ECE 445: SENIOR DESIGN LABORATORY
FINAL REPORT

Bracelet Aid for d/Deaf People

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ABSTRACT

This report is about the project ‘Bracelet Aid for d/Deaf people’ by Group 59 for the course ECE445 (Capstone Project) at the University of Illinois at Urbana-Champaign. The device should sit on the wrist of the user, detect sounds in the environment and notify the user in the form of visual and haptic feedback. The report details the project more in-depth and the design procedure that went into creating the device. This project also includes details of the major requirements we had for the project and the steps taken for the verification of said requirements.

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1. Introduction

1.1 **Problem Statement**

We are constantly hearing sounds around us that notify us of events occurring, such as doorbells, fire alarms, phone calls, alarms, or vehicle horns. These sounds are not enough to catch the attention of a D/deaf person and sometimes can be serious (emergency/fire alarms) and would require the instant attention of the person. In addition, there are several other small sounds produced by devices in our everyday lives such as washing machines, stoves, microwaves, ovens, etc. that cannot be identified by D/deaf people unless they are observing these machines constantly.

Many people in the D/deaf community combat some of these problems such as the doorbell by installing devices that will cause the light in a room to flicker. However, these devices are generally not installed in all rooms and will also obviously not be able to notify people if they are asleep. Another common solution is purchasing devices like smartwatches that can interact with their mobile phones to notify them of their surroundings, however, these smartwatches are usually expensive, do not fulfill all their needs, and require nightly charging cycles that diminish their usefulness in the face of the aforementioned issues.

1. 2 **Solution**

A low-cost bracelet aid with the ability to convert sounds into haptic feedback in the form of vibrations will be able to give D/deaf people the independence of recognizing notification sounds around them. The bracelet will recognize some of these sounds and create different vibration patterns to catch the attention of the wearer as well as inform them of the cause of the notification. Additionally, there will be a visual component to the bracelet in the form of an OLED display which will provide visual cues in the form of emojis. The bracelet will also have buttons for the purpose of stopping the vibration and showing the battery on the OLED.
For instance, when the doorbell rings, the bracelet will pick up the doorbell sound after filtering out any other unnecessary background noise. On recognizing the doorbell sound, the bracelet will vibrate with the pattern associated with the sound in question which might be something like alternating between strong vibrations and pauses. The OLED display will also additionally show a house emoji to denote that the house doorbell is ringing.

1.3 **Block Diagram**

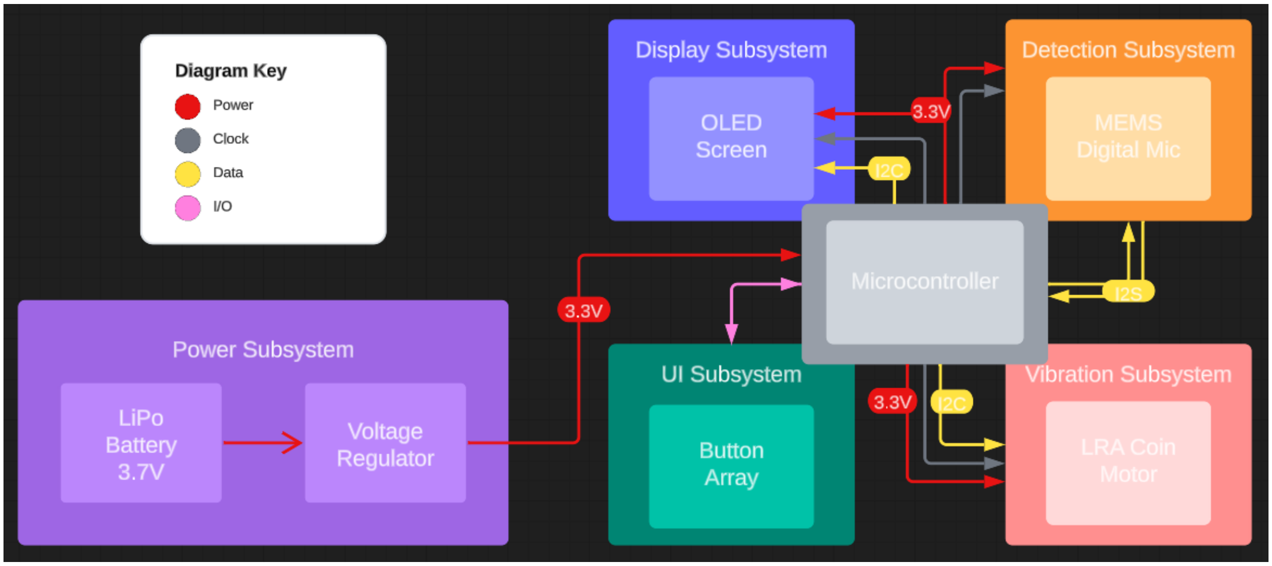

Figure 1: Block Diagram

The block diagram gives us an overview of the subsystems of the device. We can see that the device's heart is the microcontroller that is responsible for communicating with all the other subsystems. The power subsystem is responsible for accepting the power from the battery, regulating its current and voltage, protecting against over/under current/voltage, and supplying this regulated power to the microcontroller.

The detection subsystem is responsible for capturing sounds and communicating with the microcontroller, via the I2S protocol, which can process and run FFTs to detect the preconfigured sounds. The vibration subsystem is responsible for communicating haptic feedback to the users based on the unique vibration pattern associated with the sound identified by the device. It consists of the motor driver IC and the motor itself. The microcontroller communicates the unique identifier for the vibration pattern to the motor driver that generates a signal that makes the vibration motor vibrate in the said unique pattern.

The UI subsystem allows the user to communicate with the device to either display the battery percentage or to dismiss the notification the device has detected. This is achieved via two push buttons. The display subsystem is responsible for communicating visual feedback to the users based on the unique icon associated with the sound identified by the device or the battery percentage based on the user pressing the battery UI button. It consists of an OLED display that communicates with the microcontroller via the I2C protocol.

1.4 **High-level Requirements**

1. The device should have a small form factor and should be light such that it can sit on a person's wrist without feeling bulky or overbearing, as the device will sit on their wrists for most of the day. It should weigh less than 70 grams for a successful product.

2. The device should be able to recognize multiple notification sounds and create different vibration patterns that are recognizable and distinguishable by the user. It should be able to produce at least 10 distinguishable vibration patterns.

3. The device should have a feedback time (i.e. time taken for the device to recognize crucial sounds and notify the wearer) of at most 10 seconds

2. Design

2.1 **Power Subsystem**

2.1.1 Design procedure

The guiding design principles of the power subsystem was based on the longevity of the battery life and the ease of swapability of the battery itself. This is due to the defined success criteria in the developmental process. Our goal was to ensure that the battery was able to power the device for a minimum of 24 hours, in addition to being able to swap the battery such that one of the batteries provided can be charged while the other is in use.

Therefore to achieve the 24-hour battery life we decided to estimate the power consumption of our device so we could determine the minimum capacity of the batteries while maintaining the restrictions on the size and dimensions of the device. Equation (1) was used to determine the minimum capacity:

$$\text{Capacity}_{\text{min}} = \text{Current Draw}_{\text{avg}} \times \text{Usage Hours}_{\text{min}} \tag{1}$$

In addition to the battery capacity we also needed to consider the auxiliary charging circuit provided with the device to charge the secondary battery while the primary is in use. There were both physical as well as electronic constraints to consider while designing the charger circuit.

One of the physical requirements was that the charger and battery have a convenient and secure connector to ensure the user's ease of use while swapping batteries, as well as the battery terminals, are securely connected to the charger while connected. We considered many standard connectors and decided on the JST brand quick connectors. One of the biggest reasons for this choice was the fact that these connectors are commonly used in remote-controlled devices that require the connectors to have a high resistance to wear and tear that occurs while connecting and disconnecting the connector. In addition to the durability of these connectors, they are also rated for a high current draw due to the fact that it is the primary point of contact between the battery and the charger PCB. The same connector was also used on the device's main PCB for the same reasons.

Similarly, we also had to consider how the charger circuit would be powered. Since our device is focused on making the experience seamless for the user we decided that we needed a ubiquitous connector standard. We decided on using the USB-A standard as we learned that most households already have USB-A wall sockets due to how often they are used to charge other electronic devices. Additionally, out of all of the USB standards, USB-A was the most resilient to wear and tear as well as easy to use, while still being commonplace.

On the other hand, the electrical constraints for the charger circuit were that it would be able to charge the battery quickly so that the secondary battery is ready for use well in time while the primary battery runs out. Once we decided on the 1900mah battery capacity, we thought a 4 hour charge time would be appropriate. So using the equation (2) we decided on how much current we could safely and rapidly charge the battery:

$$\text{Current}_{\text{charge}} = \text{Capacity}_{\text{battery}} / \text{Time}_{\text{charge max}} \tag{2}$$

Finally, on the device side of the power subsystem we had to incorporate a power regulator that was able to clean the raw power coming from the battery and provide it to the rest of the circuit. One of the biggest factors in deciding on a power regulator IC was the dropout voltage. Power regulators dropout voltage is the amount of voltage that decreases from the source in order to clean and regulate the power coming from the source. Due to the fact that we were using LiPo batteries, which are rated at 3.7V nominal voltage, and that our microcontroller requires 3.3V, our maximum dropout voltage could be 400mV. So we decided on an LDO voltage regulator IC that was rated for a maximum of 350mV dropout at peak current draw.

2.1.2 Design Details

As explained above, the capacity of the battery was a fundamental part of choosing the battery. Based on equation (3) and plugging in an expected 70mA current draw and 24-hour usage time we get a minimum capacity of:

$$\text{Capacity}_{\text{min}} = \text{Current Draw}_{\text{avg}} \times \text{Usage Hours}_{\text{min}} \tag{3}$$

$$\text{Capacity}_{\text{min}} = 70\text{mA} \times 24\text{hr}$$

$$\text{Capacity}_{\text{min}} = 1680\text{mAh}$$

Based on these calculations we knew we had to have a battery of at least 1680mAh. However, when a notification is recognized, we expect the current draw to increase to a maximum of 150mA, due to the high current draw from the vibration motor. Taking that into consideration, expecting a hundred notifications in a day on average, we got an expected 73.64mA. Based on this more precise constraint on the average current draw we arrived at a more accurate lower bound for the battery capacity using equation (4):

$$\text{Capacity}_{min} = \text{Current Draw}_{avg} \times \text{Usage Hours}_{min} \tag{4}$$
$$\text{Capacity}_{min} = 73.64\text{mA} \times 24\text{hr}$$
$$\text{Capacity}_{min} = 1767.36\text{mAh}$$

Based on this, more constrained, estimate we found a 1900mAh LiPo battery that fit both the dimensional and capacity constraints.

As for the JST connector, we decided on a 2-pin connector commonly used in RC applications which was rated for the current and usage of our device. As can be seen in the top right of Figure 18, also shown below in Figure 2, we can see how the female JST connector is soldered on the bottom PCB of the device which will receive the male JST connector on the battery, thus providing a secure connection.

