



Haptic Vibrations for Hearing Impaired to Experience Aspects of Live Music

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Abstract. Listening to music contributes to community building and benefits mental health. The ability of hearing-impaired and deaf individuals to experience and benefit from music is hindered. Musical instruments vibrate to generate sound. The tactile feelings of these vibrations were utilized by deaf historical figures of Beethoven and Hellen Keller. Snakes have a keen sense of tactile sensations induced by both ground-borne and airborne vibrations, and the induced neural processing occurs in both the somatic system and the auditory cortex. Congenitally deaf individuals have been shown to have an enhanced ability to process tactile information, including processing in the auditory cortex. Wearable garments and furniture have recently been developed to convert audible sounds and music into vibrations to enable hearing-impaired and deaf individuals to have some level of experience. These devices show promise, but more work needs to be done to improve the conversion of sound into haptic vibrations in a more meaningful way. The objective of our project was to develop a wearable electronic system that would extract volume and frequency features from the recent moments of live music, and to use that information to generate vibrations at multiple locations on the skin toward enabling an experience of the music. A prototype was designed and developed. Several submodule tests were conducted to evaluate functionality. A human-subject pilot test was conducted to evaluate whether the vibration pattern would relate to the music, and possibly help to distinguish types of songs that had different genre. In the test, subjects were tasked with selecting which song was being used by the systems to generate the haptic vibrations. The subjects appeared to be only slightly more accurate in their song selection than would be expected by chance. The system shows promise, but more development and testing would be required toward wider application.

Keywords: Tactile · Impact vibrations · Deafness · Wearable electronic

1 Introduction

Hearing impaired individuals have difficulty experiencing the benefits of music. Music has been used through history as a means of entertainment, community building and

expression. Music has numerous health benefits [1, 2]. The art of music has been shown to have beneficial value for humans in many ways, such as cognitive and academic improvement for children and seniors, pain relief, relaxation, and exercise [2]. However, individuals who are hearing impaired or deaf are unable to fully perceive music or reap the benefits that come with listening to music. Individuals with deafness typically would not have audio induced neural stimulation from the audio sensory receptors in the cochlea to be processed in the auditory cortex. Vibration of tactile sensors in the skin induces some neural stimulation with similarity to auditory signals [3, 4].

Before studies comparing neural activity from audio and tactile vibrations were conducted, some intuition on the connection was observed in the popular culture. Percussion and string musical instruments undergo observable vibrations as sounds are generated. The story of historical composer Ludwig Van Beethoven is well known, in which he became deaf prior to composing what arguably became his greatest symphony. During that period, he would arrange to sense tactile vibrations from a piano to perceive some aspects of his music. He would lay the piano chassis directly on the floor, sit next to it and hit the keys hard. He would also bite a rod attached to his piano to feel the vibrations through his teeth [5]. A century later, the deaf and blind historical figure of Hellen Keller would learn to listen and then to speak with an audible voice by placing her hand on her teacher's mouth and feeling the vibrations from their voice [6]. Electronic speakers can generate vibrations that can be felt by tactile sensors in the hand. The 1995 movie of *Mr. Holland's Opus* portrayed the story of a high school music teacher who had a deaf son. To allow his son to experience some aspects of music he would have his son touch or sit on an electronic speaker that would be playing the music with high volume [7].

Understanding of the physiology connecting auditory sensory systems and tactile sensory systems was aided by experiments with snakes. Snakes have both an auditory sensory system (inner ear, VIII cranial nerve) and a somatic sensory system (skin mechanoreceptors, neural signals passing through spinal cord). Both the auditory and somatic sensory systems were found to respond to airborne sound, either focused near the head or along the body [8, 9]. The snakes were found to respond both with neural activity and behaviorally in similar ways as stimulated by either airborne or ground-borne vibrations [8, 10].

Such stimulation of both auditory and tactile sensory system was not only observed in snakes, but also in humans. Brain imaging studies found neural activity in the auditory cortex induced by tactile vibration [11, 12]. This phenomenon of tactile stimulation inducing activity in the auditory cortex was found to be enhanced in congenitally deaf individuals compared with normal-hearing individuals [12, 13]. Neural plasticity following long-term auditory sensory deprivation appeared to improve the ability of the auditory cortex to process tactile information [13]. Extending from sound to music, the full experience of "hearing" music involves many neural systems, not just the cochlea and auditory cortex, but other regions as well [13, 14].

