ECE 445 Senior Project Spring 2024
Design Document: Haptic Headset

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Introduction

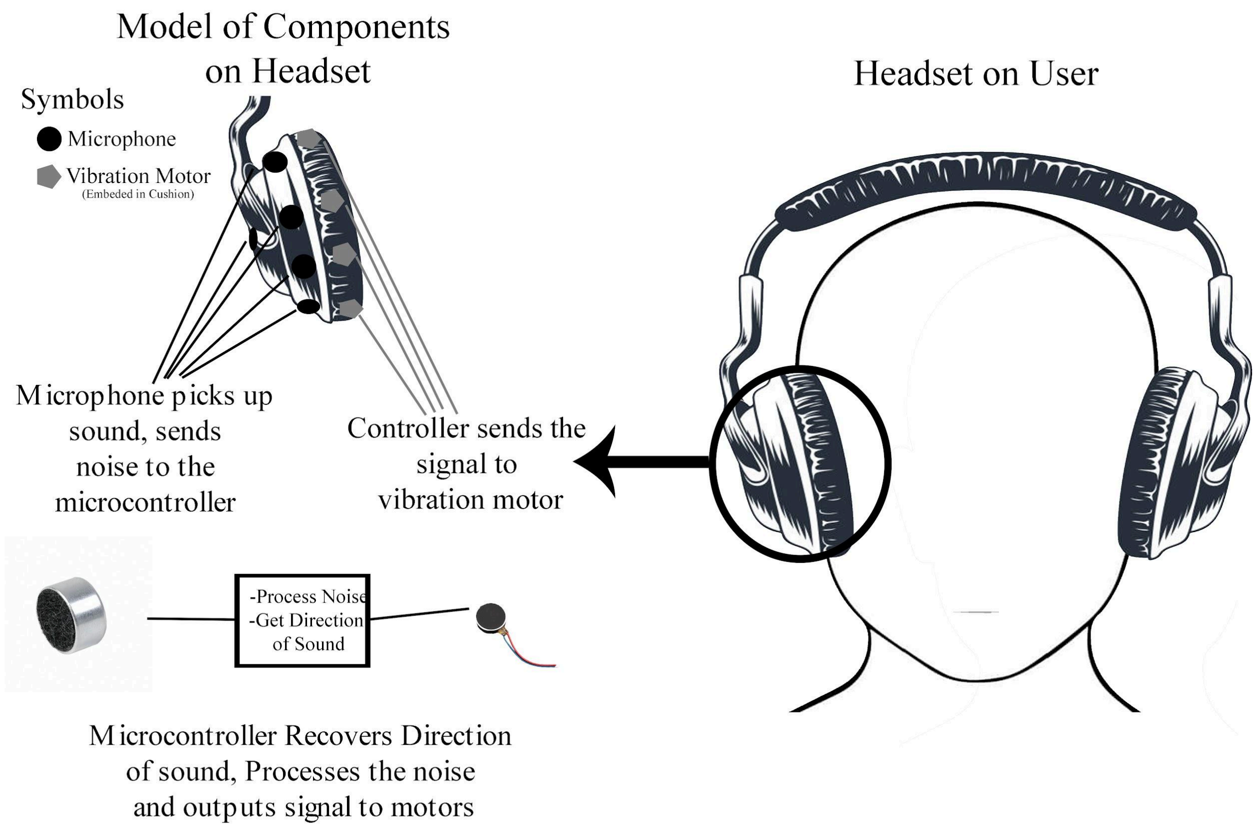
Problem:

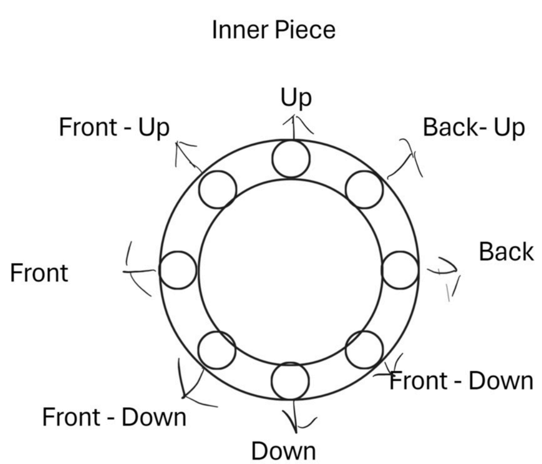
The property of hearing offers great advantages for survival as most alerts can be heard before they are ever seen. Deaf individuals, and those hard of hearing, have lost those advantages; Due to this, they lack the awareness of their environment offered with sound. Statisticians estimate that a little over 6% of the world is either deaf, or has experienced severe hearing loss throughout their life. While only 2-3 out of 1,000 babies on average are born deaf, roughly 15% of adults (+18) report that they experience some form of hearing loss from ages 18-69. These percentages may seem small right now, but when scaled to the massive population of the Earth, over 450 million people are affected by deafness and hearing loss. These people have lost a key sense that is vital in mitigating their safety in everyday life as a pedestrian. They are forced to go about their days without the ability to sense people and automobiles that aren't within their line of vision. The National Library of Medicine states that very little has been done in terms of research worldwide to remedy these struggles based on a study done in the UK. We aim to mitigate some of the struggles of those with deafness and hearing loss and contribute our aid to an issue that has received little acknowledgement in the past.