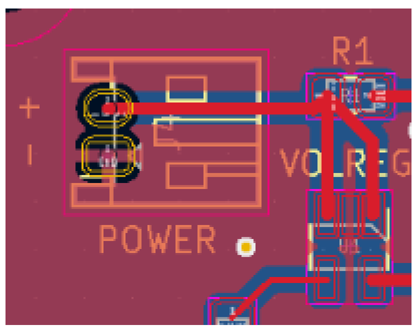

Figure 2: JST connector in bottom PCB

Placing the JST connector at the very edge of the PCB also helped us satisfy the high-level requirement of the battery being easy to swap as this placement made the connector easy to reach for connecting and disconnecting.

Similarly, for the USB side of the charger circuit, we decided to use the USB-A standard. However, another decision we had to make was whether to use the female or male USB-A connector. We decided on the male type following the same design ideology we used for the rest of our design decisions: Easy of use. We determined that the charger circuit should have the USB-A male header sticking out from one side so that the user could plug it into any USB-A type wall connector or even a laptop. This can be seen in Figure 19 which shows the footprint of the charger circuit. This also meant that the user did not have to connect a USB-A to a USB-A cable between a wall socket/laptop and our charger, as they would have had to if we chose to use a USB-A female header.

As discussed above, another consideration we had to make was the charging current of the charger circuit. Based on the preliminary calculations we arrived at a charging current of 475mA using equation (5):

$$\text{Current}_{\text{charge}} = \text{Capacity}_{\text{battery}} / \text{Time}_{\text{charge max}} \tag{5}$$
$$\text{Current}_{\text{charge}} = 1900\text{mAh} / 4\text{h}$$
$$\text{Current}_{\text{charge}} = 475\text{mA}$$

However, as we worked through our design and learned more about safety guidelines we should be adhering to while designing a product for the masses, we reconsidered the charge time and decided to compromise on it for a safer charging current. We determined that a charging current of 100mA was safer while still providing a charge time that was acceptable within the bounds of our high-level requirements. A charge current of 100mA meant our charge time was changed to 19 hours using equation (6):

$$\text{Time}_{\text{charge max}} = \text{Capacity}_{\text{battery}} / \text{Current}_{\text{charge}} \tag{6}$$
$$\text{Time}_{\text{charge max}} = 1900\text{mAh} / 100\text{mA}$$
$$\text{Time}_{\text{charge max}} = 19\text{h}$$

Despite 19 hours being well within our maximum time constraint of 24 hours, we also learned that the charge time would be even more conservative than the calculated 19 hours as LiPo batteries keep approximately 20% of their capacity in reserve for longevity reasons due the electrochemistry of the Li-Po batteries. This meant that our actual charge time would be 15.2 hours using equation (7):

$$\text{Time}_{\text{charge max}} = \text{Capacity}_{\text{battery}} / \text{Current}_{\text{charge}} \tag{7}$$
$$\text{Time}_{\text{charge max}} = (1900\text{mAh} \times 0.8) / 100\text{mA}$$
$$\text{Time}_{\text{charge max}} = 1520\text{mAh} / 100\text{mA}$$
$$\text{Time}_{\text{charge max}} = 15.2\text{h}$$

We were able to control the charge current as the charging IC we chose, taking inspiration from a charger circuit created by Adafruit, the MCP73831T. This IC has a pin called VSS, seen in Figure 5, which lets us control the charge current by attaching resistance between this pin and the ground. Based on the datasheet we determined that a resistance of 2kΩ would translate to a charging current of 100mA.

Finally, we decided to choose max linear's SPX3819 voltage regulator due to its low dropout voltage. Based on the dropout voltage vs. current draw graph given in the datasheet, shown below, at 70mA would be 135mV, and at our maximum current draw of 150mA, the dropout voltage would be 180mV:

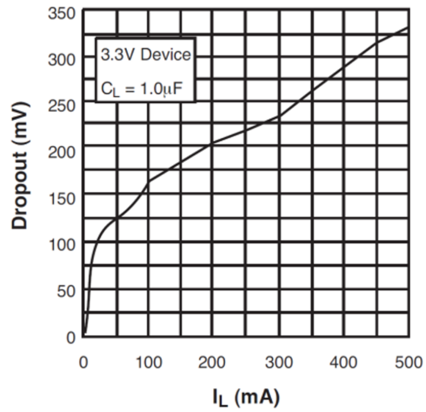

Figure 3: Dropout voltage of the Voltage Regulator

These dropout voltage characteristics, in addition to its 3.3V regulated output voltage made the SPX3819 an ideal choice for out voltage regulator IC for the device's power needs.

2.2 **Sound Detection Subsystem**

2.2.1 Design procedure

The underlying design principles of the sound detection subsystem was based on the accuracy of the measurements by the microphone and processing speed. This is due to the minimum success criteria and high-level requirements that we established earlier in the ideation phase. The minimum success criteria dictate that we should be able to use the device to detect at least 10 different notification sounds, which means the measurements need to be accurate enough for the post-FFT analysis. Meanwhile, the High-Level Requirements required the time between the sound and the detection to be under 10 seconds, which means that we need a high sampling rate, perform several real-time FFTs, and analyze them as fast as possible.

Therefore, it was decided that we would pick a microphone module, with high accuracy, low noise, and a fast sampling rate. In addition, since we had decided on using an ESP32 microcontroller, we needed the microphone module to be a digital microphone, with a modern I2S-based digital chain, which would mean we would not have to use a preamplifier, ADC, and DAC needed in a traditional audio chain. Based on the microcontroller choice, we can define the size of the DMA buffer and from the microphone choice, we get the maximum sampling frequency. These two values give us an idea of the time it would take the microphone to collect the minimum number of samples for a non-repeated FFT. The equation for this minimum time period, referred to as *D*, is given below:

$$D = \frac{DS}{FS} \tag{8}$$

where *DS* is the DMA buffer size, and *FS* is the sampling frequency. Other than the microphone choice, we also had to decide on the design of the sound detection software. While it would be best to design a neural network-based sound classification system, this type of system would be difficult to program, given the high training time and the massive amount of data input required. This is why we decided on a simpler analysis system, that simply checks the frequency peaks against known patterns for the 10 sounds, over several time periods. An image explaining the system is shown below.

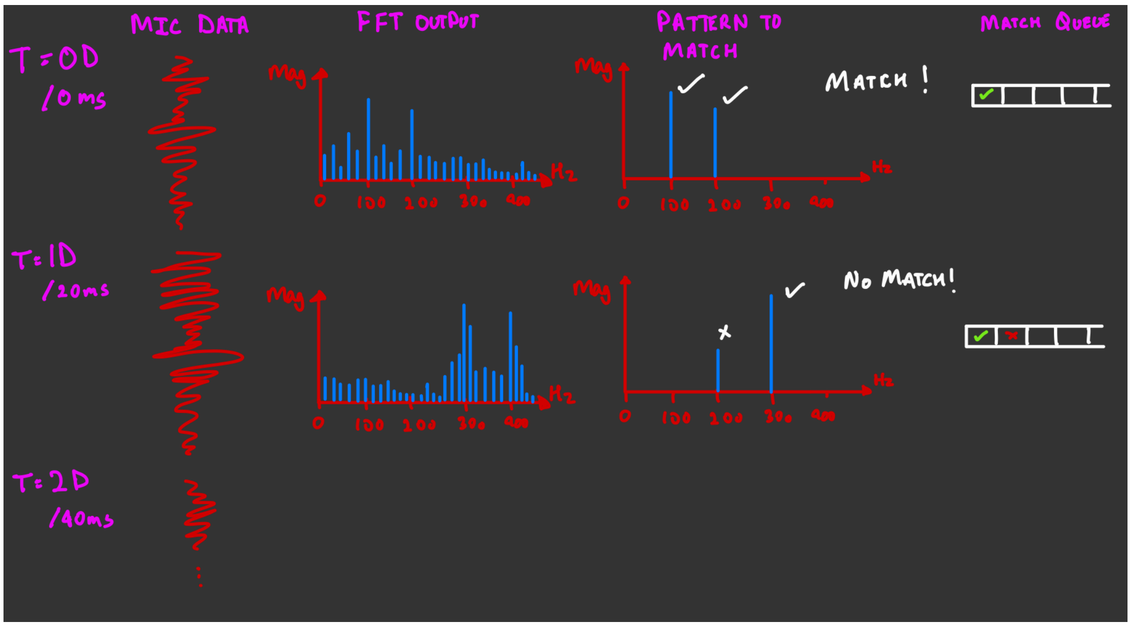

Figure 4: Sound analysis explanation

For each *D* time period, we take a *DL*-sized FFT, which produces peaks at different frequencies as can be seen in the image. Next, for a particular sound, if the peaks are expected to be at 100 Hz and 200 Hz in the first time period, we check it against the actual FFT. In this example, we can clearly see that it is a match, and record the match. For the next time period, if this sound was played, we expect to see peaks at 200 Hz and 300 Hz, however, that is not the case, which is why we record that no match was seen in this time period. We continue this process for each time period, and match peaks for each sound, until we record a series of matches, signifying that the sound was actually played in the background, and we raise the flag for a successful sound detection.

2.2.2 Design Details

As explained above, a critical part of the subsystem is microphone selection, which is done using criteria including a high sampling rate, low noise, high accuracy, and digital output. Initially, we had chosen the INMP441 microphone, however, after doing some more research, we realized that this module was quite old, and there were newer, better iterations of similar microphones that had a higher sampling rate. This is when we decided to go with the ICS43434, which had a sampling rate almost double that of the INMP441, and better noise characteristics as well. Although the maximum sampling frequency is 55 kHz, we chose to set the sampling frequency to 48 kHz as a power-saving measure and to ensure data quality. Since the chosen microcontroller had a DMA buffer of size 1028 Bytes, we used the above equation to obtain the minimum time period needed to collect 1028 samples, which was 21.34 ms. This means that the subsystem will collect a single batch of data in 21.34 ms, which is the bottleneck time period for analysis. While timing the analysis, we found that FFT for this data took just under this number, taking about 20 ms per loop.

Other than this, another important detail for the design of this subsystem was the schematic design, which is shown in the image below. The microphone's datasheet included pin descriptions and recommendations on the schematic design. The datasheet recommended that the Vdd pin be decoupled to GND using a 0.1 uF capacitor, and a pull-down resistor of 100 kΩ be connected to the SD pin. Since the datasheet made no mention of tolerances, we chose the minimal possible tolerance components found online.

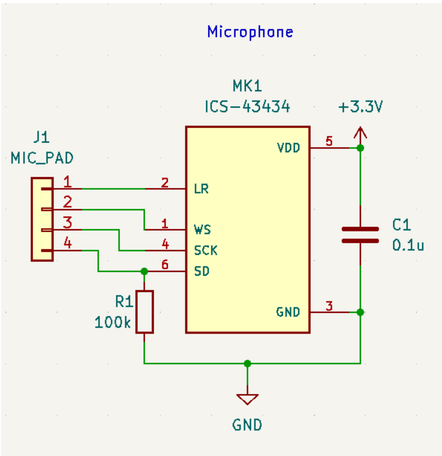

Figure 5: Sound Subsystem

The purpose of the decoupling capacitor is obvious, in that it is used to ensure enough voltage is present to the Vdd pin in case there are spikes or dips in the supplied voltage. On the other hand, the pull-down resistor is there to ensure that the bus is discharged when the microphone output has tristated and is done sending data to the microcontroller.

