ECE 445 Senior Design Laboratory

Design Document

Voice Dosimeter

Team 79

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I. Introduction

Problem

Professional voice users – teachers, singers, actors, actresses, broadcasters, clergy, salespeople, courtroom attorneys, telemarketers, and health care specialists – constitute about 30% of the working population [1]. Many of these people will commonly experience voice disorders associated with high voice usage that can negatively affect productivity. The US societal costs of voice-related teacher absenteeism and treatment expenses alone have been estimated to be as high as 2.5 billion dollars annually [2]. Such absenteeism could be prevented for teachers and other voice professionals if they were able to measure how much they were using their voices every day through the use of a voice dosimeter. Measurement of voice usage can also be used in recovery of voice disorders as vocal rest is often recommended. Despite the apparent utility of voice dosimeters, there are currently none that are commercially available. Some devices were available in the past, but they cost thousands of dollars. A low-cost and widely available voice dosimeter would allow for clinical and research use of voice-related problems and voice therapy options.

This project will be conducted in collaboration with graduate student Charlie Nudelman and Professor Pasquale Bottalico at the College of Applied Health Sciences. Their group had previously developed a DIY voice dosimeter using a contact microphone and a portable audio recorder. They are still using this device today, but there are a few improvements they would like to see.

Solution

The device that Charlie and Pasquale are using is bulky and requires a wired connection. It is impractical for patients to wear daily and collect data for a long period of time. We aim to create a cheaper and more comfortable voice dosimeter that is capable of recording data for long periods of time without recharging while the data can be uploaded to another device wirelessly.

To achieve this goal, we will be using an accelerometer instead of a contact microphone that Charlie and Pasquale's initial design used. This will allow us to record the vibrations from the vocal cord with a smaller form factor. Afterward, this data can either be transmitted via

Bluetooth onto an external computer or be stored on-board if a computer is not nearby. Finally, this data will be processed to extract critical information about vocal usage and strain, which researchers can then analyze to improve voice therapy options.

Visual Aid

As shown in Figure 1, the voice dosimeter will be a small device that can comfortably be attached to the vocal cord above the collarbone. It will record the user's vocal vibrations as they speak.

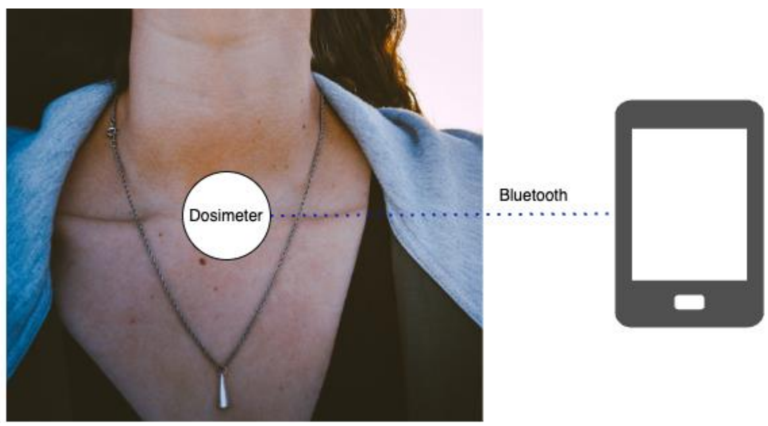

Figure 1: Visual aid of voice dosimeter system

High-level Requirements

1. The device shall accurately measure voice features including sound pressure level within 2dB, fundamental frequency within 5Hz, and cepstral peak prominence within 2dB.
2. The receiver phone or computer shall have an app or website for viewing voice features in real time with less than 1 second of latency.
3. The device shall have 8 hours of battery life to last through a full workday.

