the system by connecting the tray's input to the power supply.
- 3.2 Using the DMM, place the positive lead on the pogo pin delivering power and the negative lead on the corresponding ground pin.
- 3.3 Record the voltage across the pogo pins. Confirm that the measured voltage matches the expected charging voltage range of 5 volts.

4. Current Measurement:

- 4.1 Switch the DMM to the current measurement mode.
- 4.2 Insert the DMM in series between the pogo pins and the 2 Ohm resistor, so the ground of the DMM goes to the ground pogo and the other connection goes to the resistor, and the resistor is connected to 5V on the pogo pins.
- 4.3 Before completing the circuit, ensure the body of the resistor is under water to minimize overheating, and also be sure that none of the other wiring is allowed to in the water
- 4.3 Record the current supplied by the pogo pins.

Test 4 - Ease of Use Test

To assess the usability of the tray design, an ease-of-use test was conducted using a survey based on the System Usability Scale (SUS). The test involved 100 participants following a predefined set of instructions to insert and remove sensors from the tray, then rating their experience. The survey evaluated the ease of use, perceived safety, and overall satisfaction, providing valuable insights into user interactions with the product.

Equipment and Materials:

1. Unit cell with sensors and charging ports.
2. Standardized set of instructions for sensor insertion
3. Data collection platform or tools (e.g., Google Forms, Excel).
4. Stopwatch or timer.

Procedure:

1. Participant Selection and Setup:

- 1.1 Recruit 100 participants representing a diverse user base.
- 1.2 Provide each participant with the tray, sensors, and survey instructions.
- 1.3 Ensure participants understand the purpose of the test and confirm informed consent.

2. Test Instructions:

- 2.1 Provide a clear, standardized set of instructions for the task, such as:
    - "Insert the sensor into the tray until it clicks into place."
- 2.2 Allow participants to read the instructions and ask any clarifying questions before starting.

3. Task Execution:

- 3.1 Have each participant perform the task (inserting the sensor)
- 3.2 Time how long it takes participants to complete the task and record observations.

4. Survey Administration:

- 4.1 Provide the survey immediately after the task to capture real-time feedback.
- 4.2 Include the following key questions, adhering to SUS principles:
  - How easy was it to insert the sensor into the tray? (1 = Very Difficult, 5 = Very Easy)
  - How easy was it to remove the sensor from the tray? (1 = Very Difficult, 5 = Very Easy)
  - How confident did you feel performing the task? (1 = Not Confident, 5 = Very Confident)
  - Did you feel the tray was safe to use during the task? (1 = Not Safe, 5 = Very Safe)
  - Would you use this product regularly based on this experience? (1 = Strongly Disagree, 5 = Strongly Agree)
- 4.3 Include an open-ended section for participants to provide additional feedback or suggestions.

5. Data Collection and Analysis:

- 5.1 Collect completed surveys and task timing data
- 5.2 Calculate average ratings for each question to assess overall usability, safety, and satisfaction.
- 5.3 Analyze patterns or trends in the data, such as common challenges or positive feedback.
- 5.4 Compile participant feedback from open-ended responses to identify areas for improvement.

Appendix VII - Raw Testing Data

Degradation Test Data Table

Each Trial	Width (mm) (Original 6.4)	Length (mm) (Original 1.03)	Height (mm) (Original 1.2)
200 Uses	6.4	1.03	1.2
400 Uses	6.4	1.03	1.2
600 Uses	6.4	1	1.2
800 Uses	6.4	0.95	1.2
1000 Uses	6.4	0.90	1.2
1200 Uses	6.4	0.90	1.2

Figure 30: *Raw Data From Degradation Test.*

Ease of Use Test Data Table

Trial	Time(s)
1	2.01
2	4.87
3	6.03
4	6.55
5	4.35
6	5.44
7	4.61
8	5.5
9	4.79
10	4.65

11	5.86
12	4.71
13	6.53
14	4.17
15	5.15
16	3.38
17	4.07
18	5.61
19	3.59
20	1.62
21	4.73
22	6.66
23	2.31
24	5.05
25	5.67
26	5.54
27	4.86
28	4.19
29	5.4
30	4.93
31	3.34
32	5.89
33	4.39
34	4.3
35	3.5
36	5.38
37	7.56
38	4.78
39	5.65
40	5.22
41	2.91
42	2.94
43	2.01
44	4.17
45	4.01

46	3.03
47	3.19
48	5.88
49	5.74
50	4.16
51	5.1
52	32.15
53	33.18
54	30.1
55	6.17
56	5.49
57	4.98
58	4.8
59	4.94
60	5.33
61	4.48
62	3.13
63	4.68
64	5.44
65	5.99
66	2.39
67	3.01
68	5.01
69	1.88
70	4.07
71	6.31
72	3.54
73	4.63
74	3.3
75	2.99
76	3.6
77	5.26
78	7.83
79	3.54
80	5.22

81	3.84
82	6
83	5.29
84	4.76
85	2.12
86	2.15
87	1.75
88	4.96
89	6.45
90	3.04
91	5.46
92	4.75
93	4.65
94	4.56
95	2.88
96	4.81
97	5.44
98	2.27
99	3.92
100	5.03

Figure 31: *Raw Data From Ease of Use Survey.*