Inspired by these observations in nature, physiology and experience, some prototype physical devices have been developed toward helping hearing-impaired or deaf individuals experiences some aspects of sound and music. A Sound-Shirt was developed and marketed by CuteCircuit (<https://cutecircuit.com>) [15]. In this Sound-Shirt, vibration actuators woven into the fabric of the garment translated musical sounds into touch-like

sensations on the wearer's back, sides, shoulders, and arms [15, 16]. The sensation of music may not be complete, but the idea shows promise to allow some aspects of the music to be experienced [16, 17]. Another prototype project placed the vibration actuators in chairs and furniture, such that when a deaf person sits within the chair, vibrations were generated to different parts of the body. The vibrations were based on certain correlations with the music, and were intended to allow the individual to experience some aspects of the music [18].

These devices that attempt to translate the audio aspects of music to haptic sensations to allow deaf individuals to experience music have limited function and success, yet show promise for the concept. More development needs to be done toward exploring the mapping of music to haptic vibrations. The purpose of our project was to explore methods to map audio waveforms to haptic vibrations within a wearable band.

2 Materials and Methods

2.1 Design

Hardware Design

A prototype was designed for the following functions. A microphone was used for audio input. Algorithms running on a microcontroller processed the audio signal to extract key features within recent small time-windows, specifically frequency and volume. These features were mapped to drive two pairs of vibration actuators within a band to be worn, allowing for haptic tactile sensations of the vibrations. The intent was for some aspects of the music to be conveyed by the pattern of vibrations on the skin.

The following components were selected for the prototype. The microphone was an Adafruit Max 9814 component (New York City, NY, USA). This microphone module had a small size and included a built-in op-amp of adjustable gain and ability to adjust the sensitivity in response to sudden changes in volume. The microcontroller was an Arduino (www.arduino.cc) Uno. As the prototype becomes further developed toward a wearable, mobile system, the Arduino Uno could be replaced with an Arduino Lilypad, more suitable for wearable electronics. The Arduino digitized the analog waveforms from the microphone, ran algorithms to process the audio signal, and output pulse width modulation (PWM) signals to motor drivers. The motor drivers were Adafruit DRV8871 modules, which generated the required 5 V and 80 mA to drive the motors. The motor for vibration was a linear resonant actuator (LRA) motor (#G0825001D, Jinlong Machinery & Electronics, Wanchai, Hong Kong). These coin motors generated vibrations that would induce noticeable tactile sensation on the skin and had a size suitable for incorporating into a wearable band.

LRAs are one of several methods to develop haptic vibrations, typically utilized for smartphones and game controllers. LRAs use magnetic fields and electrical currents to create a force, similar to the mechanisms in classic magnetic coil audio speakers. Changes in the current through the coil changes the magnetic force, causing movement

of a magnetic mass. Driving the magnetic mass up and down causes the displacement of the LRA and thereby the haptic vibration.

Algorithm

A mapping is necessary between the wide range of frequencies of audio waveforms and the more limited frequencies of vibrations to be generated on the skin for haptic sensation. The range of audio frequencies detected in the cochlear and the range of haptic tactile vibration frequencies detected by mechanoreceptors in the skin are different. Audio frequencies are generally considered to have a wide range from 20 Hz to 20 kHz, but skin tactile vibration frequencies have a narrow range, generally considered to be less than 500 Hz. For example, the low frequencies generated by a bass speaker may be felt when one touches the speaker, but not when only the higher audio frequencies are being generated.

Another limitation for the mapping of frequencies is the use of the LRAs to generate the haptic sensation. Unlike a classic magnetic audio speaker that can vibrate the speaker diaphragm at a wide range of frequencies, a LRA can only vibrate near its resonant frequency. The frequency in sound waves is the pitch of the sound, thus representation of music requires generation of multiple frequency vibrations.

To overcome these limitations that tactile sensation can only sense a small portion of the lower range of audio signals, and the LRA can only vibrate at one frequency, a concept of mapping the audio information to multiple LRAs located at different locations along the skin was employed. Vibrations at one location would reflect certain of the features of the audio signal, and vibrations at another location would reflect different features of the audio. With time and learning, possibly the brain could interpret these spatially distinct vibrations as different aspects of the audio signal. Figure 1 and Fig. 2 shows such the system design for this concept.

The algorithm to process the digitized audio waveform and extract the key features ran on the Arduino. Samples of the audio signal were analyzed sequentially to extract two features: a frequency and a volume for the recent samples. The algorithm was customized and adapted from an Instructible Sample Code [19]. The customized algorithm utilized in the prototype determined a frequency value as follows. The slope between two consecutive samples was calculated. A slope of ~ 0 indicated a local minimum or maximum peak in the signal. The time between two consecutive peaks was used to calculate a frequency value. In parallel with the slope and frequency algorithm, an estimate of average amplitude for the most recent samples was estimated. Changes in the amplitude or volume correlated with certain aspects of the music, such as reflecting beat or rhythm.