II. Design and Requirements

Block Diagram

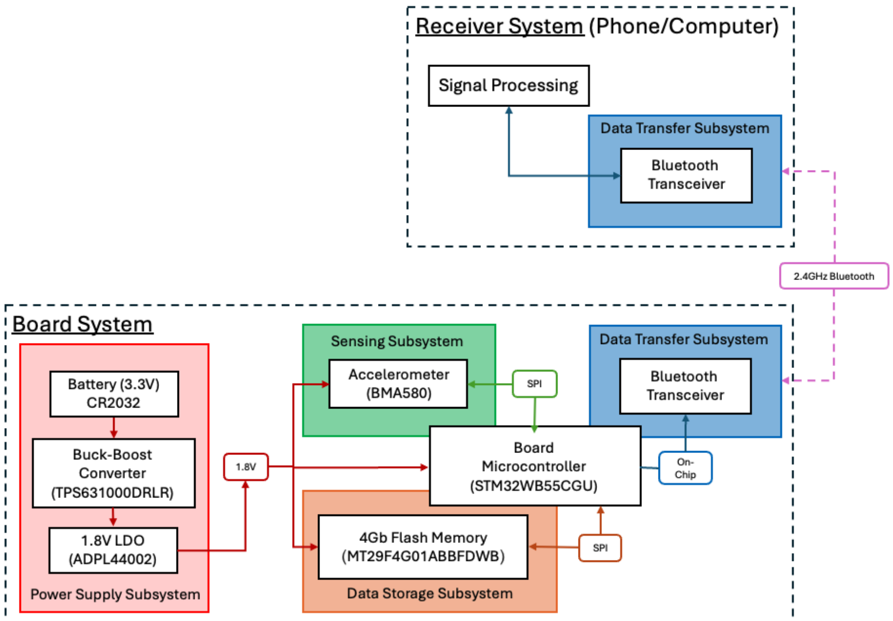

Figure 2: Block diagram of the overall system

Electrical Subsystems Overview

Power

One of the most critical subsystems of the device will be power management. As this is a wearable device, we want to ensure that even with a small battery, our device is able to run continuously for at least 8 hours. Thus, we will use a 3.3 V button battery, stepped down to 1.8 V for supply level. We use a buck boost converter in series with an LDO. The buck boost converter has high efficiency and the LDO has noise isolation. The buck boost converter can also step up the battery voltage to the LDO input if the battery is depleted.

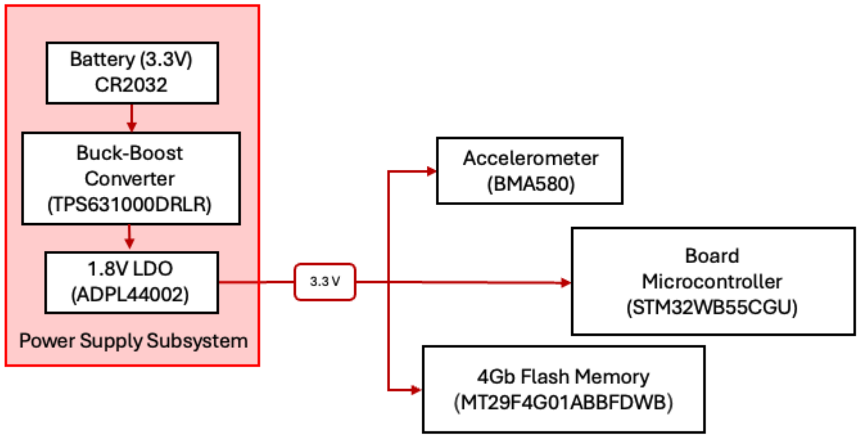

Figure 3: Block diagram of the power subsystem. The battery is connected to the PMIC which then distributes power to the accelerometer sensor, the MCU, and the flash memory IC.

Requirements	**Verification**
1. The power subsystem shall be able to supply power for at least 8 hours of continuous usage.	• To verify the requirement, a user shall wear the device for a full eight hours starting with full battery. For this verification, the SOC shall read the voltage of the battery every ten minutes and store the voltage value. • At the end of the eight hours, functionality will be verified on the receiver and battery voltage over time will be read.
2. The power subsystem shall be able to supply power for battery voltages from 2.0 V to 3.5V	• To verify this requirement, the battery shall be replaced with a variable voltage power supply. Functionality of the dosimeter will be tested with supply voltages of 2.0 V to 3.5 V in increments of 0.5 V.