2.3 **Vibration Subsystem**

2.3.1 Design procedure

The major design principles guiding the process for this subsystem were based on precise motor control, and the ability to produce detectable haptic feedback. Both of these arose from our High-Level Requirements, which required the device to be able to produce distinguishable and detectable vibrations. After outlining the design tenets, we had to decide on the motor, the motor driving circuit, and finally the software to drive the hardware. For the vibration motor, we chose an LRA coin vibration motor used in the Samsung Galaxy Watch, which produced at least 0.9 G_{rms} of acceleration at low frequencies too, which meant that the motor would be easily detectable when not being run at its peak.

For the motor driver circuit, initially, we chose a simple PWM-driven circuit, such that we could set the switching frequency of the motor ourselves by looping between low and high voltage. This would also require us to create patterns for the motor ourselves, by coding the timings out in the main processor loop. However, due to the additional effort required to manually code each vibration pattern, we decided to use a Motor Driver IC with a built-in ROM of vibration patterns. This would come at the cost of more components since the motor driver requires additional physical components to drive but with the benefit of simple, distinguishable vibration patterns. When using a motor driver IC, we would be able to use the associated library to simplify and streamline the software aspect, leaving only the timing aspect unknown.

2.3.2 Design Details

Based on the design criteria for the vibration motor, we chose the LRA Coin Vibration Motor, produced by Vybronics, the VG1040003D. The motor has a minimum acceleration of $1.8G_{rms}$ at ~170 Hz Sine wave $2.5V_{rms}$ voltage, which would be more than enough to produce a strong detectable vibration. Another important component of the design of this subsystem is the motor driver IC. Based on the aforementioned specifications, we decided to use the TI DRV2605, which is an I2C protocol-based motor driver that comes with a package of 171 distinct haptic feedback patterns, once again, easily meeting our base requirements.

Since most of the heavy lifting in terms of producing the vibration was offloaded to the motor driver, we also needed to assemble the vibration subsystem around this component. This can be seen in the schematic diagram below. Since the motor driver provides two easily accessible output voltage differential pins, we can simply connect the vibration motor to OUT+ and OUT-. The datasheet for the motor driver specifically required a 1 uF capacitor to be connected to the VDD pin, in order to decouple this pin, in case the power subsystem outputs spikes or dips in voltage. The datasheet also required us to add a 1 uF capacitor to the REG pin, connecting it to GND, as this pin internally connects to an overcurrent protection system to safeguard the component. The SCL and SDA pins both have pull-up resistors, each with a value of 2.2 kΩ, which is a common requirement on these I2C devices since these pins are supposed to be pulled up to high voltage when all outputs tristate. Finally, the SCL, SDA, and PWM pins are connected to the microcontroller, with the latter giving us the potential to work with a PWM-based trigger pin and further streamline the vibration subsystem.

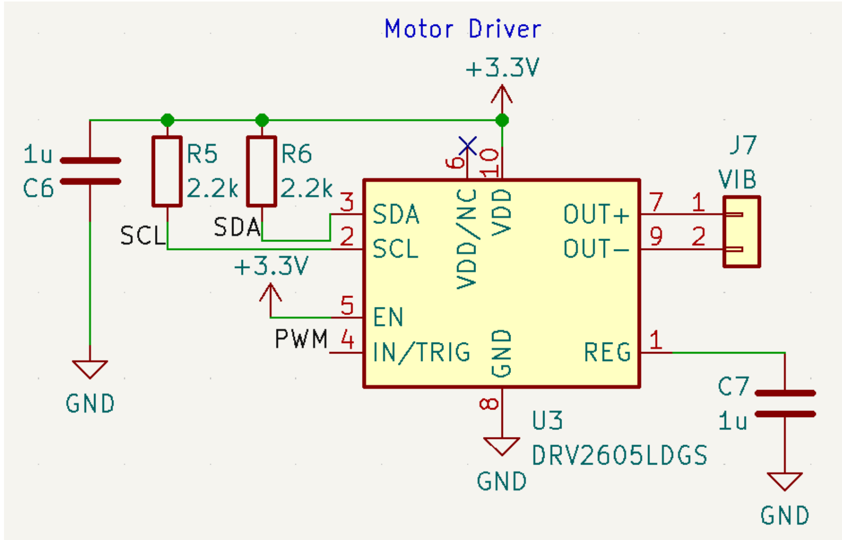

Figure 6: Vibration Subsystem

The major benefit of this component was the library and the increased ease of use that it gave us in terms of writing software, and higher flexibility in terms of deciding vibration timings in relation to sound detection. The library used is called the Adafruit 2605, which allows us to define a custom Two Wire object for the I2C protocol, and pass it on to an object that has built-in functionality to produce the 171 distinct vibrations. From this point on, we simply had to choose different patterns that were dissimilar enough to be distinct, which was a relatively simple process with the help of a dedicated focus group, which will be further discussed below, in the requirements and verifications section.

2.4 **Display Subsystem**

2.4.1 Design procedure

The display subsystem is responsible for providing the users with visual feedback once a sound is detected by the watch. The visual feedback is in the form of icons related to the sound and so each sound has its own unique symbol. There are a few reasons behind providing the user with visual feedback on top of haptic is to allow the user. For instance, toward the beginning of a user wearing the watch, they might not remember which vibration is for which sound. Or when in a panic, they might not be able to recognize the vibration so easily. For situations like these, we decided to provide the user with an additional way to identify the sound detected which is through visual cues.

We chose to use an OLED display breakout board for the subsystem. The reason behind using a breakout board is to avoid having to solder the ribbon cables of the display which is an extremely difficult process. The breakout board contains a chip that allows for communication with the microcontroller through the I2C protocol using the SCL and SDA connections. The OLED display has a SSD1306 controller and we make use of the Adafruit SSD1306 library in order to display text and bitmap images. For the images, we first resize them 128x64 pixels in size and also ensure that they include white icons on black backgrounds in order to light up a lower number of pixels on the display each time, leading to a lower amount of current drawn by the overall subsystem. We then used an online bmp image to bitmap converter tool to generate the bitmap which is used by the library to produce the icons we need.

2.4.2 Design Details

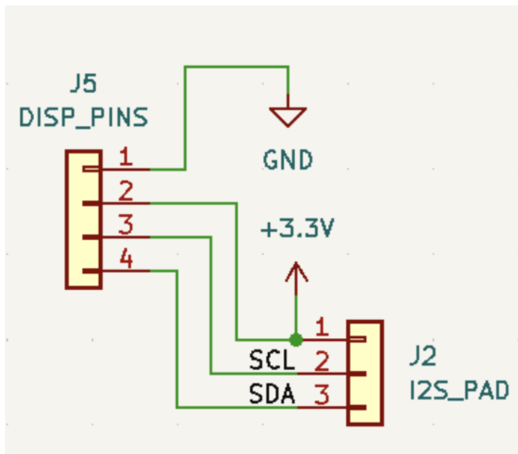

Figure 7: Display Subsystem

Figure 7 above shows us the schematic for the display subsystem. It is relatively easy and includes the female receptacles for the OLED display board as shown by J5. So the OLED display basically sits on our PCB like a daughterboard. J2, which is the I2S_PAD is used to bridge the connection between the display subsystem on the top PCB to the microcontroller on the bottom PCB. So the SCL and SDA connection of the display goes to the corresponding connections of the microcontroller.

2.5 **User Interaction Subsystem**

2.5.1 Design procedure

The underlying idea behind this subsystem was to give the watch some features which attributes to better usability. As previously mentioned in the Power Subsystem, we wanted the user to be able to wear the watch 24/7. To do so, we provided them with swappable batteries and a charger circuit that could be used to charge said batteries. We wanted to provide the user with a way to be able to check if the battery currently in the watch is running low. Otherwise, the only indication the user would get about the battery being low is if the battery fully drains out and the watch stops working. Considering the fact that this watch is supposed to notify the user of a serious event happening around them, we did not want there to be even a slight possibility of the watch to stop working. For this reason, we added a button to the watch which when pressed displayed the battery percentage on the display. The user can use this button to check if the battery is running low on charge in which case they can simply swap the batteries out. We also added a second button onto the watch which can be used to stop the vibrations which occur when a sound is detected along with resetting the display to its idle screen. The vibrations already stop within 10 seconds of detection however we added this additional feature for the user to be able to switch off the vibrations immediately once notified.

2.5.1 Design Details

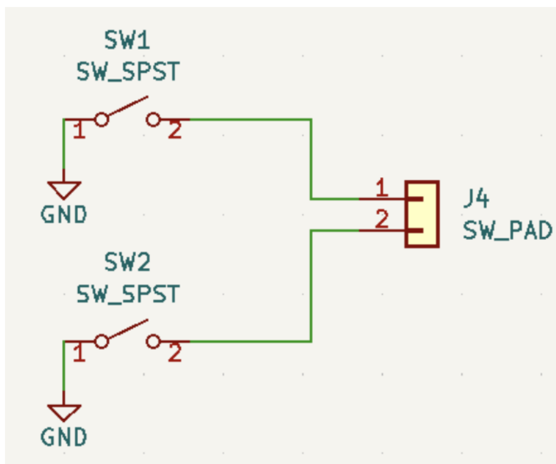

Figure 8: UI subsystem

Figure 8 above shows the relatively simple schematic for our User Interaction subsystem which is located on the top PCB as we want the buttons to be accessible to the user from the top of the watch. SW1 and SW2 are the two buttons we are using to achieve our functionality and SW_PAD is used to bridge the connection between the buttons on the top PCB and the microcontroller on the bottom PCB. The connections between the UI subsystem and the microcontroller are shown in Figure 14. The buttons work by interrupting the system whenever pressed and depending on which button is pressed, the corresponding action takes place.

3. Testing and Verification

3.1 **Power Subsystem**

The power subsystem had 3 major requirements which can be found in Table 1 of the appendix. The first requirement was that the charging circuit and device should not charge or discharge the battery at more than 1C. This meant that the charging current or our current draw should be less than 1900mA. We measured the charging current while charging the battery and the current draw of the device when the motor was playing its strongest vibration to verify these requirements. This requirement was satisfied as the charger charged the battery at 100mA as can be seen in Fig. 20 and the device discharges or draws a maximum of 150mA, both of which are under 1900mA. These verifications are also shown in Table 1 in the appendix.

The second requirement was that the microcontroller be provided a constant, uniform voltage of 3.3V with a maximum noise of ±1%. We measured the voltage between the VOUT of the voltage regulator and the ground to determine the voltage the microcontroller would receive in order to verify this requirement. This requirement was also satisfied as the voltage regulator's output to the microcontroller hovered between 3.296V and 3.304V which was a variation of about ±0.12%. This can be seen in Fig. 21 of the appendix.