These features of amplitude and frequency were used to determine the PWM signals to drive each LRA. The prototype had two pairs of LRA, intended to be symmetrical for the left and right side of the band. A pair consisted of two LRAs. The first LRA was driven mainly by the amplitude feature if the frequency value was below a threshold, such as 1 kHz. The second LRA was also driven by the amplitude, but only if the frequency value was above the threshold value. In this way, the spatially separate locations of vibrations on the skin would convey low frequency amplitude in one location, and high frequency amplitude in the other location. Having vibration patterns differ based on frequency could deliver a more dynamic experience to the user and potentially improve the ability to distinguish between types of music or songs.

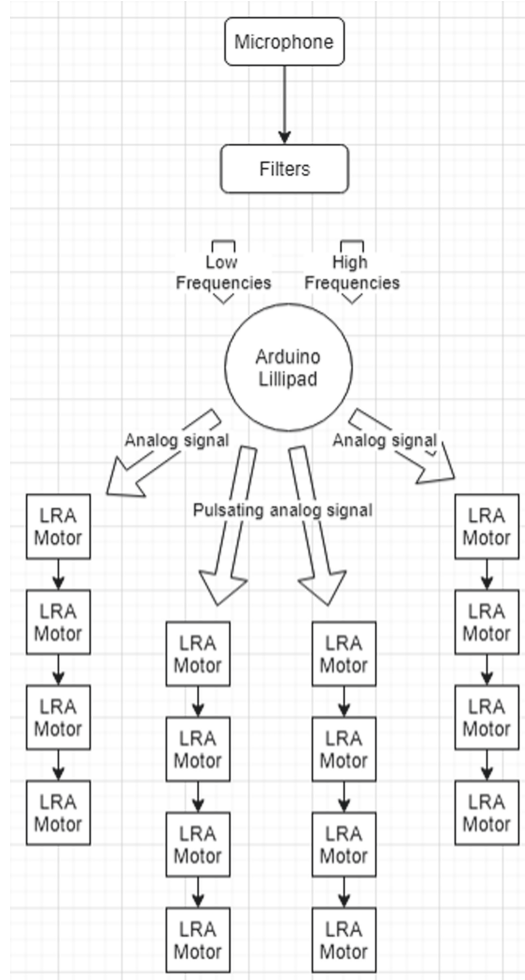


Fig. 1. Concept diagram of multiple vibrations at spatially different locations on the skin to map different features of the audio signal. Audio signals from a microphone, pass through filters to control the frequency content. Then the signal is digitized and processed by algorithms in the Arduino microcontroller. These extracted features are used to drive the LRA to generate vibrations at spatially different locations on the skin for haptic tactile sensations.

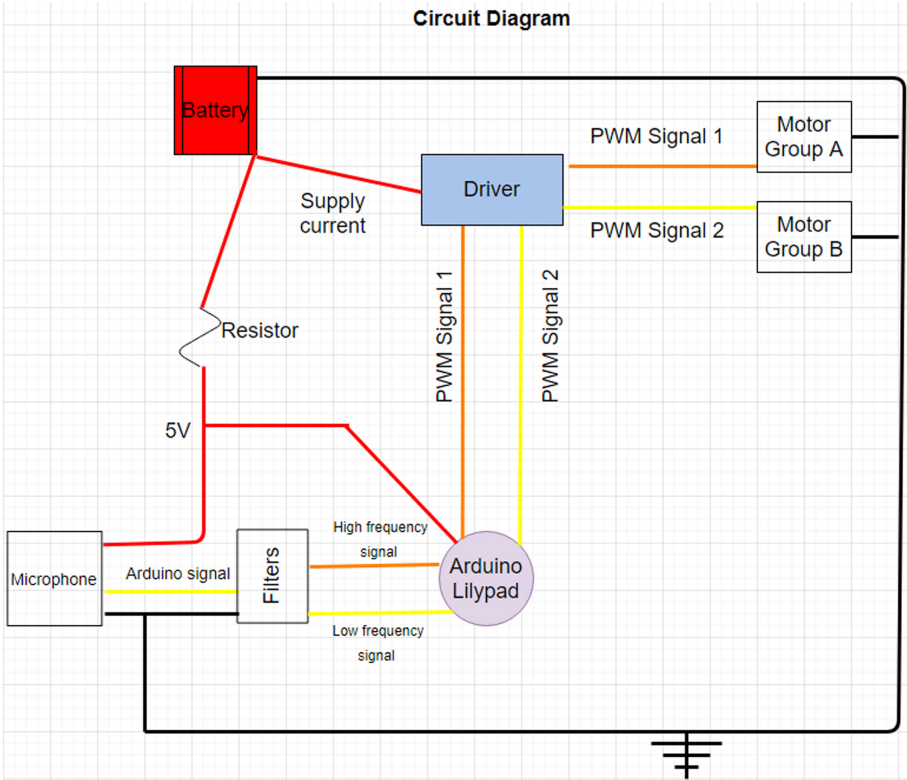


Fig. 2. Circuit design for the prototype system. Each of the PWM signals transmitted by the Arduino was mapped to one of the filtered signals. The motor drivers passed the appropriate signals to drive the motors.