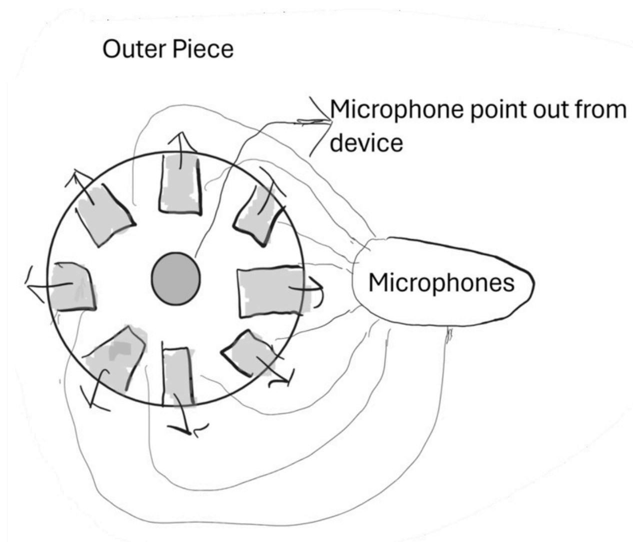
Solution:

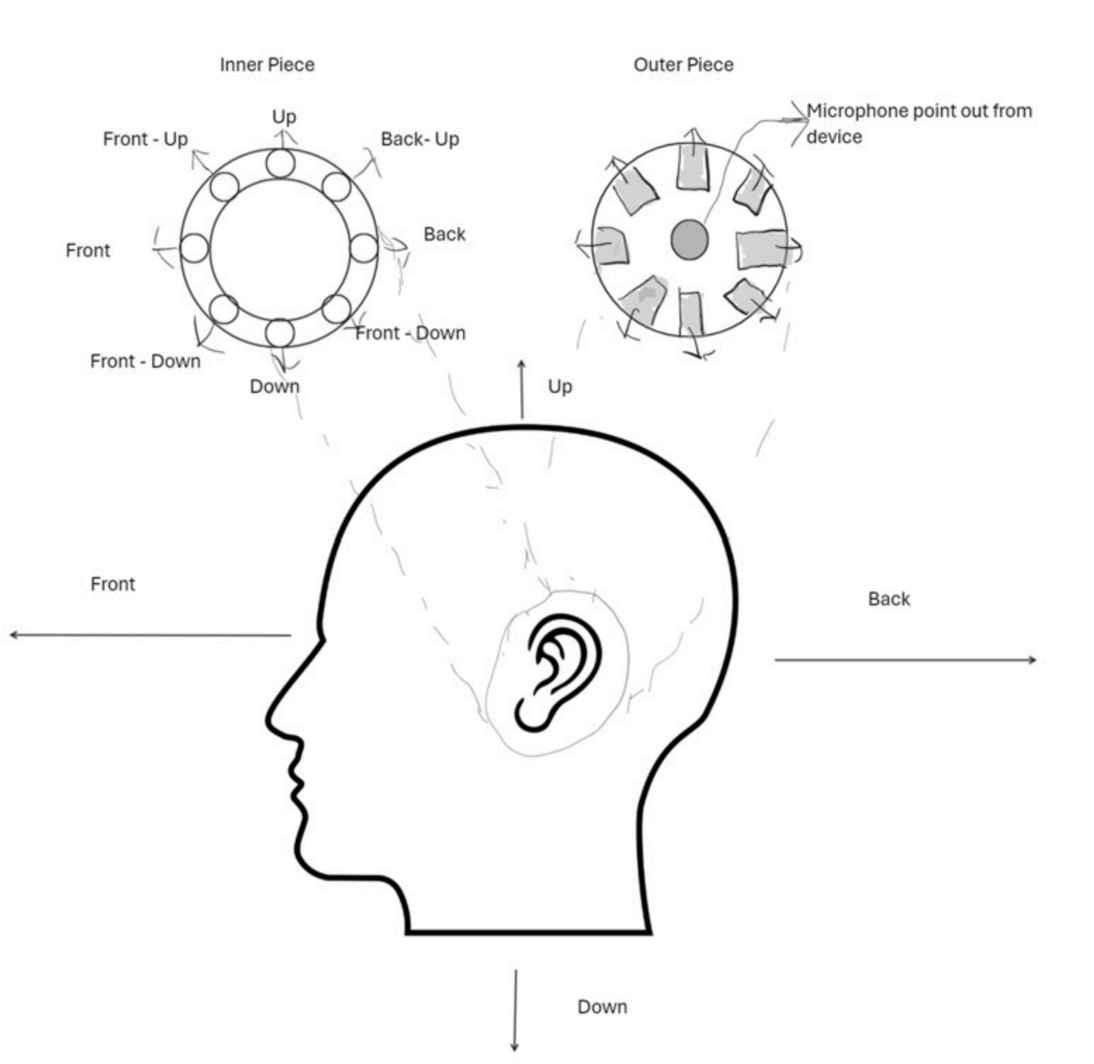
As a solution, rather than relying on the sense of sound, they can use the sense of feeling to get information they need from their immediate surroundings with directional haptic feedback. Haptic feedback is the use of vibration to convey information to the user (for example play station controllers or phone notifications). The idea is to place individual vibration motors along the outer rings on each side of over-ear headphones or ear mufflers. When a loud enough sound is played from any direction to the user, each individual motor vibrates in a way to give the user a sense of directional feedback. The goal of this device is to give the user heads up on where to look to see where the sound came from regardless of how little they can hear from their surroundings.