The final requirement for the device was that its battery should last for at least 24 hours. To test this, we measured how much power the device consumed while vibrating for each of its 10 unique vibration patterns, as well as how much power it used when not vibrating. To calculate the expected battery life, we averaged the power consumption of the different vibration patterns (seen in Table 28), multiplied it by 0.00277778 (which represents 10 seconds in hours), and then multiplied it by 100, which is the highest number of notifications we expect the device to detect in a day. We added this number to the average power consumption when the device is not vibrating and then calculated how long the battery would last based on this total power consumption. We found that the battery would last for 25.8 hours when the device detects 100 notifications, which means that this requirement was successfully met. This can be seen by the graph shown in Fig. 22 of the appendix.

3.2 **Sound Detection Subsystem**

The sound detection subsystem had one major requirement that it should be able to recognize sounds between frequencies 200 Hz and 15 kHz. This requirement was necessary since most of the notification sounds including alarms and bells usually have major frequency patterns in the higher frequency range, larger than 1 kHz. This was easily achieved by programming the device to print the maximum frequency detected and printing it on the screen over UART. The verification of this, however, was in the form of a video which is why it is not available in this report. Another confirmation of the device's ability to meet this requirement comes from the datasheet for the microphone.

The second requirement for the sound subsystem was that it should have a maximum current draw of 5 mA, since we wanted to limit power consumption by the microphone. As can be seen in the appendix's sound subsystem verification image, we were able to achieve this and had a total current draw of 0.5 mA, which was a tenth of the maximum acceptable value. This shows that despite the high accuracy of the microphone, there is no tradeoff with power usage. Finally, the last requirement was that the sound detection subsystem should be able to detect sounds within 10 seconds of the sound being produced. This was also easily achieved by our device, with an average detection time for all sounds standing at around 5 seconds. Once again, the verification for this was in the form of a video, which could not be attached to this report, however, verification of this was provided at the demo and presentation.

3.3 **Vibration Subsystem**

The first major requirement for this subsystem was that it should be able to produce a strong detectable vibration, for which we chose a threshold voltage differential of 3.6 V across the two terminals of the motor. Although we were able to produce strong detectable vibrations, the subsystem was unable to meet the threshold value. At the time of creating the verification methods, we were unaware of the capabilities of the motor driver, which could not supply that much voltage in the first place, and we did not realize that the motor itself produces the best output at 2.5 V_{rms} according to the datasheet, which is close to what we achieved, which was 2.44 V_{rms}. Verification for this can be seen in the appendix, in the vibration subsystem's verifications.

The second major requirement was that it should be able to produce 10 unique vibration patterns. Once again, this requirement was met easily, which was verified by taking a survey, asking them if they felt that the 10 vibrations we asked them to feel were different or not. Although initially, some participants felt that a few were too similar, we made appropriate changes to the vibration patterns, and by the end, almost all of the survey participants felt that the vibrations were unique and dissimilar to each other.

Finally, we required the vibration subsystem to have a maximum delay of less than 10 seconds in its vibration production. This was set in order to meet the high-level requirements and was also achieved. Although the verification for this requirement is also not attached to this report, the tests were performed physically during both the demo and the presentation, where we displayed how the vibration subsystem met this requirement.

3.4 **Display Subsystem**

The display subsystem had two major requirements which can be found in Table 8 under Appendix. The first requirement was for the subsystem to be able to clearly display icons associated with the detected sounds and for the icons to be distinguishable from each other. We surveyed a group of 15 students by showing them all 10 of our chosen icons and asked them whether the icons were appropriate for their corresponding sounds and whether they could clearly identify the sounds and distinguish between them. The results of this survey are provided in Figure 27. From the results, we can conclude from the unanimous yes that the icons were clearly displayed and distinguishable. The second requirement was related to the peak current draw of the subsystem which we hoped to keep under 15mA. We probed the Vin and Vcc pads of the subsystem in order to verify this requirement, the image of which is provided in Figure 25. As shown in the figure, we achieved a current draw of approximately 7.46mA which is well under our required peak current draw. We were therefore able to achieve both of our subsystem requirements.

3.5 **User Interaction Subsystem**

The User Interaction Subsystem had two major requirements and the R&V table can be found in the appendix. We wanted the two buttons which constitute the subsystem to be easily accessible. Our first requirement was for the buttons to be easily accessible from the top of the watch facing the user. In order to meet this requirement, we ensured that the buttons were the only components exposed from the enclosure's top surface and ensured that the buttons have enough height clearance to clear the enclosure even when fully depressed. The second requirement we had for this subsystem To accomplish this, we decided that the buttons should be at least two button widths apart. Additionally, as a further quality-of-life improvement, we decided to place the buttons at least one button width away from the edge of the enclosure. The width of the buttons we decided to use is 6mm. As shown in Figure 26, the distance between both buttons is 15mm which is more than twice the width of one button. Similarly, the distance between the button and the edge of the enclosure is 13mm which is also greater than one width of a button. Therefore, we were able to achieve both of our subsystem requirements.

4. Cost Analysis

4.1 **Labor**

The average hourly starting salary of a typical ECE major is \$38. The total number of hours we took to complete the project which includes research and planning is ~10 hours per week. We worked for 10 weeks. Therefore, the total number of hours worked = 10 x 10 = 100 hours. Therefore, for per person,

Salary = \$38 x 2.5 x 100 = \$9,500

For all three members of the group, the total salary comes out to be \$28,500

We had originally planned to make our enclosure by the machine shop. However, we realized that the machine shop, due to the load of their work, was unable to create customized enclosures for all groups. Therefore, we decided to create our own enclosures, both for the watch and the charger circuit. The time taken for the modeling and creation of the enclosures is already included in the salary of the members. The cost of the material used is included under Parts.

4.2 **Parts**

The total cost of the parts required to build this project is provided in table 17. This includes only the parts we used in our final rendition of our working project. It does not include the components we chose to forego due to design changes or parts we ordered as spares.

The cost of all the parts is coming out to be $30.70. The list of all the parts used and their prices can be seen in Table 10 in the appendix.

4.3 **Sum Total**

The sum total of our costs comes out to be $28,500 + $30.70 = $28,530.70

5. Conclusion

5.1 **Summary and Accomplishments**

In summary, our team successfully developed a functional prototype device called "A Bracelet Aid for d/Deaf people", which provides visual and haptic feedback for sound-based notifications in daily life, specifically catering to d/Deaf users. Our device is equipped with the ability to identify 10 unique notification sounds and produces the corresponding 10 unique vibration patterns and visual feedback as specified in our high-level product requirements.

One of our biggest success criteria was the device's ability to maintain power for at least 24 hours, and we are proud to have achieved this milestone. In addition, we were able to keep the device's weight to a minimum, weighing just under 70 grams at 69.5 grams, which is crucial for user comfort and convenience. We were also able to meet the success criterion of recognizing a notification sound and alerting the user via visual and haptic feedback in under 10 seconds.

Furthermore, we were proud of being able to design and produce the device's enclosure ourselves, using CAD modeling and 3D printing, which allowed us to customize the device's aesthetics and ensure its durability.

Overall, our team's efforts culminated in the successful development of a prototype device that meets the needs of d/Deaf individuals, providing a reliable and efficient means of receiving sound-based notifications. We are proud of our accomplishments and believe that this project has the potential to make a positive impact in the lives of many individuals.

5.2 **Future Improvements**

One of the biggest improvements that can be made in this project is the sound detection subsystem's software component. Currently, we use a frequency matching technique, which is easy to implement and decently accurate. However, using a neural network-based sound detection system would be vastly superior in classifying these sounds, with the expense of higher computational requirements. With a large enough dataset of notification sounds, and an average training module, we could easily train a deep neural network for this task. In addition, the ESP32 module that we used, the ESP32C3, is more than capable of running such deep neural networks, especially with some optimizations. This would grant us a more robust and accurate detection system, improving the commercial viability of the product.

Another major improvement would be in the realm of physical design. Currently, although we meet the high-level requirement for the weight of the product, it is still rather bulky in terms of size and dimensions. We would have to compress the PCBs used and use a slimmer battery of some sort, and maybe even use a smaller microcontroller in order to create a comfortable and light device that can sit on users' wrists without causing much discomfort.

Finally, the third major improvement to be made would be with regard to the material used for the enclosure. Since we had designed and 3d printed the enclosure by ourselves, we had to use a common filament that, unbeknownst to us at the moment, was quite shock absorbent. Due to this, before assembling the final product, and while conducting the focus group interviews, everybody in the group felt that the vibrations were strong and very easily detectable. However, post-assembly, the shock-absorbent nature of the material was realized, and the vibrations were significantly muted. In the next iteration of this product, we could use another filament or material that would allow the vibrations to permeate through to the users' wrists.

5. 3 **Safety and ethics**

5.3.1 Ethics

Our group followed the [9] IEEE Code of Ethics and the [8] ACM Code of Ethics to commit ourselves to the highest ethical standards possible which includes the following:

1. According to the IEEE Code of Ethics 1.1, we will promptly disclose any factors of our product which might cause harm to the user and will prioritize safety, health, and welfare of our customers while designing and building our product. This includes ensuring that we use safe and top quality material and components for our technology and disclose any safety hazards to our projects, more of which can be found under the 'safety' section.

2. According to the IEEE Code of Ethics 1.5 and ACM Code of Ethics 2.4, we will seek and accept any criticism about our technology and work on improving it. This includes meeting with our assigned TA and Mentor Jack Blevins regularly to keep them updated on the progress of our technology and get feedback on any possible improvements. We will also ensure that we credit and cite all possible sources and references used.
3. According to the IEEE Code of Ethics 1.6 and ACM code of Ethics 2.6, we will use this opportunity to develop our skills and experience. We will make certain that each of us has the proper certification required to take on a particular technological task. Each of the members completed the lab safety training before using the lab and underwent soldering practice and training before undertaking the task of soldering for our final technology. We also ensured to complete any other training as assigned by the course.

5.3.2 Safety

Safety concerns have been considered in the design of this proposal, illustrated in the following points:

1. Since we will be using a set of two, hot-swappable Li-Po batteries in this product, we will have to consider safety precautions for the user. This necessity for Li-Po battery safety stems from the issue of spontaneous combustion which can occur from excessive or rapid charging and discharging. To ensure that we do not face any issues related to this, we will ensure that we read through the datasheet for the battery carefully, and design our power subsystem around this issue. Further details on how we are mitigating safety concerns related to battery handling can be found in the battery lab safety manual in the appendix.
2. On a similar note, we will have to ensure that the electrical components in the device are properly enclosed and are not at risk of short-circuiting and causing battery issues. To combat this potential issue, we will work with the machine shop to ensure that none of the important and/or dangerous electrical components are exposed, especially the power subsystem.
3. Another smaller safety issue is regarding the charging circuit. This circuit will also have to be shielded and enclosed from the user and the surroundings, which is why we will ensure that the charging circuit also has an enclosure designed by the machine shop.

6. References

[1] Texas Instruments, “DRV2605 Haptic Driver for ERM and LRA With Built-In Library and Smart-Loop Architecture datasheet (Rev. E),” Accessed 23 February 2023. [Online]. Available: https://www.ti.com/lit/gpn/drv2605.