The system was designed to be incorporated within a wearable band that could be worn around the head, arm or chest. Figure 3 shows the design for the wearable band. The base material was a flexible fabric with adjustable Velcro straps. The band was designed to incorporate the electronics: microphone, Arduino, battery, motor drivers and two pairs of two LRA motors each.

For the prototype that was utilized for the testing reported in this paper, Fig. 4 shows the circuit connections of the primary components and the wearable band. The band was composed of a 2-inch elastic fabric strip with pockets sewn into either side. The electronic components were sewn into these pockets in the arrangement seen in Fig. 4. The two pairs of LRA motors were wired to their respective driver modules. Wires connected the driver channel input pins and common wire to an external Arduino Uno and microphone assembly. The prototype band was made to be positioned on the head at the forehead and temple position. The adjustable Velcro strap allowed for proper fitting.

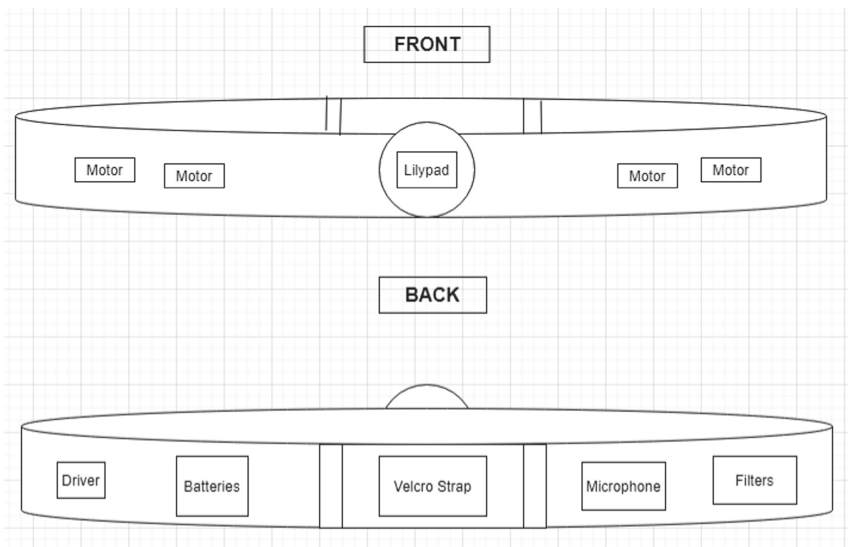


Fig. 3. Concept diagram of the headband design. All components were sewn into elastic fabric pockets with the necessary wires running around the band. Motors were placed symmetrically around the wearer’s temple with other components placed with the goal of optimizing wire length

3 Testing and Results

3.1 Frequency Detection Test

The ability of the algorithm to extract frequency values was tested by having the input sound be a constant tone of known frequency. In one trial, a tone of 440 Hz frequency was played on a sound wave generation smartphone app with the speaker of the phone placed near the microphone. In a second trial, a tone of 950 Hz was used. The results are shown in Fig. 5 with the 450 Hz trial on the left, and the 950 Hz trial on the right. The upper plots show the input waveform of the tone as displayed by the Arduino serial plotting tool. The plots on the bottom show the frequency values determined by the algorithm. In both trials, the correct frequency was often found, as shown by the upper values of ~450 on the bottom left plot and ~950 on the bottom right plot. Both also had many erroneous values of lower frequencies. This was considered acceptable for the prototype in that the algorithm to characterized recent frequency values was intentionally simple in order to not bog down the processor and allow for almost real-time characterization. The correct value, or lower values were found throughout these trials.

3.2 Volume Detection Test

While the algorithm was determining values for frequency, amplitude was also estimated to find the volume level for the recent samples. Within the code, the absolute value of the amplitude of the recent samples was calculated. This amplitude value indicated a volume level. To test this detection of volume, periodic short bursts of noise was generated near