Visual Aid/Design:









High-level requirements list:

1. Audio Sensing: Sound sensors are able to pick up loud sound from the surrounding environment (>= 10 dB above average ambience from surrounding environment) 3 meters away and determine the direction of the sound within 45 degrees based on the trigger sensors.

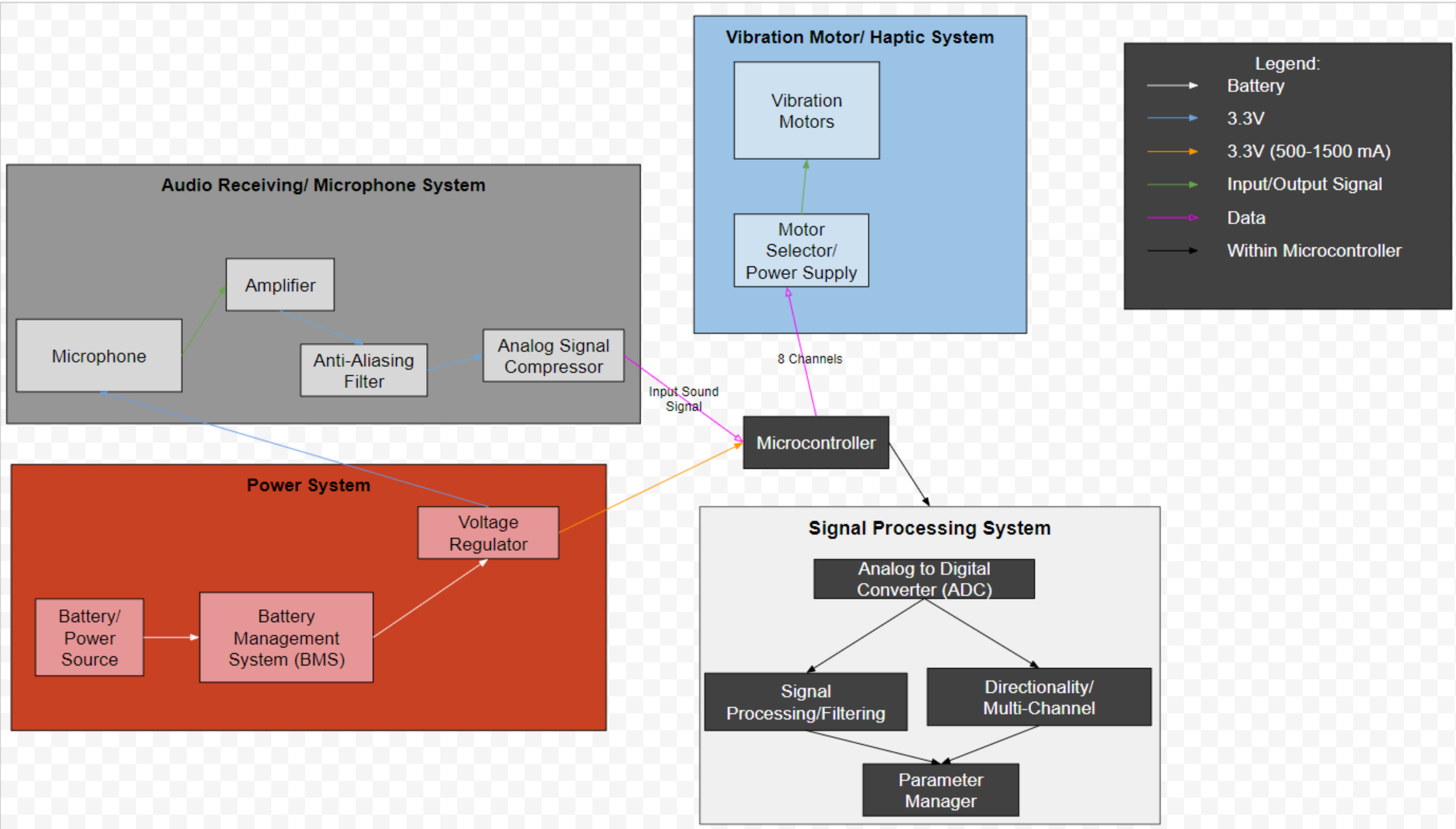
2. Haptic Feedback: When given a direction, the appropriate vibration motors will trigger to inform the user of the direction. Motors should receive at least 2V for low-priority sounds, and receive increasing voltage (5V at max) for high-priority sounds.