[2] Adafruit, “SSD1306 (pdf),” Accessed 23 February 2023. [Online]. Available: https://cdn-shop.adafruit.com/datasheets/SSD1306.pdf.

[3] Engineering IT Shared Services, “Course Overview,” Course Overview :: ECE 445 - Senior Design Laboratory. [Online]. Available: https://courses.engr.illinois.edu/ece445/.

[4] U.S. Battery Mfg. Co., “Battery Maintenance Safety Tips- U.S. Battery Mfg. Co.: The Leader in Deep Cycle Batteries,” Accessed 23 February 2023. [Online]. Available: https://www.usbattery.com/safe-handling-tips-battery-maintenance/.

[5] MalCare, “WP-Content: A Beginner's Guide to Wordpress' Most Important Directory,” Accessed 27 January 2023. [Online]. Available: https://www.malcare.com/blog/wp-content-uploads/.

[6] Vybronics, “LRA Coin Vibration Motor - VG1040003D,” Accessed 19 December 2022. [Online]. Available: https://www.vybronics.com/coin-vibration-motors/lra/v-g1040003d.

[7] Vibration Therapeutic, “G-Force of Vibration Plate,” Accessed 22 December 2021. [Online]. Available: https://www.vibrationtherapeutic.com/G-force-of-vibration-plate.html.

[8] Association for Computing Machinery, “ACM Code of Ethics and Professional Conduct,” Accessed 9 February 2023. [Online]. Available: https://www.acm.org/code-of-ethics.

[9] IEEE CAS, “IEEE Code of Ethics,” Accessed 9 February 2023. [Online]. Available: https://ieee-cas.org/about/ieee-code-ethics.

[10] Last Minute Engineers, “Insight Into ESP32 Sleep Modes & Their Power Consumption,” Accessed 9 February 2023. [Online]. Available: https://lastminuteengineers.com/esp32-sleep-modes-power-consumption/.