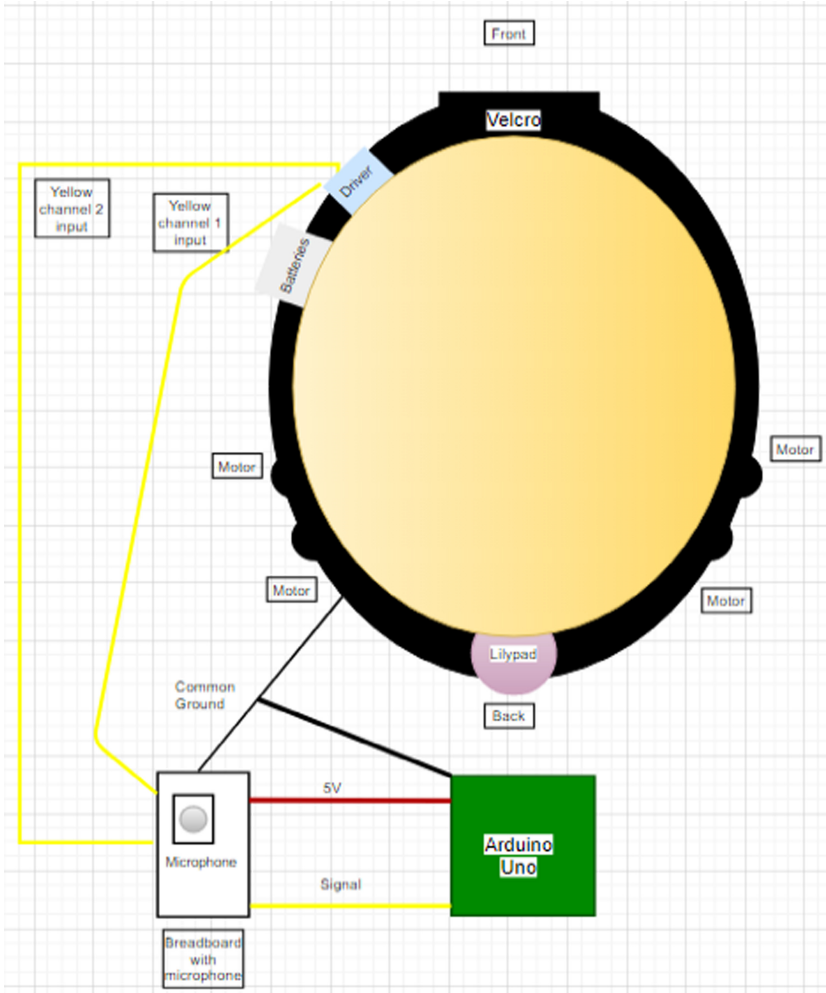


Fig. 4. Top view of the prototype. The microphone was left separate from the main headband and powered by the Arduino Uno for convenience in testing procedures and to avoid power distribution issues.

the microphone with periods of quiet between these bursts. The resulting plot of volume is shown in Fig. 5. The algorithm was able to determine an estimate of the volume of recent audio samples.

3.3 LRA Vibration for Volume Test

The volume value from the algorithm for the audio signal was used to set the duty cycle for the PWM signal to drive the motor. A higher volume value was mapped to a higher duty cycle. The higher duty cycle drove the LRA to vibrate for a larger percent of the time. The tactile sensation of vibrations with a higher duty cycle could be interpreted as

Table 1. Frequency detection for tones of constant frequency. The left half shows results for a trial of a tone having 450 Hz. The right half shows results for a trial of a tone having 950 Hz. The upper plots are the input waveforms as plotted by an Arduino plotting function. The bottom half shows the frequency. In both cases, the correct frequency was often detected as shown by the high values (~450 on the bottom left and ~950 on the bottom right), with other erroneous values having lower frequencies.