3. Comfortable Fitting: The device fits well and comfortably on the user.

4. User Efficiency: Users can effectively tell where external sound is coming from through the haptic feedback.

Design

Block Diagram:



Subsystem Overview:

Power Subsystem

One of the most important subsystems for an electrical project is the power component. After research, we plan on using a rechargeable lithium ion battery to power our system(safety specs outlined in ethics and safety portion). Standard industry practice is to use a battery that supplies between 2.75 and 4 volts. After creating detailed design plans we can narrow down exact voltage specs. The Li ion battery will be hooked up to a battery management system(BMS) and a voltage regulator which is standard practice when commercially working with batteries to make sure that power levels stay at a safe value.

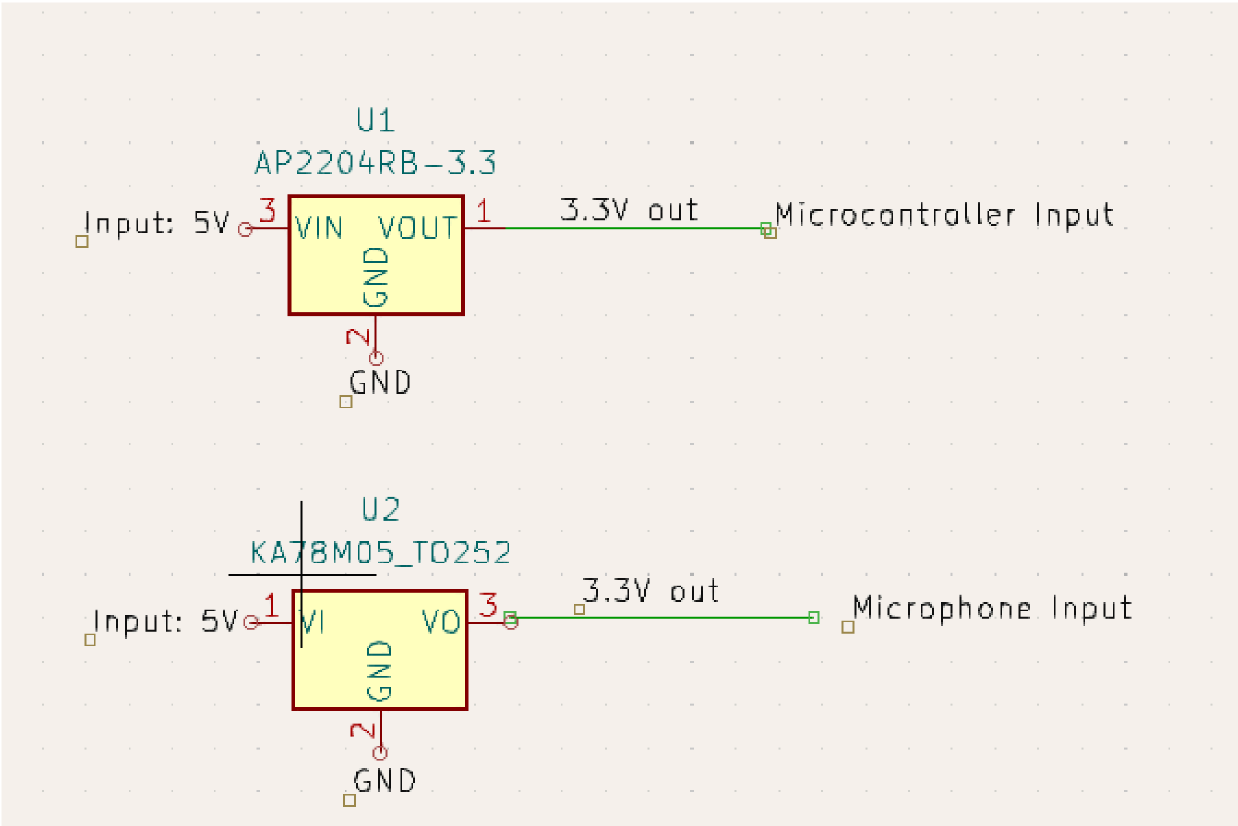
Table 1. Power Subsystem R&V Table

Requirements	Verifications

For ESP32-S3, supply 3.3V +/- 0.3V & [500, 1500] mA	1. Place a voltage sensor between the 3.3 V power rail and ground.
	2. Disconnect the power line to the microcontroller from the microcontroller.
	3. Make sure the power subsystem is turned on.
	4. Verify that the voltage between the power line and ground is below 3.6V.
	5. Verify upper power limit:
	    1) Place a 2Ω (±0.2Ω) resistor between the power line and ground.
	    2) After 1 minute, measure the voltage again and verify it is <= 3.3 V.
	6. Verify lower power limit:
	    1) Place a 6.8Ω (±0.2Ω) resistor between the power line and ground.
	    2) After 1 minute, measure the voltage again and verify it is >= 3.3 V.

For MAX4466 preamplifier, supply 3.3V +/- 0.3V & [24, 48] uA	1. Place a voltage sensor between the 3.3 V power rail and ground.
	2. Disconnect the power line to the microphone subsystem from the microphone subsystem.
	3. Make sure the power subsystem is turned on.
	4. Verify that the voltage between the power line and ground is below 3.6V.
	5. Verify upper power limit:
	    1) Place a 65kΩ (±5%) resistor between the power line and ground.
	    2) After 1 minute, measure the voltage again and verify it is <= 3.3 V.
	6. Verify lower power limit:
	    1) Place a 145kΩ (±5%) resistor between the power line and ground.
	    2) After 1 minute, measure the voltage again and verify it is >= 3.3 V.