Sensing

The sensing subsystem is the primary driver of this device. Without this, there would be no purpose to wearing this device. We will be using an accelerometer to measure the vibration of the user's throat as they speak. Furthermore, as the accelerometer will be placed close to the user's neck, external sounds and vocalizations will be significantly attenuated. The data collected from the accelerometer will be sent to the microcontroller via SPI protocol.

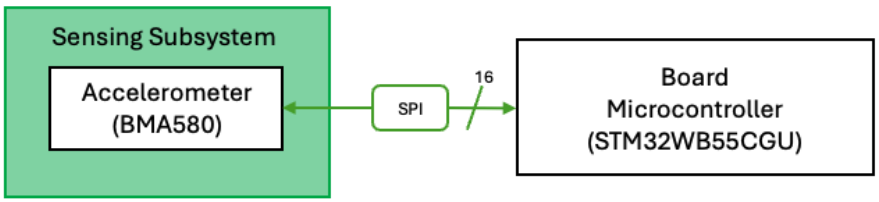

Figure 4: Block diagram of the sensing subsystem. The accelerometer transfers 16 bits of data at a time to the microcontroller through an SPI interface.

Requirements	Verification
1. The sensing subsystem should pick up the user's voice.	• To verify requirement one, our device shall be worn by a user. The user will speak at a moderate volume while the dosimeter is recording.
2. The sensing subsystem should isolate external noise by 20 dB.	• To verify this requirement, this device should be worn in a quiet room with an external speaker and measurement microphone. The external speaker, user and microphone will be arranged in an equilateral triangle of one meter. • Both the dosimeter and the microphone will be turned on to record. The user will speak for ten seconds. Then, the speaker will play white noise for ten seconds.

	• The power of the speech vs white noise will be compared between the measurement microphone and voice dosimeter.

MCU/Bluetooth

The MCU chosen for this device is the STM32WB55CGUx, which has an onboard Bluetooth transceiver. In this system, the Bluetooth low-energy stack on the MCU functions as the peripheral device, whereas the Bluetooth module on a phone or computer functions as the central device. When data from the accelerometer is received, the MCU either stores the data on a memory IC or sends the raw accelerometer/vibration data to the phone or computer when the two devices are bonded. An external antenna and RF front-end consisting of a pi matching network and a low pass filter are also needed.

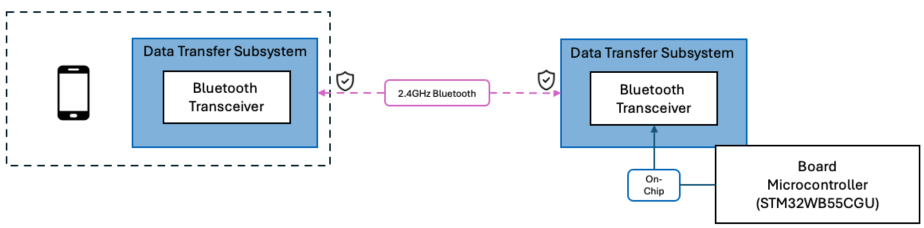

Figure 5: Block diagram of the Bluetooth communication subsystem. The data will be routed to the microcontroller before transmitted through Bluetooth to a central phone or computer to perform the necessary data processing.

Requirements	**Verification**
1. The Bluetooth subsystem should be able to transmit real-time accelerometer data with less than 1 second of latency.	• Our device shall be worn by a user in a quiet room. A camera will be set up that can view the computer/phone screen of the receiver. The user will record a video of the screen while making a vocalization. Afterwards, the video will be

	viewed in a video editing software to measure latency.
2. The Bluetooth subsystem should be able to transmit at a range of at least 5 meters.	• During regular use, we will place the device that we want to connect to through Bluetooth at varying distances and record if we are still able to receive the accelerometer data. If we are able to consistently receive data for the devices being separated by at least 5 meters, then the verification is a success.