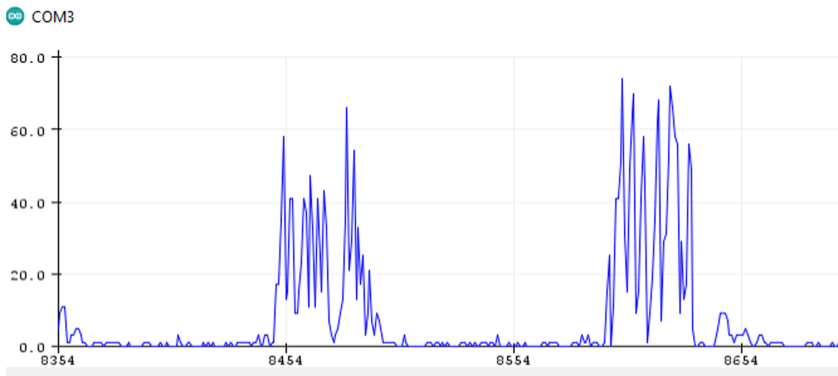
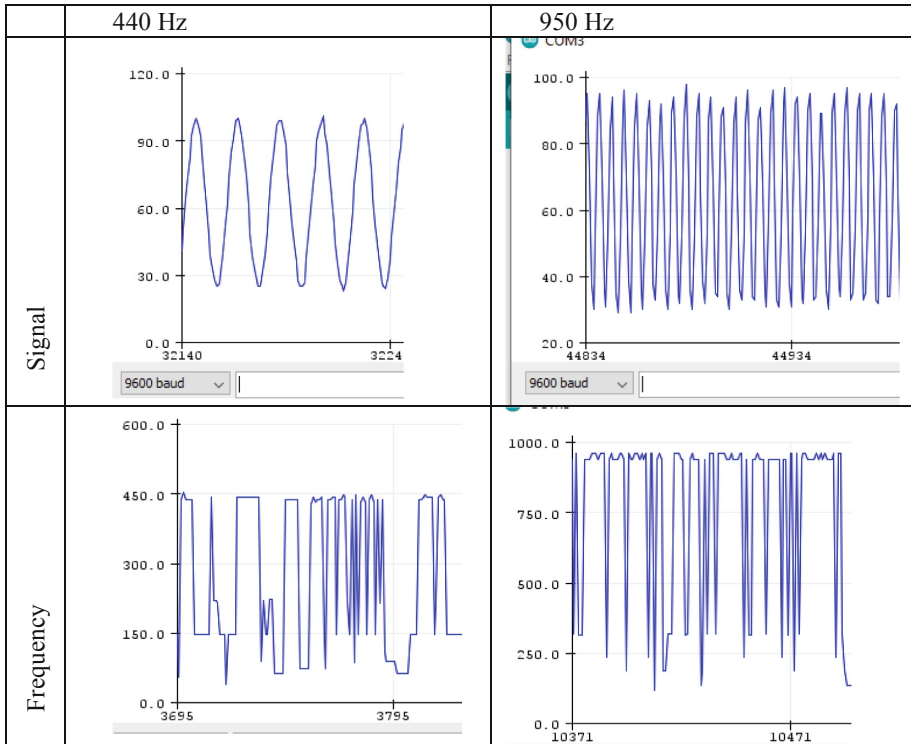


Fig. 5. Volume level of the recent samples as estimated by the algorithm.

a higher volume, and vibrations with a lower duty cycle could be interpreted as a lower volume. To have visual feedback during testing, the PWM signal was also feed to an LED. A higher duty cycle would result in a visually brighter LED, and a lower duty cycle would result in a dimmer LED. The PWM was the same one intended to drive the LRA for vibration. The mapping program on the Arduino set the duty cycle of the PWM to be proportional to the estimate of the volume of the audio waveform. Figure 6 shows the circuit used to conduct this test.

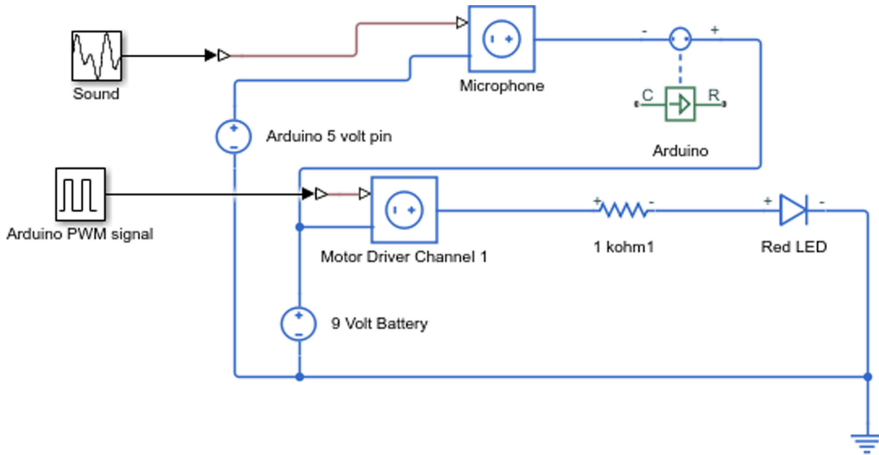


Fig. 6. Circuit of system to test the mapping of the estimate for volume of the audio signal to the duty cycle for the PWM signal. The PWM would drive the LRA for vibration. For visual feedback during testing, the PWM also drove an LED, thus the higher the duty cycle, the brighter the LED.

As audio input for this volume and PWM test, periodic bursts of vocal popping noises were generated near the microphone, with periods of silence between these bursts. The LED was observed to turn on in correlation with the bursts of noise. The louder the burst, the brighter the LED. The LRA was gently held by the fingers during this test as subjective feedback of haptic feedback. Figure 7 shows a photograph of the testing setup with LED and the LRA being held by the fingers for haptic detection of vibration.

The intensity of the LRA vibration was found to be correlated with the timing of the bursts of noise. The louder the bursts, the stronger the feeling of vibration on the fingers. This functionality was considered acceptable for the prototype.