Power System Schematic:



<u>Microphone Subsystem</u>

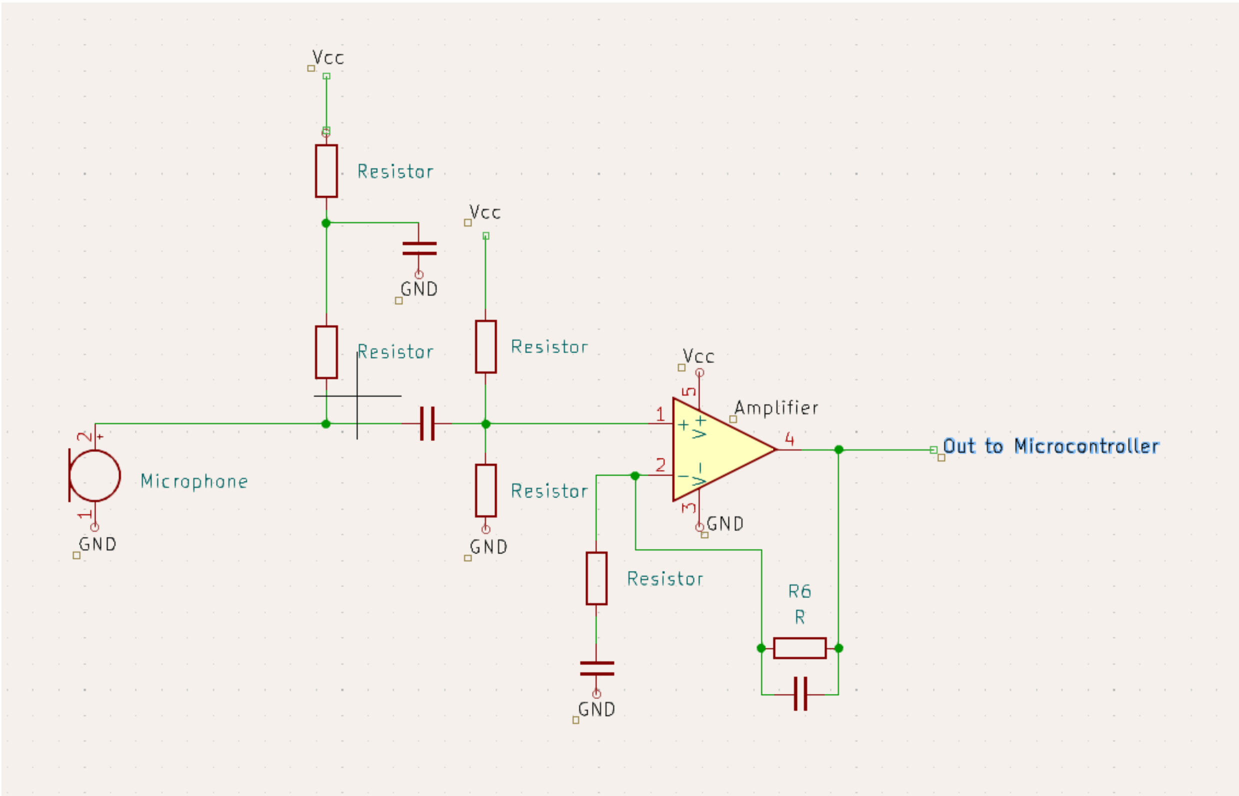
This subsystem uses 2 circular microphone arrays, one centered around each of the user's ears, to pick up the sound from the surrounding environment. Each array consists of 9 small unidirectional microphones, each pointing to a different direction including the following: Front, Up, Down, Back, Front-Up, Front-Down, Back-Up, Back-Down, as well as Left or Right depending on if the array is centered around the user's left ear or right ear. This is intended to preserve the directionality from the audio picked up from the surrounding environment.

There is a raw signal to ADC pipeline for each microphone in the microphone arrays, and it consists of the following: a microphone circuit[5] with power supplied by a voltage regulator, an amplifier circuit that increases the signal amplitude, an anti-aliasing filter that limits the signal's bandwidth, and one more voltage regulator that compresses the output signal voltage between 0V to about 3V in order to protect the microcontroller's ADC while converting the signal from analog to digital.