Storage

The storage subsystem consists of a 32 Gb flash memory IC. The flash memory has enough storage for at least eight hours of raw accelerometer data. When the central Bluetooth transceiver is not connected, the data is stored on this flash memory IC. Then, when the voice dosimeter is close enough to connect to the central transceiver, the MCU proceeds to read and transmit the stored data. The NAND flash memory IC that has been chosen interacts with the MCU through a parallel interface.

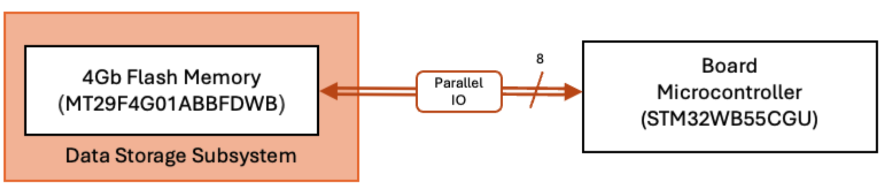

Figure 6: The 32Gb flash memory uses 8-bit addressable memory and a parallel interface. This means that the memory IC will be connected to the MCU with an 8-bit wide bus.

Requirements	Verification
1. The device shall be able to write sensor data to the	• The user shall create a timer on the MCU and measure the speed of writing 96 kilobytes of data to

flash memory in real-time.	flash. This should take less than 1 second as 96 kilobytes corresponds to 1 second of sensor data.
2. The device shall be able to read sensor data from the flash memory in real-time.	• The user shall create a timer on the MCU and measure the speed of writing 96 kilobytes of data to flash. This should take less than 1 second as 96 kilobytes corresponds to 1 second of sensor data.