7. Appendix

7.1 **Visual Aid and Physical Design**

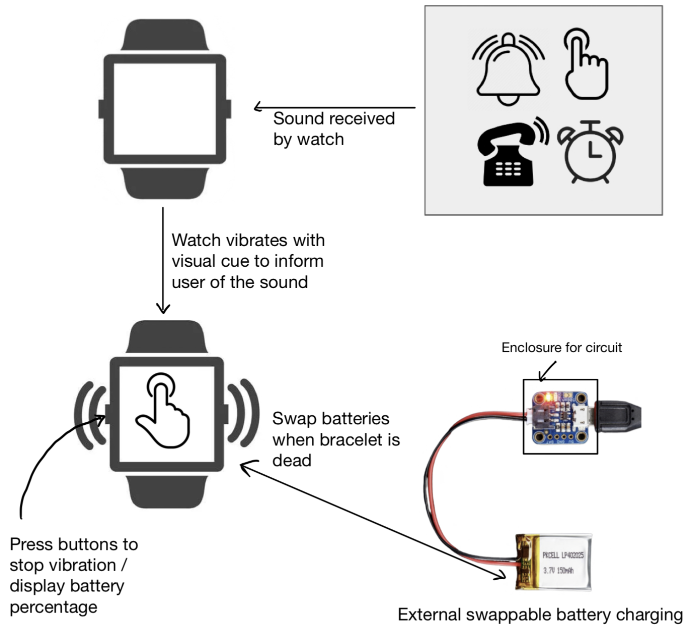

Figure 9: Visual Aid on how the bracelet works

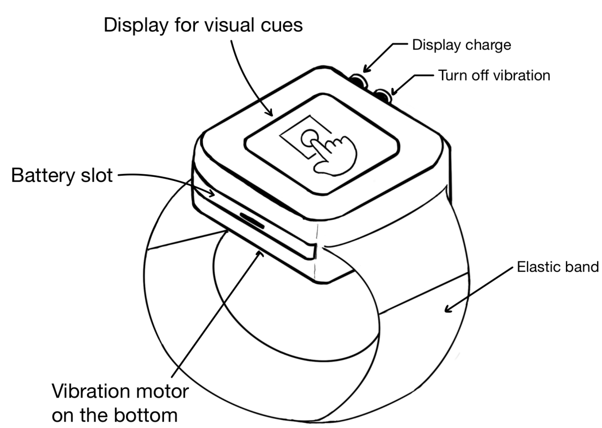

Figure 10: Initial Bracelet Prototype Physical Design

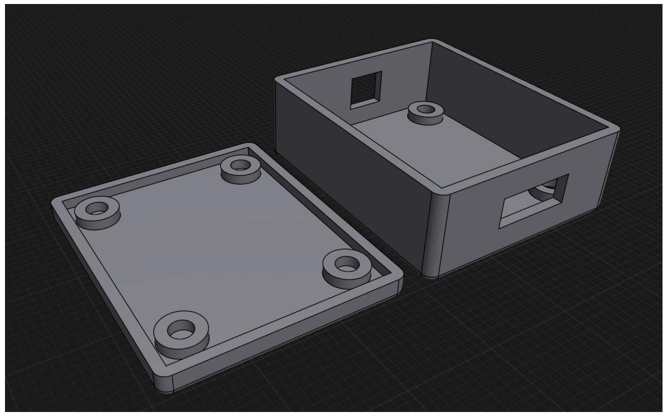

Figure 11: Charger Circuit Enclosure

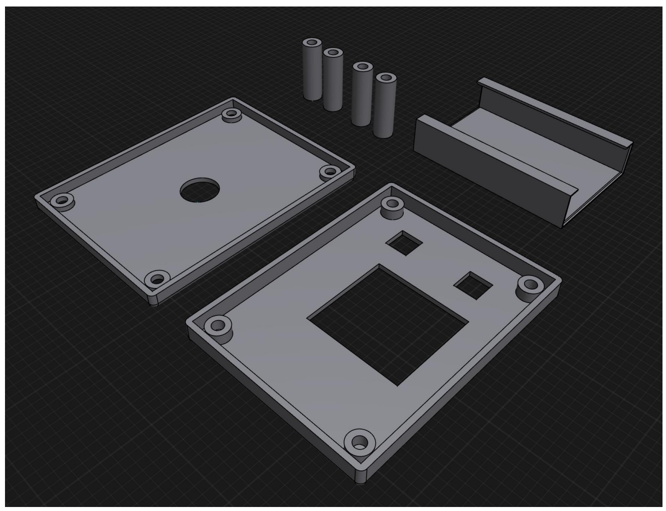

Figure 12: Device Enclosure

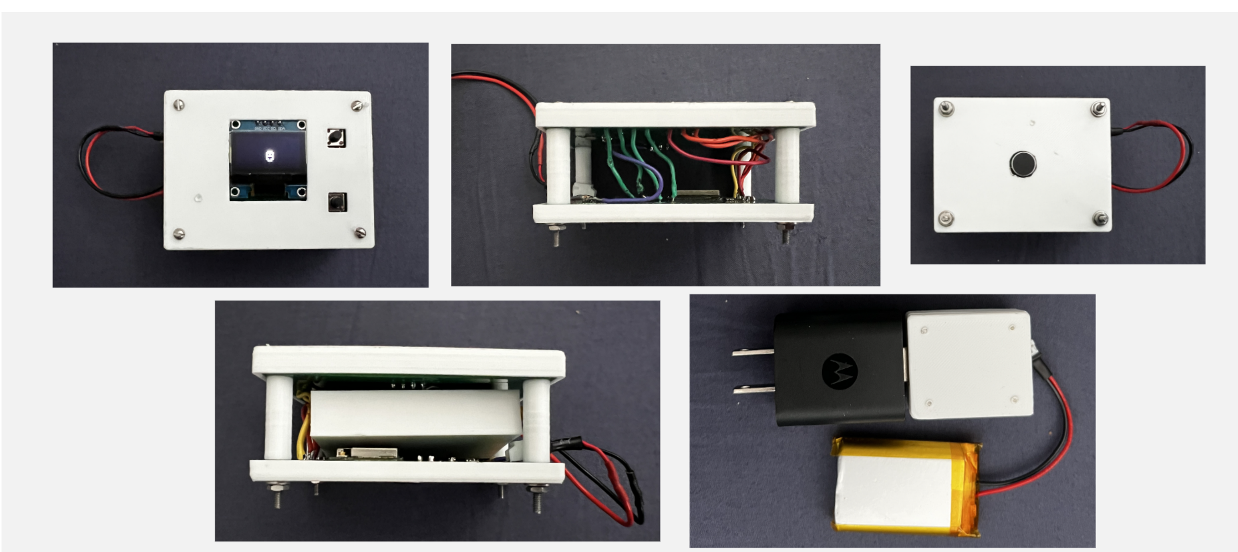

Figure 13: Our final Device

7.2 Schematic Layout and PCB Designs

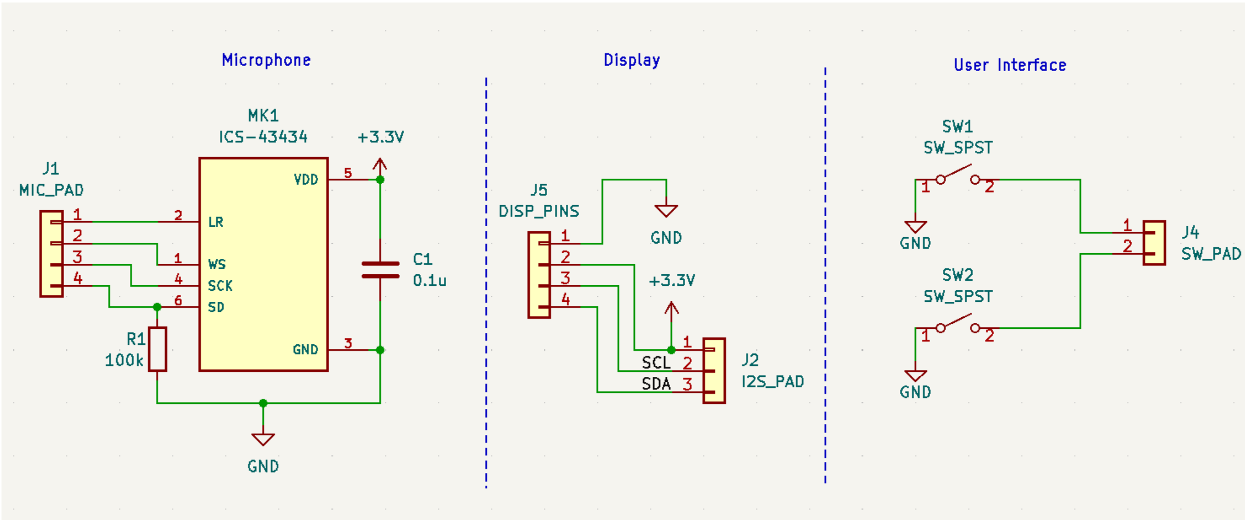

Figure 14: Top PCB Schematic

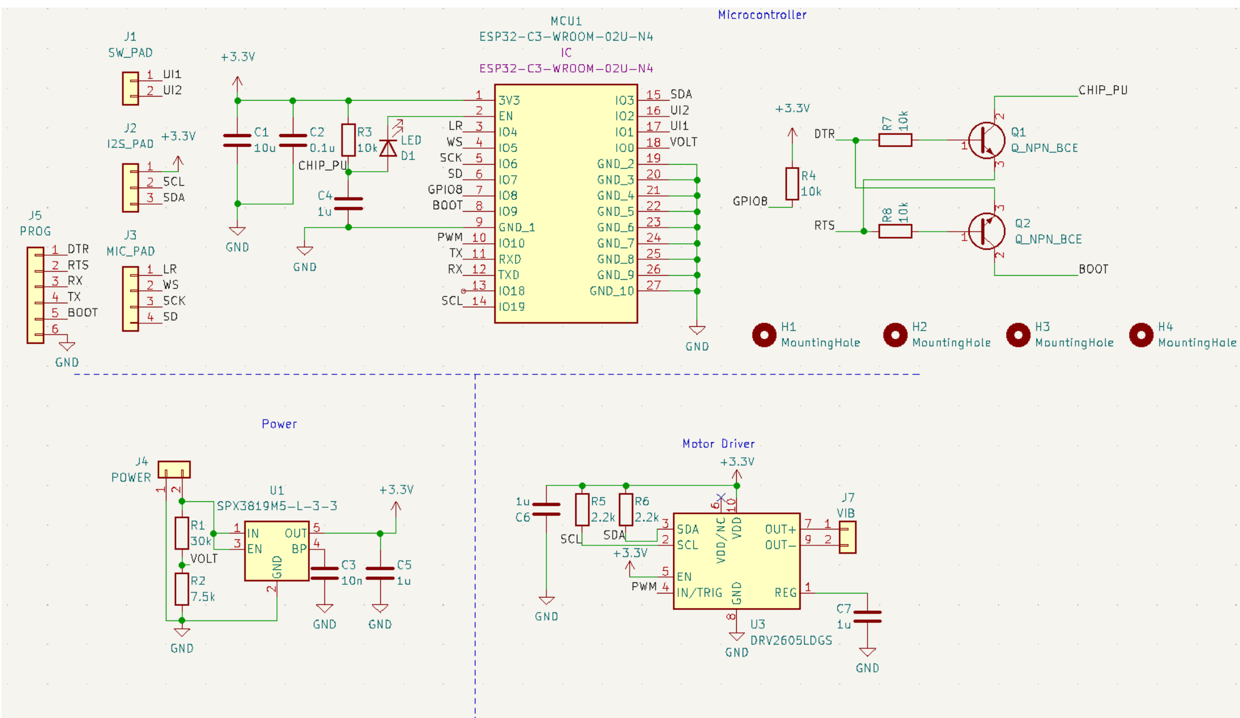

Figure 15: Bottom PCB Schematic

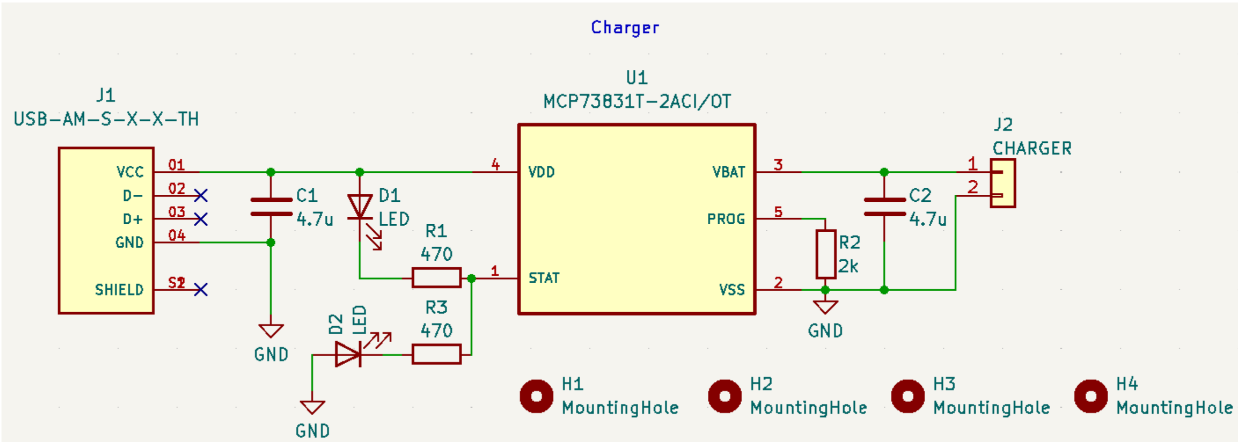

Figure 16: Charger circuit Schematic

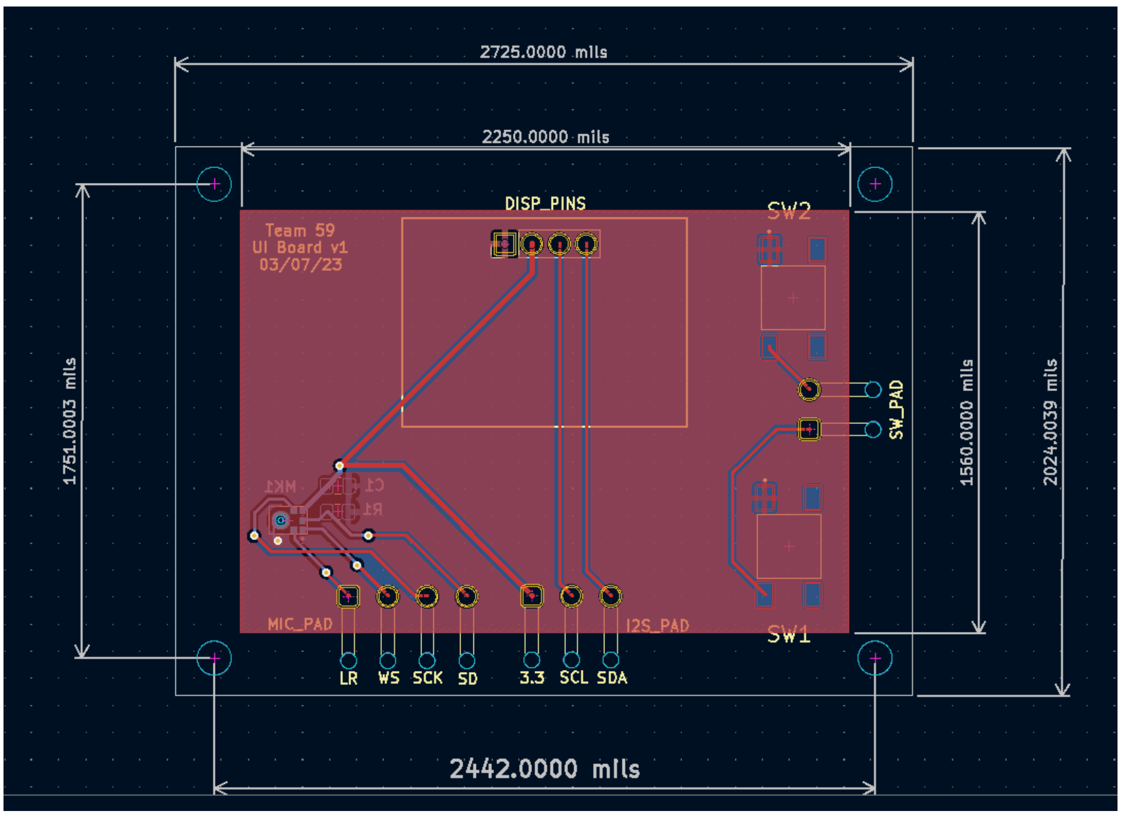

Figure 17: Top PCB with dimensions

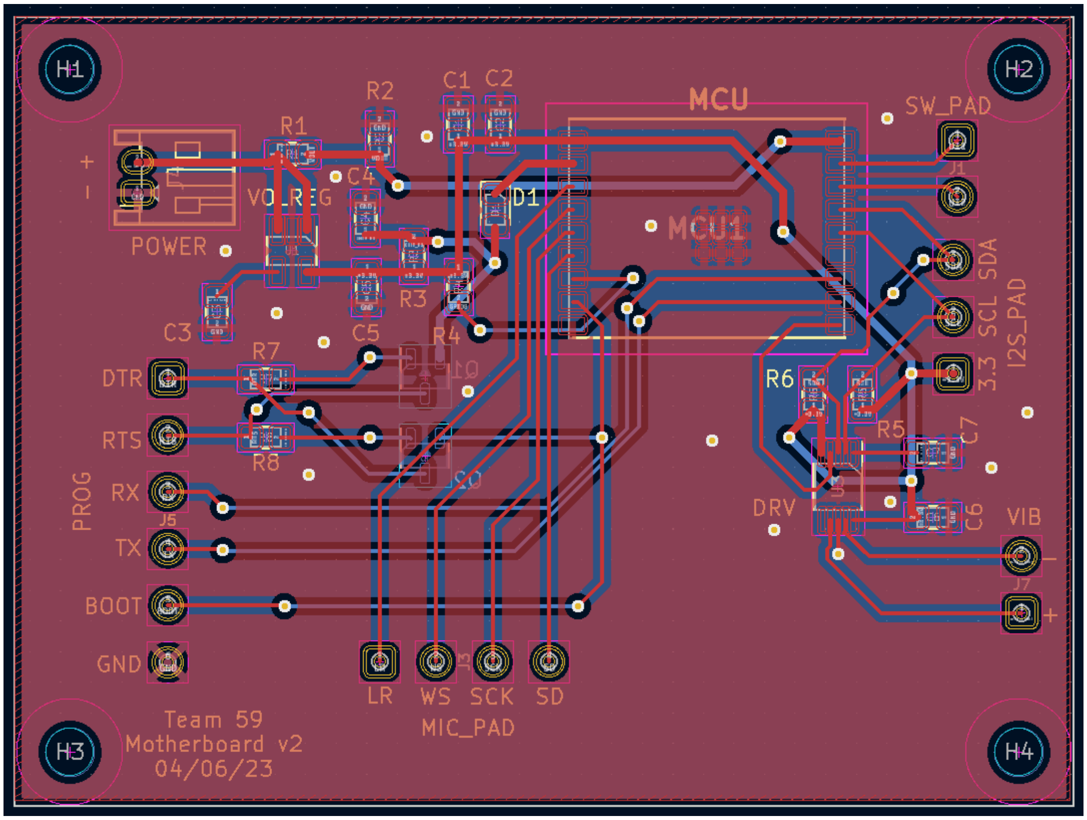

Figure 18: Bottom PCB (same dimensions as Top)