Table 2. Microphone Subsystem R&V Table

Requirements	Verifications
- Keep noise floor 10dB below sound of interest from 3m away before signal compression - Verify that signal bandwidth is below 20k Hz to avoid aliasing	1. Make sure microphone subsystem is receiving proper power supply 2. Disconnect microphone subsystem from signal compressor & microcontroller 3. Connect oscilloscope probes to signal and ground 4. Run frequency analyzer 5. Capture snapshot of frequency analyzer when there's no sound playing; calculate average/ RMS noise level 6. Play sound of car siren from phone at max volume 3+/- 0.1 m away from subsystem 7. While the sound plays, capture snapshot of frequency analyzer 8. There should be certain frequencies (most likely around 1k Hz) at least be 10 dB higher than other frequencies on the spectrum 9. Verify that frequencies after 20k Hz are at noise floor level
Input voltage to ADC pins must be <= 3.3 V	1. Make sure microphone subsystem is receiving proper power supply 2. Disconnect microphone subsystem from microcontroller 3. Connect voltage sensor in parallel to output signal from an arbitrary channel in microphone subsystem 4. Play constant loud noise directly into microphone corresponding to chosen channel 5. Verify that the output voltage is always <= 3.3 V even with complete audio clipping

Microphone Subsystem Schematic



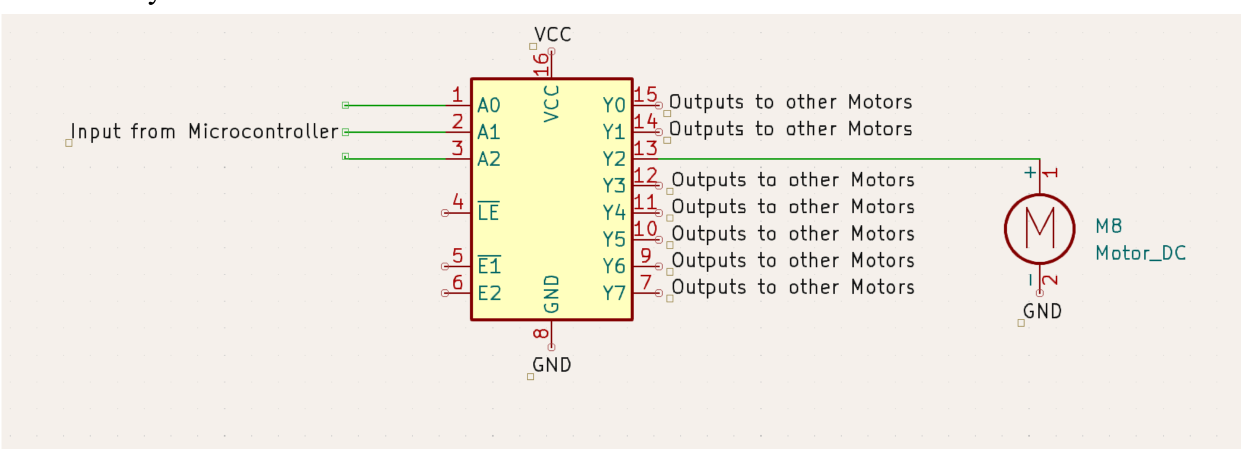
<u>Vibration Motor/ Haptic System</u>

The information about a sound and where it is coming from is relayed through haptic feedback from the vibration motors along the ear. Vibration motors will be placed along the ring of each earpiece on both sides of the headphones. Each earpiece (left and right) will have 8 vibration motors around the ear (Front, Up, Down, Back, Front-Up, Front-Down, Back-Up, Back-Down). Based on the sensor's read, the corresponding vibration motors will trigger to give the impression of direction from the user. For example: Sound coming from directly to the left, will trigger the vibration motors on the left earpiece; Sound coming from above and behind, will trigger the Back-Up, Up, and Back vibration motors on both the left and right earpiece; Sound coming from above and in front but to the right, will trigger the right earpiece's Front-Up, Front, and Up vibration motors. The path flow of the subsystem is from the microcontroller to the motor selector (likely a MUX) to the appropriate vibration motor. The Motor selector will supply the power to the motor based on the input received from the controller.

Table 3. Motor Subsystem R&V Table

Requirements	Verifications
When a sound of interest is played within range (as previously specified), microcontroller must be able to give appropriate input signals to motor selector - Select input & enable bits to turn on correct motor/ motors/ no motor - Vary Vcc so that motor selector outputs [2.5, 5] +/- 0.5V depending sound intensity	1. Make sure microcontroller and motor subsystem are receiving proper power supply 2. Connect oscilloscope probes to microcontroller ground and output pins connected to motor selector 3. Hardcode direction & (varying) intensity in microcontroller for each possible motor position 4. When no motor is selected, select enable should be off 5. When a motor is selected, select enable should be on and correct voltages should be sent to select input bits - Voltage for select/ enable low should be 0 +/- 0.5 V - Voltage for select/ enable high should be [Vcc - 0.5 V, Vcc] 6. Vary vibrational intensity for selected motor from lowest intensity above threshold to maximum intensity - Voltage for lowest intensity should be 2.5 +/- 0.5 V - Voltage for highest intensity should be 5 +/- 0.5 V

Motor Subsystem Schematic



Signal-processing Subsystem

The signal processing continues to preserve the directionality of the audio signals by processing each signal in its individual channel. It first converts the input signals from analog to digital at a set sampling rate that is at least twice the highest frequency from the input signals. Then it isolates the sound source(s) of interest (ex: car horn, siren, bike bell) while attenuating noise or otherwise irrelevant sound sources. Once a sound source of interest is identified, then its parameters (amplitude, frequency, etc.) will be compared with the corresponding threshold parameters in order to determine if the sound source is loud, close, and or important enough to the user to warrant activating the motor corresponding to the channel.