Software Overview

Software Flowchart

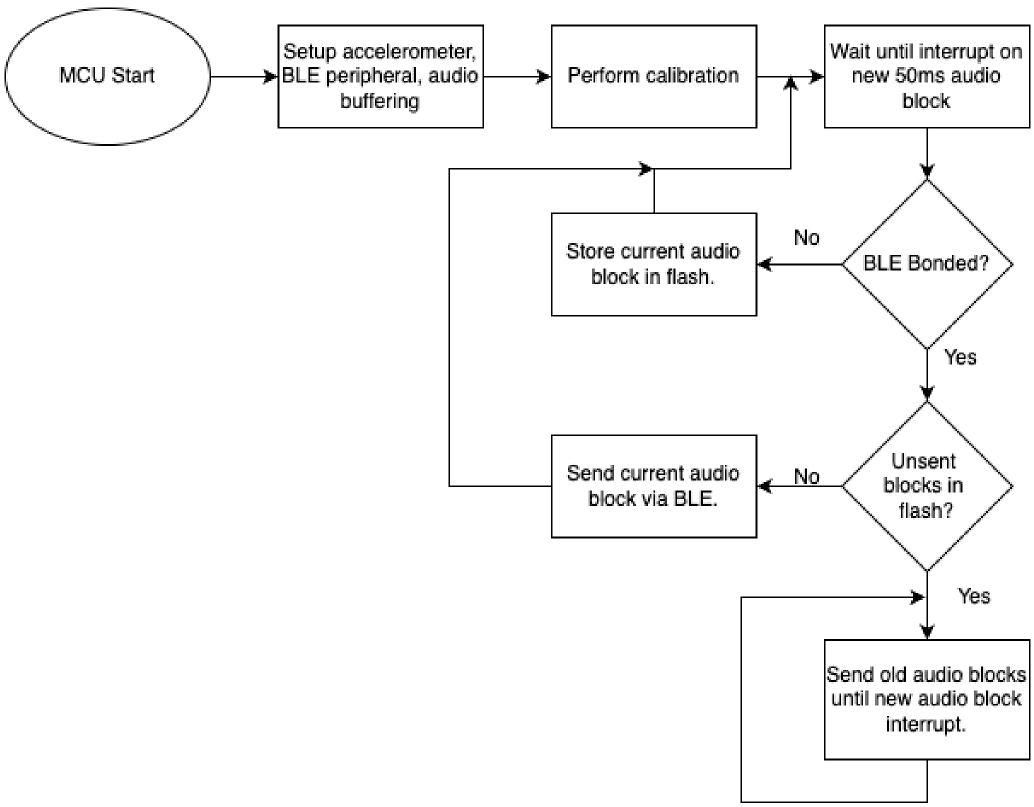

Figure 7: The flowchart for the microcontroller firmware.

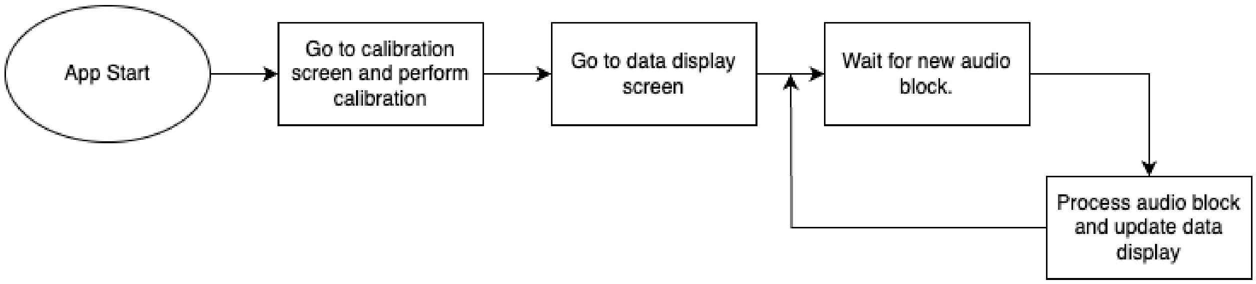

Figure 8: The flowchart for the app software.

Calibration

The SPL and CPP measurement will need to be calibrated on first wearing of the voice dosimeter due to differences in placement or contact affecting mechanical coupling. The first screen of the app will prompt the user to perform calibration. The user will be instructed to place an SPL meter or SPL meter phone app 0.5 meters from the user's mouth. Then, the user will press record on the app and make a long A vowel sound for 10 seconds. The user will then enter the SPL measured during the vowel sound. The app will measure the gain between the dosimeter and the SPL meter and store that number for calculating SPL and CPP.

Processing

The processing subsystem will estimate the following features of the user's voice in real time: sound pressure level (SPL), fundamental frequency (f0), cepstral peak prominence (CPP), and the vocal doses. These features are extracted from the raw accelerometer data and will be displayed accordingly in a web application. SPL is calculated using total energy, which is dependent on the calibration process. F0 is estimated using the Praat autocorrelation algorithm. The CPP is calculated using the algorithm in Hillenbrand et al [4]. We will take the Fourier Transform of the accelerometer data to obtain the Power Spectrum. Then we will take the square of the log of the Power Spectrum, and then take the Fourier Transform of that again. Finally, we take the difference in amplitude from a peak prominence to the baseline, and that defines the CPP.

Vocal doses is calculated using a weighted sum of the three other values. There are different types of vocal doses based on the weights. The Vocal doses that we will calculate based on the algorithms in Assad et. al. [11] are the following: Dynamic dose, Energy Dose, Radiated Dose, and their normalized forms. The Dynamic Dose indicates the total time of vocal fold vibration in the workday. The Energy Dose is the quantitative descriptor of energy delivered to the vocal folds. Radiated Dose represents the sound energy emitted from the vocal folds during vocal activity. The normalized forms are just normalized by the total duration of vocal activity (this is needed because during an eight-hour window, no one ever speaks for the entire time).