3.4 Low Pass Filter Test

The design of the prototype had two LRAs in each pair. One LRA was to vibrate according to the volume of lower frequency sounds and the other was to vibrate according to the volume of higher frequency sounds within the music. A low pass filter (LPF) and high pass filter (HPF) were used to separate the musical content into lower frequency and higher frequency components.

A passive, single order, resistor-capacitor (RC) filter was constructed with a cutoff frequency of 339 Hz. Figure 8 shows a diagram of the LPF circuit used for testing. The

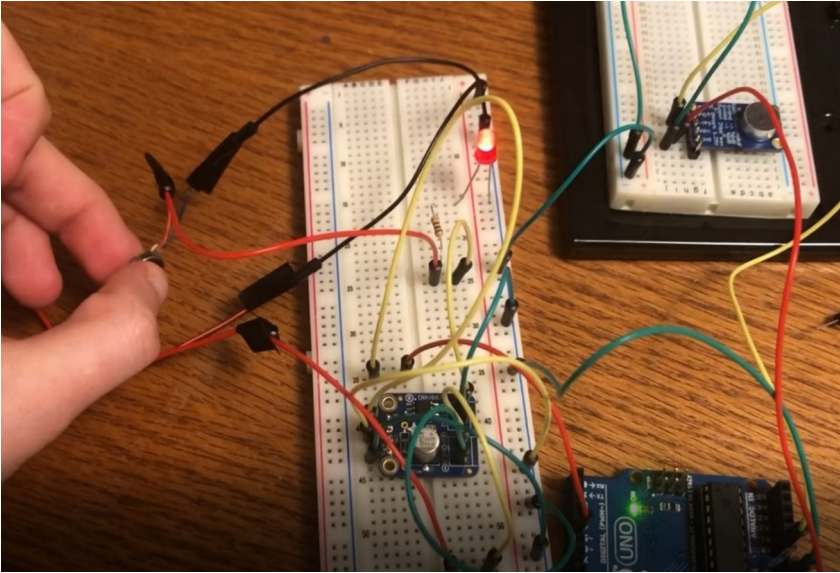


Fig. 7. Photograph of prototype during testing of the correlation between volume of the sound and duty cycle of the PWM signal. The larger the duty cycle, the brighter the LED would be illuminated and the more intense the feeling of haptic vibration as felt by the fingers gently holding the LRA.

goal of the test was to determine the level of attenuation of the signal by the filter, and the estimation by the algorithm of frequency and volume. This was done for two tones. One tone at 300 Hz, which was below the cut-off frequency. The other tone was at 2000 Hz, which was above the cut-off frequency. The voltage amplitude of the filter output could be used in future versions of the algorithm as a boundary at which the program would ignore the signal and not determine the frequency values.

For the tested LPF with a cutoff frequency of 339 Hz, the LPF was observed to attenuate by ~33% the average amplitude of the 2000 Hz tone compared to the amplitude of the 300 Hz tone. According to the theoretical Bode plot for such a LPF, even higher frequency tones would be expected to be attenuated even more. In either case the algorithm was still able to detect the frequency value. Such a LPF and a HPF could be used to separate the frequency content of music into lower and higher frequency components, but the separation would be sharp, and much overlap in frequency content would occur. In the further testing of the prototype for this paper, the filter was not utilized.

3.5 Dual PWM for Two LRAs Test

This was a test to see if the system could generate two different PWM signals to drive the two LRAs. The algorithm on the Arduino calculated an estimate of the frequency and volume of recent samples of the audio waveform. Then the value for volume (regardless of the corresponding frequency) was used to generate the PWM to drive the first LRA. Then, only the volume that corresponded to frequency values above the threshold of 1 kHz was used to generate the PWM to drive the second LRA. In intension was for

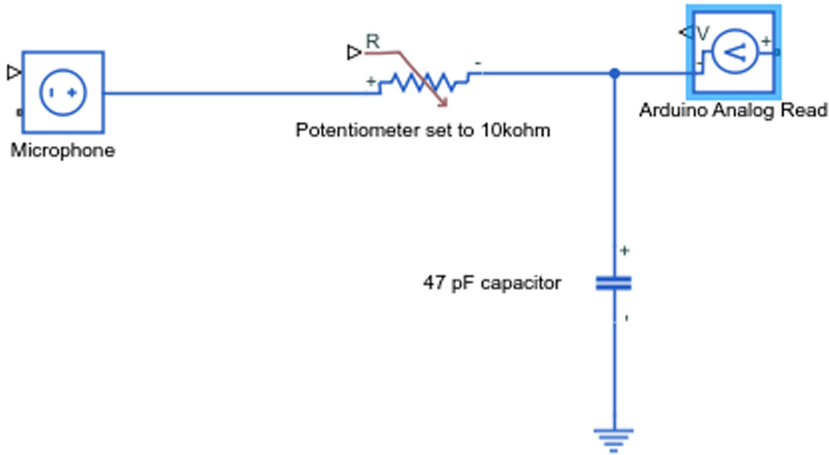


Fig. 8. Passive LPF circuit composed a resistor and a capacitor. The cutoff frequency of the filter was 339 Hz.

the motors to be driven differently depending on the corresponding frequency. Figure 9 shows a diagram of the system used for this test.