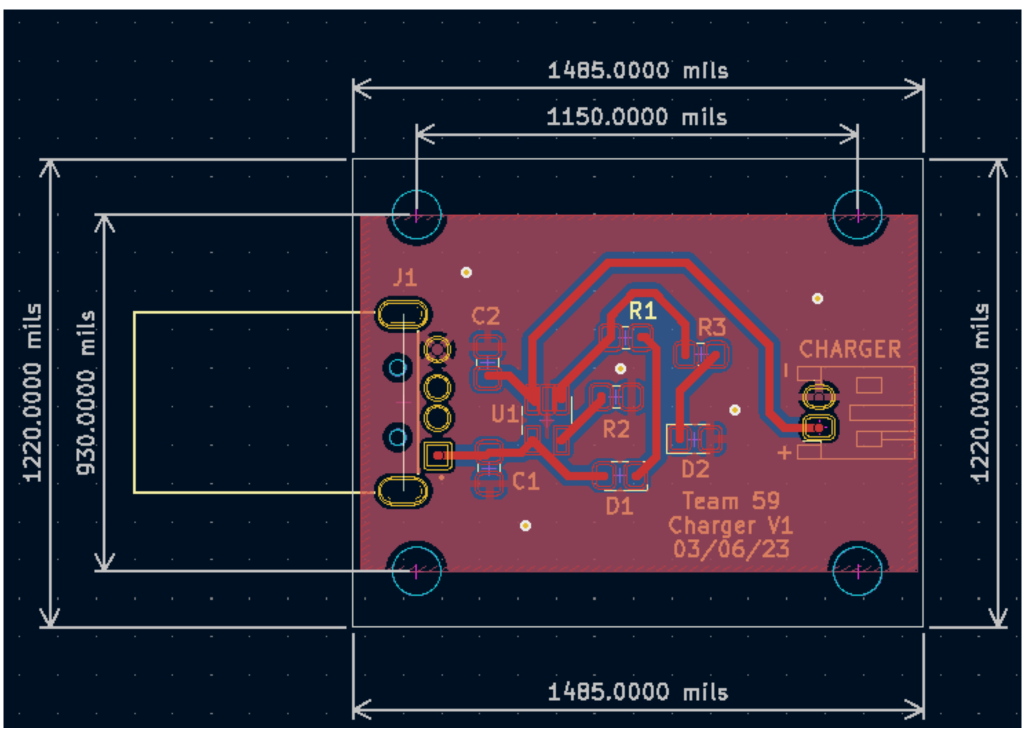

Figure 19: Charger circuit PCB with dimensions

7.3 **Requirements and Verification Tables**

Power Subsystem

Requirements	Verification
The charging circuit should have general Li-Po battery protection and should ensure that the battery is not charged or discharged at a rate larger than 1C.	- Connect a USB cable to a power source and connect the cable to the board - Connect one of the two discharged Li-Po batteries to the JST ports on the charging circuit and ensure that the LED turns on - Measure the voltage across the two terminals with an ammeter and verify that the constant current provided is 500mA

Table 1: R&V for Power Subsystem

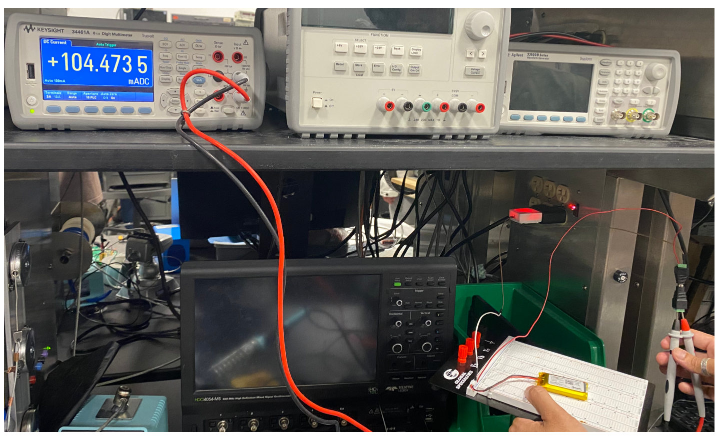

Figure 20: Power Subsystem Verification 1

Requirements	Verification
The microcontroller should be provided with a constant, uniform 3.3V with minimal noise and a tolerance of up to ±1%	- Connect a charged battery to the device - Ensure that the bracelet is powered on, and measure the voltage between the 3V3 and GND - Verify for 1 minute that the voltage doesn't change by more than 33mV

Table 2: R&V for Power Subsystem

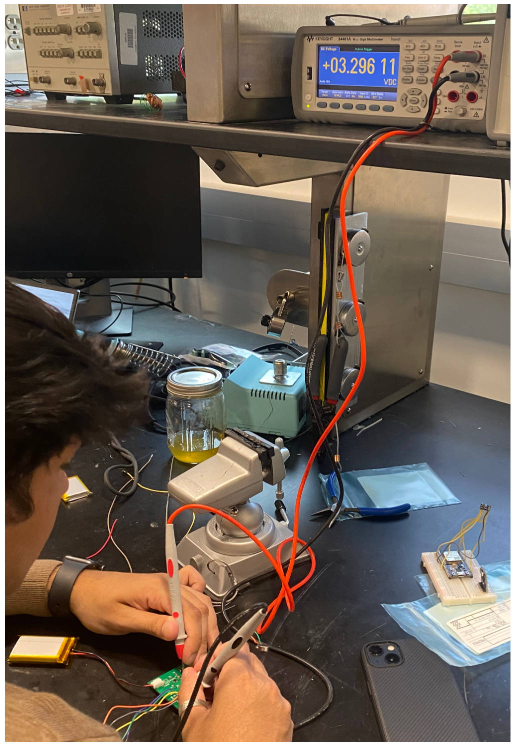

Figure 21: Power Subsystem Verification 2

Requirements	Verification
It should be able to keep the device powered for at least 24 hours.	- Assemble the bracelet with a complete vibration subsystem - Connect a fully charged battery to the device - Ensure that the bracelet is powered on, and verify that the bracelet can be interacted with for at least 24 hours

Table 3: R&V for Power Subsystem

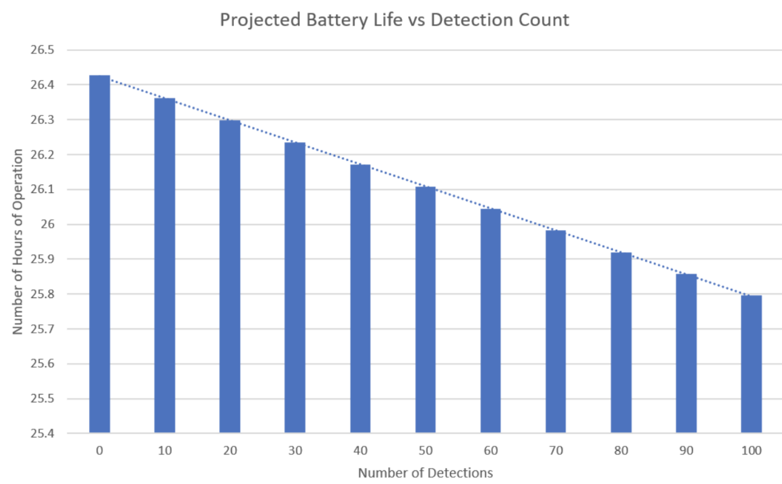

Figure 22: Power Subsystem Verification 3

Sound Detection Subsystem

Requirements	Verification
The subsystem should be able to detect different sounds with a frequency range of at least 200 Hz to 15 kHz when placed in the enclosure	- Produce a 200Hz with a laptop or computer and verify that the sound is detected by the bracelet when worn - Repeat the above with a 15kHz sound and verify detection
It should have a maximum current draw of 5mA during heavy use	- Program the device to detect regular sounds as needed by the user - Connect an ammeter between Vcc of the system and the Vin pin of the subsystem - Verify that the current draw is never above 5mA regardless of the quantity or amplitude of background sounds present

Table 4: R&V for Sound Subsystem

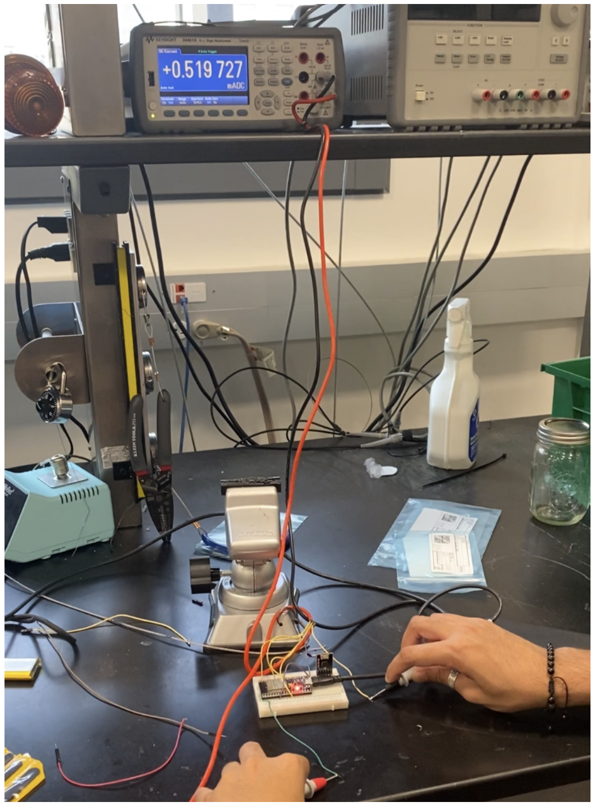

Figure 23: Sound Subsystem Verification 1

Requirements	Verification
It should take less than 10 seconds of notification to produce a successful sound detection	**-** Assemble the bracelet with a complete microphone subsystem - Program the device to detect regular sounds as needed by the user - Trigger one of the sounds on loop, at a distance of at least 10 feet and start a stopwatch - Wait for successful detection and stop the stopwatch as soon as the sound is detected - Repeat last two steps for 5 more of the programmable sounds added on the device

Table 5: R&V for Sound Subsystem

Vibration Subsystem

Requirements	Verification
It should be able to produce a strong detectable vibration	- Wire up the motor to the motor driver circuit - Ensure that the bracelet is powered on, measure the voltage across the motor when playing a “strong click” to be 3.6V [1] - Ensure a detectable vibration is felt when motor is pressed against skin

Table 6: R&V for Vibration Subsystem

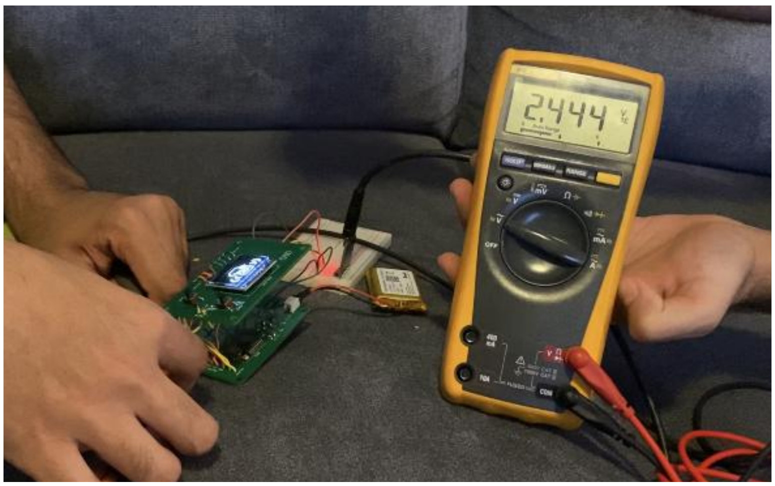

Figure 24: Vibration Subsystem Verifcation 1

Requirements	Verification
It should be able to produce at least 10 unique vibration patterns	- Assemble the bracelet with a complete vibration subsystem. - Wire up the motor to the motor driver circuit - Run 10 different vibration combinations made up of the 123 individual vibration patterns. [1] - Survey a study group of 15 people to determine whether or not the can distinguish the 10 different vibration patterns
The subsystem should successfully produce a vibration within 10 seconds of when a sound is produced	- Assemble the bracelet with a complete microphone subsystem & vibration subsystem - Program the device to detect regular sounds as needed by the user

	- Trigger one of the sounds on loop, at a distance of at least 10 feet and start a stopwatch - Wait for a vibration to occur and stop the stopwatch as soon as the device vibrates - Repeat last two steps for 5 more of the programmable sounds added on the device

Table 7: R&V for Vibration Subsystem

Display Subsystem

Requirements	Verification
It should be able to clearly display symbols associated with detected sounds.	- Assemble the bracelet with a complete display subsystem. - Wire up the OLED display to the OLED driver circuit, and microcontroller. - Ensure when the symbol is quantized to 128x64 pixels is clearly distinguishable. - Survey a study group of 15 people to determine whether or not the can distinguish the 10 different symbols
Its peak current draw should be less than 15mA. [2]	- Ensure that none of the symbols we display are not going to use all 128x64 pixel - Ensure that the current draw does not exceed 15mA while displaying all 10 battery symbols by connecting voltmeter probes between Vin pad and VCC.