Requirements	**Verification**
1. The sensing subsystem should be accurate enough to determine the sound pressure level within 2dB, fundamental frequency within 5Hz, and cepstral peak prominence within 2dB.	* To verify requirement one, our device shall be worn by a user in a quiet room. A measurement microphone will be placed one meter from the user's voice. The user will read the first ten Harvard sentences at three different volumes [3]. * The three voice features will be compared from our voice dosimeter to the features using the measurement microphone and the same algorithms. Average error will be computed for each voice feature.

Mechanical Overview

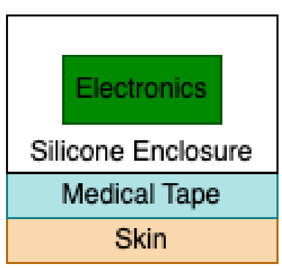

Figure 9: Diagram of mechanical design

Enclosure

The PCB will be enclosed in a silicone (Rogers HT-6000) enclosure. The enclosure will allow acoustic coupling between the PCB with the accelerometer and the skin while being more comfortable. The enclosure will be made by 3D printing a mold and curing the silicone enclosure. The enclosure also prevents the accelerometer from picking up on brushing from clothing.

Medical Tape

The enclosure is attached to skin using double sided medical tape. The tape should hold for at least eight hours.

Requirements	**Verification**
1. The silicone enclosure should be both comfortable and allow for accurate accelerometer recording.	• We will test comfort by having a sample population try on the device and state their comfort level. • Use we app to ensure that data is being transmitted by the accelerometer with the silicone enclosure.
2. The tape should hold for at least eight hours.	• We will make sure that the tape is appropriately attached and do actual trial runs to make sure that the tape stays on for at least eight hours.

Tolerance Analysis

Device	**Part No.**	**Operating Power**	**Size**	**Packaging**
Battery	CR2032	2.9V / 150mAh	17mm x 17mm	Button Battery
MCU	STM32WB55CGUx	1.7-3.6V / 58uA (Flash), 5.4mA (TX/RX)	7mm x 7mm	QFN48
Buck-Boost Converter	TPS631000DRLR	1.6-5.5V Input – 1.2-5.3V Output	1.6mm x 2.1mm	SOT-583
1.8V LDO	ADPL44002AUJZ-1.8-R7	2.7-40V Input – 1.8V, 2.5V, 3.3V, 5.0V output	2mm x 2mm	TSOT-23-5
Accelerometer	BMA580	1.6-3.6V / 125uA	1.2mm x 0.8mm	WLCSP

NAND Memory	MT29F4G01ABBFD WB-IT:F	1.7-1.95V / 40mA	8mm x 6mm	U-PDFN

Accuracy

There is some risk that the voice features calculated from the measurements of our accelerometer won't match with the voice features calculated from a microphone due to the lower sample rate. The BMA580 accelerometer has a sample rate of 6 kHz while high quality digital microphones typically have sample rates of 44.1 kHz or higher. However, most of the energy of an average human voice will be below 3000 Hz [5], which can be detected with our accelerometer. Furthermore, we will calibrate the accelerometer to a measurement microphone for better accuracy.

Latency

All three of our voice feature algorithms will run on blocks of 50ms. Bluetooth Low Energy (BLE) communication on our SOC has a minimum latency of 7.5ms [6]. We can increase the BLE latency to decrease power consumption. This gives us a minimum latency of 57.5ms. The latency and power consumption estimates could be calculated from the power profiler provided by the manufacturer.

Power

The worst-case power efficiency of the buck-boost converter is 0.8 [12]. The power efficiency of the LDO to drop from 1.9 V to 1.8 V is 0.95. This gives us an overall power efficiency of both power supplies of 0.758.

We can estimate the power consumption of the MCU from power measurements of the heart rate monitor example project that STMicroelectronics provides [13]. This project sends heart rate data from the MCU to a cell phone via BLE. STMicroelectronics have measured the current draw of this project at an average of 200 μA. However, this example has some differences such as running on a higher supply voltage and a lower Bluetooth data throughput. We estimate that this could be up to 4 times increase in current draw for our application. This gives us a current draw of 800 μA.