Table 4. Signal-processing Subsystem R&V Table

Requirements	Verifications
Able to isolate the sound of interest (ex: car horn, siren, bike bell) & identify direction of sound - Correctly identify noise floor within 5 dB - When a channel receives audio of sound of interest 10 dB above noise floor, it recognizes it as a sound of interest - The subsystem must be able to distinguish the direction of sound sources within 45 degrees.	1. Make sure microphone subsystem and signal-processing subsystem are receiving proper power supply 2. Choose an arbitrary channel in the 2 subsystems 3. Connect oscilloscope probes to input signal to compressor and ground for that channel in the microphone subsystem 4. While there's only ambience sound, run frequency analyzer on oscilloscope to estimate ambience level 5. Compare ambience level estimated by oscilloscope to ambience level estimated by signal-processing subsystem & verify that the latter falls within +/- 5 dB of the former 6. Play the sound of a car siren to the Left-Back of the microphone subsystem loud enough to be at least 10 dB louder than previously determined ambience level using oscilloscope 7. Verify that the signal-processing subsystem recognizes the sound of interest 8. Verify that the signal-processing subsystem recognizes the direction of the sound to be one of the following: - Left-Back

	- Left-Back-Up - Left-Back-Down - Left
The subsystem must be capable of doing the above in real-time (within 1 second).	1. Record a slow-motion video doing the above verification steps 6-8 2. Verify that the signal-processing subsystem gets the correct results within 1 second after from when the siren sound is played

Tolerance Analysis

The biggest hurdles that our project must overcome will be picking up the noise through the microphone effectively, processing the noise within the microcontroller, and determining the direction of one or even multiple sound sources. When it comes to sensing the sounds from the environment, the capability of the hardware is limited. We must find microphones that can reliably pick up sounds coming from the direction they are pointing at and ignore the sounds coming from different angles. The importance of finding reliable microphones will directly impact the sound sensing sub system and the noise processing of the microcontroller. When it comes to processing the noise in the microcontroller, we expect to differentiate the various ambient noise of the environment and the sounds that are cause for notice to the user. For the project to be successful, the processing must be fast and efficient from the given signal to the output signal. The area of risk is programming the microcontroller to process many sounds from different environments at different intensities and determining what to send to the motors and what to ignore. Many microcontrollers are efficient in audio processing; Arduino is compatible with many controllers such as the ESP32 and the STM32 which do have capabilities with sound processing. Furthermore, many microphones are capable of reading noise from only the direction they are pointing at a frequency range around from 100Hz and 20kHz. Thirdly, when it comes to determining the direction many complications can arise with the varying distance, presence of echoes and the potential of multiple sound sources feeding into the headset at once. The device should be able to take in all the various inputs and only vibrate to the sources of sounds (either one or multiple). This requirement will be difficult as it relies on both the hardware of the microphones and the capability of the signal processor. Finally, the micro controller must be able to process the many inputs of each unidirectional microphone to determine the direction of the sound. This requirement poses a risk as the microcontroller may not be able to handle the number of inputs. A solution to this could be to limit the number of inputs and outputs. This solution will also limit the precision device for the sake of hardware, precision limitations can be a benefit to the other subsystems such as the sensors as they will not need to signal as many different directions.

Table 5. Accuracy Error:

Sound Sensing in Microphones	Frequency Range: 100Hz(±30Hz) – 15000Hz (±1000Hz) Temperature range: -10℃-50℃ (±10℃)
Environmental Variability Directionality/ Distance/ Multiple Sources	Angle Accuracy: < 45° Distance Range: 0m-5 m respectively of Hz. Number of Sources read: 2 if distinct.
Noise Processing	Noise threshold: 75dB (Sound of a Person Yelling or Normal voice when close) Midrange frequency (5kHz- 10kHz) priority (Sound of Alarms and Sirens)
Input and Output Channel Limitations	8 input channels up to 3.3V input 8 output channels up to 5V output to motors

Cost

Component	Description	Quantity	Price	Total
Earmuffs	Manufacturer: Procase Earmuffs Part Number: N/A Desc: Headset for user to wear with microphones and motors attached. Link: here	1	$10.00	$10.00
ESP32-S3	Microcontroller Component Manufacturer: Espressif Part Number: ESP32-S3-DevKitC-1 Desc: Microcontroller used to process input. Link: here	2	$15.00	$15.00
Vibration Motors	Manufacturer: DFRobot Part Number: 1738-FIT0774-ND	16	$0.99	$15.84

	Desc: Motors for user Haptic Feedback Link: here			
Microphones	Manufacturer: CUI Devices Part Number: 102-1728-ND Desc: Mics for Sensors in the Device Link: here	18	$1.63	$29.34
Amplifier	Manufacturer: Analog Devices Inc./Maxim Integrated Part Number: MAX4466EXK+T Desc: Audio Amplifiers for Mic Link: here	18	$0.90	$16.20
Resistors 2kΩ 10kΩ	Manufacturer: Edgelec (Various) Part Number: EFR-W0D50-A:MF Desc: Resistor for circuits	108 54 (Round up: 100) 54 (Round up: 100)	$12.60 per 200 $6.30 per 100 $6.30 per 100	$12.60
Capacitors 0.01µF 0.1µF	Manufacturer: E-Project Part Number: B-0004-H15 Desc: Capacitor for circuit	72 36 36	 $5.41 per 25 $6.99 per 120	$17.81
8-Out Decoder	Manufacturer: Texas Instruments Part Number: SN74HC138DR Desc: Used in Motor Selector. IC DECODER/DEMUX 3:8 Link: here	2	$0.42	$0.84
Parts Total:				$117.63
Hourly Salary: $40 Hours per Week: 10 Number of Weeks: 9 Number of People: 3 Labor Total: ($40.00) * (10* 9 * 3) * 2.5 = $27,000				$27,000
Grand Total				$27,117.63