Table 8: R&V for Display Subsystem

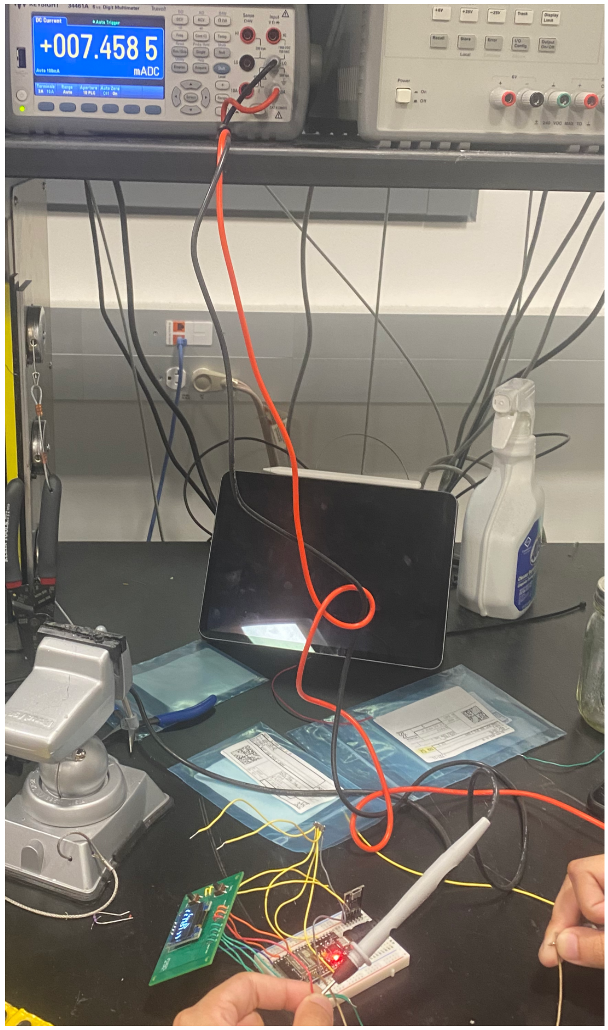

Figure 25: Display subsystem verification 1

User Interaction Subsystem

Requirements	Verification
They should be easily accessible from the top of the watch facing the user	**-** The buttons will be soldered on to the top PCB of our layered PCB system - Ensure that the buttons have enough height clearance to clear the enclosure even when fully depressed - Ensure the display and the button are the only things exposed from the enclosure's top surface

They should be spaced far enough apart to ensure buttons aren't accidentally pressed	- The buttons should be atleast one button width (6.00 mm) away from the edge of the enclosure as well as the two buttons should be two button widths (12.00 mm) apart. [5]

Table 9: R&V for User Interaction Subsystem

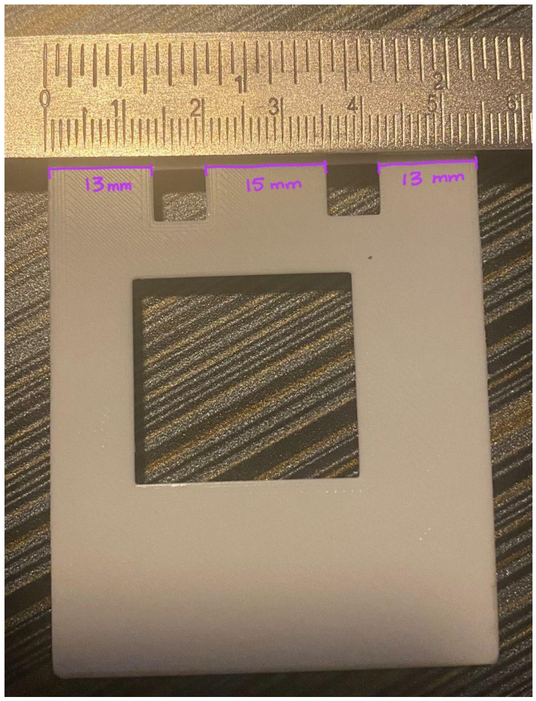

Figure 26: UI subsystem verification 1

Study Group Survey Results:

We asked a group of 15 people to verify whether they can differentiate between our 10 vibrations and 10 symbols. The results were as followed			
Name	Vibrations	Display	
Anuraag Agarwal	No	Yes	Microwave and Fire alarm vibrations felt similar, changes made according to user input
Trusha Vernekar	Yes	Yes	
Achyut Agarwal	No	Yes	Phone ringing and Fire alarm vibrations felt similar, changes made according to user input
Kartik Mehra	No	Yes	Smoke Detector and Burglar alarm vibrations felt similar, changes made according to user input
Elina Mehra	Yes	Yes	
Malhar Vora	Yes	Yes	
Rohan Batra	Yes	Yes	
Eshrit Tiwary	Yes	Yes	
Panav Munshi	Yes	Yes	
Aliva Panigrahi	Yes	Yes	
Aumkar Renavikar	Yes	Yes	
Daniel Abdoue	Yes	Yes	
Sruti Kamarajugadda	Yes	Yes	
Adit Arora	Yes	Yes	

Figure 27: Survey Results

Current draw for each sound detection:

Sound	Current draw in mA
1	75.77
2	64.37
3	35.95
4	24.7
5	58.7
6	144.78
7	124.99
8	144.4
9	69.7
10	152.4

Figure 28: Current draw for each sound detection

7.4 **List of Parts Ordered**

Part Description	Manufacturer	Digikey Part Number	Quantity	Total Cost
IC BATT CNTL LI-ION 1CEL SOT23-5	Microchip Technology	MCP73831T-3ACI/OTCT-ND	1	$0.76
CONN RCPT TYPEA 4POS R/A	On Shore Technology Inc.	ED2989-ND	2	$0.96
CAP CER 4.7UF 10V X7R 0805	KEMET	399-15708-1-ND	2	$0.79
RES SMD 470 OHM 5% 1/8W 0805	Vishay Dale	541-3025-1-ND	2	$0.32
RES 2K OHM 5% 1/8W 0805	Stackpole Electronics Inc	RMCF0805JT2K00CT-ND	1	$0.10
LED RED CLEAR 0805 SMD	Inolux	1830-1082-1-ND	2	$0.66
CONN HEADER R/A 2POS 2MM	JST Sales America Inc.	455-1719-ND	7	$1.19
MICROPHONE MEMS DIGITAL I2S OMNI	TDK InvenSense	1428-1066-1-ND	1	$3.13
CONN HEADER VERT 4POS 2.54MM	Adam Tech	2057-PH1-04-UA-ND	1	$0.14
RES 100K OHM 0.1% 1/8W 0805	Panasonic Electronic Components	P100KDACT-ND	1	$0.36
CAP CER 0.1UF 100V X7R 0805	KYOCERA AVX	478-5780-1-ND	2	$0.40
CONN HEADER VERT 3POS 3.96MM	TE Connectivity AMP Connectors	644749-3-ND	2	$0.86
SWITCH TACTILE SPST-NO 0.05A 12V	E-Switch	EG4375CT-ND	2	$0.86
IC REG LINEAR 3.3V 500MA SOT23-5	MaxLinear, Inc.	1016-1873-1-ND	1	$0.67
RES 30K OHM 1% 1/8W 0805	YAGEO	311-30.0KCRCT-ND	1	$0.10
RES 7.5K OHM 5% 1/8W 0805	YAGEO	311-7.5KARCT-ND	1	$0.10
CAP CER 10000PF 50V C0G 0805	TDK Corporation	445-7519-1-ND	1	$0.29
CAP CER 1UF 25V X7R 0805	KYOCERA AVX	478-10487-1-ND	4	$1.02
CAP CER 10UF 10V X7R 0805	KEMET	399-15694-1-ND	1	$0.94
RES 10K OHM 5% 1/8W 0805	YAGEO	311-10KARCT-ND	5	$0.14
RES SMD 2.2K OHM 0.5% 1/10W 0805	Susumu	RR12P2.2KDCT-ND	3	$0.48
IC MOTOR DRIVER 2V-5.5V 10VSSOP	Texas Instruments	296-38481-1-ND	2	$6.32
TRANS NPN 25V 0.8A SOT23-3	onsemi	KSC3265YMTFCT-ND	2	$0.48
SMD MODULE, ESP32-C3, 4MB SPI FL	Espressif Systems	ESP32-C3-WROOM-02U-N4C	1	$2.15
RES 10K OHM 1% 1/4W 0805	Stackpole Electronics Inc	RNCP0805FTD10K0CT-ND	2	$0.20
0.96" SSD1306 I2C IIC SPI Serial 128X64 OLED LCD Display	Amazon		1	$7.29

Table 10: List of Parts Ordered

7.5 **Battery Lab Safety Manual**

In order to ensure maximal battery handling safety, all members are expected to:

1. Complete the Laboratory safety Training
2. Complete additional fire safety and fire extinguisher training
3. Have an in-depth knowledge about how the battery works by reading through its datasheets
4. Eliminate sources of sparks or flames while handling the battery [4]
5. Remove any jewelry or metal from one's person before handling the battery [4]
6. Keep the battery stored in a cool and dry place [4]
7. Dispose of dented batteries
8. Thoroughly read and understand ECE445's Battery Safety Practice Guide [3]. The members are more specifically expected to follow the following guidelines mentioned:
    a. We must ensure that a TA is present whenever batteries are being handled and have a TA supervise the first time the battery is used
    b. Ensure that the circuit and PCB are looked over by the TA before using the battery with it

c. Cover terminals of the battery with insulated material for storage and ensure proper ventilation in the storage area
d. Keep the battery datasheet and materials safety data sheet on hand when using the battery