The flash memory uses 30mA for 900μs for each 4kbyte page write [8]. We generate and store 12kbytes of vibration data per second. This gives us an average current draw of 81μA.

The accelerometer uses an average of 125μA when in high-performance, continuous operation [8].

This gives us an estimated total current consumption of 1mA at 1.8V. The CR2032 battery has a capacity of 230 milliamp hours at 3 V. With the power supply efficiency calculated above, this gives us a battery life of 289 hours.

$$\frac{230\ mAh \cdot 3V}{(800\ \mu A + 81\mu A + 125\mu A)1.8V} \cdot 0.758$$

= 289 hours

III. Cost and Schedule

Cost Analysis

The cost for components is detailed in the table below with a subtotal of $49.70. After accounting for sales tax (10%) and a flat shipping fee of $50, the total cost of components adds up to $104.67. Furthermore, the average salary of a UIUC electrical engineering graduate is around $90,000 a year, which amounts to about $40/hr. Assuming it takes around 100 hours per person to complete this project from start to finish, the cost of labor per person is $40/hour x 2.5 x 100 hours, a total of $10,000 per person. This brings the cost of labor to $30,000 for the entire team. Altogether, the total cost for the research and development of this product is $30,104.67.

Description	**Manufacturer**	**Part No.**	**Quantity**	**Cost Per Part**
IC REG LIN 1.8V 300MA TSOT-23-5	Analog Devices	ADPL44002AUJZ-1.8-R7	1	$1.51
IC FLASH 4GBIT SPI 83MHZ 8UPDFN	Micron	MT29F4G01ABBFDWB-IT:F	1	$3.56
DC DC CONVERTER	Texas Instruments	TPS631000DRLR	1	$1.42
RF ANT 2.4GHZ/5.5GHZ STAMPED MET	Abracon	PRO-OB-536	1	$1.12
CONN HEADER SMD 14POS 1.27MM	Samtec	FTSH-107-01-F-DV-K	1	$3.39
RF FILTER LOW PASS 2.45GHZ 0603	TDK Corporation	DLF162500LT-5028A1	1	$0.48
IC RF TXRX+MCU 802.15.4 48UFQFPN	STMicroelectronics	STM32WB55CGUx	1	$6.08
BATTERY RETAINER COIN 10MM SMD	MPD	BHX1-1025-SM	1	$0.87
SHUTTLE BOARD 3.0 BMA580	Bosch Sensortec	SHUTTLE BOARD 3.0 BMA580	1	$24.91
CAP SMD 0603 47UF	Murata	GRM188R60J476ME01D	1	$0.36
CAP SMD 0603 22UF	Murata	GRM188R60J226MEA0J	1	$0.16

CAP SMD 0603 4.7UF	Murata	GRM188R61E475KE11D	4	$0.19
CAP SMD 0603 2.2UF	Murata	GRM188R61E225KA12D	2	$0.11
CAP SMD 0603 1UF	Murata	GRM188R61A105KA61D	2	$0.11
CAP SMD 0603 100NF	Murata	GCJ188R71E104KA12D	6	$0.13
CAP SMD 0603 10NF	Murata	GCM188R72A103KA37D	1	$0.11
CAP SMD 0603 100PF	Murata	GRM1885C1H101JA01D	1	$0.08
CAP SMD 0603 10PF	Murata	GCM1885C2A100JA16D	2	$0.10
CAP SMD 0603 0.8PF	Murata	GRM1885C1HR80BA01D	1	$0.13
CAP SMD 0603 0.3PF	Murata	GQM1875C2ER30BB12D	1	$0.42
RES SMD 0603 100K OHM	Panasonic	ERJ-3EKF1003V	3	$0.10
RES SMD 0603 33K OHM	Panasonic	ERA-3AEB333V	1	$0.10
RES SMD 0603 12K OHM	Panasonic	ERA-3AEB123V	1	$0.10
RES SMD 0603 100 OHM	Panasonic	ERJ-3EKF1000V	1	$0.10
IND SMD 0805 10UH	TDK	KLZ2012MHR100HTD25	1	$0.20
IND SMD 0603 1UH	Murata	DFE18SAN1R0ME0	1	$0.33
IND SMD 0603 10NH	Wurth	LQG18HH10NJ00D	1	$0.18
IND SMD 0603 2.7NH	Wurth	LQG18HH10NJ00D	1	$0.10
CRYSTAL SMD 32.0MHZ	NDK	NX3225SA-32.000MHZ-STD-CSR-1	1	$0.69
CRYSTAL SMD 32.768KHZ	NDK	NX2012SA-32.768K-STD-MUB-1	1	$0.82