Schedule

Week	Task	Person/People
2/26	Order Parts	All
	Design Review	All
	Test Parts(Vibration and Microphones)	All
3/3	Start headset assembly	Tasho and Isabella
3/11	Spring Break	All
3/18	Confirm power subsystem and connections between Battery, BMS, and voltage regulator	Danny
	Get timing and other data on demux and decoding parts	Isabella
	Design PCB	All
	Finish headset assembly	All
	Work on microcontroller	Tasho
3/24	Work on microphone picking up audio and selecting correct motor through demux	Tasho and Isabella
	Finalize initial audio sensing and vibration	Isabella and Tasho
	Establish battery set up with other components in headset design	Danny
3/31	Process and Debug	All
	Confirm PCB works	Danny and Isabella
4/8	FINAL PCB ORDER DEADLINE	All
4/15	Mock Demo	All
4/22	Final Demo	All
4/29	Final Presentation and papers due	All

Ethics and Safety

Ethics and Safety

When undertaking any project it is paramount to consider the safety and ethical implications of said project. Our group's understanding is that there are not many ethical guidelines, as specified by the IEEE, that directly apply to our project. Creating a haptic headset to aid in spacial awareness for those both hard of hearing and hearing people does not raise any moral/ethical conundrums right off the bat. However, we believe that it is important for our team to keep these ideas in mind. (ACM Code of Ethics) [1.1-1.7], within this section, the ACM discusses contributing to society in a positive manner which we hope to do for the community by increasing spatial awareness with our headset. The rest of the section discusses how to make the team's efforts fair and and honest by being collaborative and not discriminatory to your teammates and potential users of your product. It is also to keep in mind (7.8 IEEE Code of Ethics) which describes many of the same topics. The IEEE code also places a big emphasis on integrity which we plan to put into every ounce of our project.

Another category that is important to the success of our project is safety. Safety goes hand in hand with ethics, and to make sure our product is as ethical as possible, it's important to make sure it is as safe as possible. Unfortunately unless you are working with a company or have special access, the IEEE will not let you look at safety specifications unless you pay for them but we are able to look into which codes offer the safety information we need. The key aspects to keep in mind when considering safety for our project are the audio and battery risks. Using the IEEE guidelines found in IEEE[269-2010], any audio that we decide to produce through our headphones(if at all) must be between 60-85 db, and 100-8500 Hz for headphones specifically. It is important that we make sure that vibration motors we use will not cause harm to the product user but the items we have researched do not have nearly enough strength for that to be a problem. After going through the lithium ion battery safety sheet provided for us on the senior design website and the overview of IEEE[1725] it is apparent that battery safety is paramount in designing our project. The Li ion batteries we have considered using would all be rechargeable and any battery we purchase we must make sure that the manufacturer is certified by either the IEEE or ACM(preferably both). We will keep an eye out for any swelling of the battery,(which we hope will never happen) in order to safely dispose of any faulty and dangerous materials we could encounter during the project. We must be wary of any faulty connections that could be made when soldering with a battery as well as connecting wires inside the headset. If we keep the battery safety in mind during the course of our project as well as headphones regulations, we are confident that we can have a safe, ethical, and successful project.

References:

[1]IEEE Code of Ethics. IEEE. Retrieved February 7, 2024, from https://www.ieee.org/about/corporate/governance/p7-8.html

[2]ACM Code of Ethics and Professional Conduct. ACM. (n.d.). Retrieved February 7, 2024, from https://www.acm.org/code-of-ethics

[3]IEEE Standard Methods for Measuring Transmission Performance of Analog and Digital Telephone Sets, Handsets, and Headsets. IEEE 269-2010. Retrieved February 7, 2024, from https://standards.ieee.org/ieee/269/4739/

[4]IEEE 1725 and battery powered products, IEEE. Retrieved February 7, 2024, from https://ieeexplore.ieee.org/document/5356015

[5] CMI-5247TF-K Datasheet - Electret Condenser Microphones | Microphones | CUI Devices, CUI Devices. Retrieved February 7,2024, from https://www.cuidevices.com/product/resource/cmi-5247tf-k.pdf

[6] ESP32-S3 Datasheet. Retrieved February 22, 2024, from https://www.espressif.com/sites/default/files/documentation/esp32-s3_datasheet_en.pdf#cd-pwr-supply

[7] ESP32-S3 Schematic Checklist. Retrieved February 22, 2024, from https://docs.espressif.com/projects/esp-hardware-design-guidelines/en/latest/esp32s3/schematic-checklist.html