Schedule

Week	**Task**	**Person**
March 3	Order first round of parts for prototyping	Everyone
	Explore web app design for data processing and viewing	Michael
	Design circuit schematic and PCB	David
	Research STM32 programming and prototyping	Jaden
	PCB Order March 3	Everyone
March 10	Create basic web app capable of basic real-time analysis	Michael
	Establish working accelerometer to MCU communication	David/Jaden
	Solder, test, and revise first prototype PCB	Everyone
	Breadboard Demo March 12	Everyone
	PCB Order March 13	Everyone
March 17	Spring Break	Everyone
March 24	Order second round of parts for prototyping	Everyone
	Establish real-time receive and processing of data	Michael
	Establish MCU to flash memory communication	David
	Establish Bluetooth transmission of data	Jaden
	Research silicone housing and physical design of device	Everyone
	Solder, test, and revise second prototype PCB	Everyone
March 31	Beta test web application software	Michael
	Finalize semi-finished version of voice dosimeter PCB	David
	Verification tests on electrical hardware	Jaden
	Finalize physical design of device	Everyone
	PCB Order March 31	Everyone
April 7	Integration tests	Everyone
	Ensure MCU to web app runs smoothly	Michael
	Verify components and subsystems are operating as intended	David/Jaden
	Solder, test, and revise third prototype PCB	Everyone
	PCB Order April 7	Everyone
April 14	Fix Remaining Bugs	Everyone
April 21	Mock Demo	Everyone
April 28	Final Demo	Everyone
May 5	Final Presentation	Everyone

IV. Ethics and Safety

As we proceed with this project, we want to acknowledge the ethical and safety considerations that are relevant to the IEEE and ACM code of ethics, as well as the steps we have taken to mitigate the concerns.

To begin, our device has been designed with health research in mind. Our device will record the user's vocal data, which can be considered personal health information. Thus, we want to ensure that such data is handled responsibly and only accessible to the relevant, permitted parties. When data is collected, it will either be temporarily stored on the device or transmitted to a computer, where it will be stored and analyzed. As the data on the device and external computer would be difficult to access without the user's permission, the point when the data is most vulnerable is during data transmission. To prevent potential information leaks, our data will be transmitted via Bluetooth, which follows standard security protocols to ensure a secure connection.

Furthermore, as per ACM Code of Ethics Section 1.6, everyone is entitled to their privacy, which must be respected. As our device records vocal data, there is the consideration that the voices of surrounding individuals could be recorded. However, our device does not use a microphone to record the user's voice; instead, we use an accelerometer placed directly on the user's vocal cord. This ensures that only the user's vocal data is recorded, preventing the potential invasion of privacy of other individuals.

Finally, there is also the concern of wearable electronics. Not only is our device designed to be directly attached to the user's skin, but our device also utilizes a lithium-ion battery. We must consider the potential hazards and dangers that this device may bring. Adhering to IEEE Code 7.8.9, we deliberately chose a low-voltage battery of 3V. Furthermore, the internal circuitry has been designed to operate at 1.8V and low currents, which further mitigates the risk to the user. Additionally, our wearable device will be enclosed in silicone for comfort, doubling as an insulating layer for protection.

V. References

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