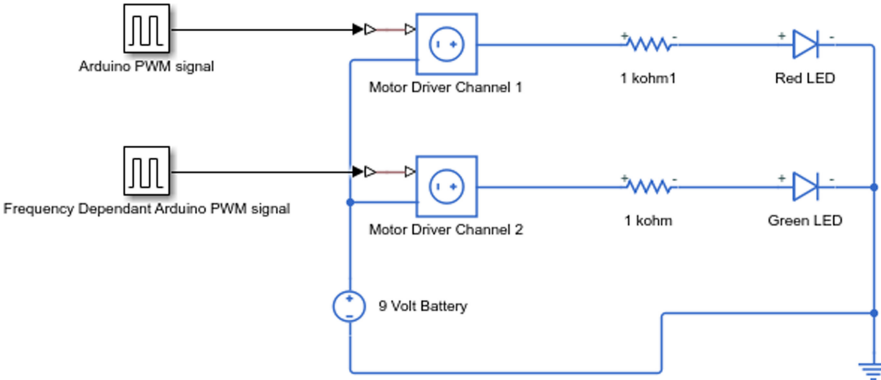


Fig. 9. Dual channel test circuit. Cannel 1 receives a PWM signal mapped to the amplitude of the signal transmitted from the microphone. Channel 2 receives the same PWM signal only when the program indicates that the sound is of greater frequency than 1 kHz.

The LED's responded as intended with the red LED varying in brightness with the sound's volume and the green LED only activating when its respective frequency is played. The green LED pulsatd due to the clipping of the calculated frequency. This clipping, as displayed in Tables 1 and 2, is caused by occasional inaccuracies in the algorithm's calculation. The incorrect frequency values fell below the green LED's minimum frequency thus prompting the green LED to turn off for that instant. The periodic deactivation of the green LED mimicked the pulsing behavior that was intended

for the secondary LRA, thus this clipping was utilized to pulsate the high frequency motors.

3.6 Response to Music

The purpose of this test was to observe the system’s response to music. Three songs of different genres were played in a large room on television speakers and the program’s interpretation of the sound’s volume and frequency. These specific songs were selected because they varied from one another in tempo and rhythm which would likely be represented in different volume and frequency patterns calculated by the algorithm. The test examined how the volume of the input music affected the boundaries of the recorded volume and frequency. Each song was played once at higher volume and a second time at a lower volume with a sample of the transmitted signal, amplitude and frequency collected at a random point in the song. The results were intended to establish reasonable boundaries of volume and frequency that would be calculated by the algorithm when responding to live music.

The songs selected for the test were as follows:

Song 1: “Through the fire and flames” by Dragonforce
 Genre: Hard Rock

Song 2: Ben Matthews’s cover of “Don’t you leave me here” by Jelly Roll Morton
 Genre: Smooth Jazz

Song 3: “Came a long way” by Dark Chocolates
 Genre: Rap

Table 2. Amplitude and frequency of music samples

Song	Peak amplitude		Frequency (Hz)	
	High speaker volume	Low speaker volume	High speaker volume	Low speaker volume
1	35	30	100–6400	200–4200
2	40	35	65–1900	190–3800
3	40	32	300–2000	300–4700

The algorithm running on the Arduino Uno could not detect a volume above 40 or a frequency above 6500 Hz in any of the song samples. These values will be used as the maximum boundaries of these parameters in the program.

Table 3. Prototype test results

Subject 1							
		1	2	3	4	5	Accuracy
Control	Played	2	3	1	3	2	0/5
	Reported	Unheard	1	Unheard	Unheard	Unheard	
With headband	Played	2	1	3	2	2	3/5
	Reported	2	1	3	3	3	
Subject 2							
		1	2	3	4	5	Accuracy
Control	Played	3	2	1	3	2	1/5
	Reported	Unheard	Unheard	Unheard	Unheard	2	
With headband	Played	3	1	3	2	3	2/5
	Reported	3	1	1	3	2	
Subject 3							
		1	2	3	4	5	Accuracy
Control	Played	1	3	2	3	1	0/5
	Reported	Unheard	Unheard	Unheard	Unheard	Unheard	
With headband	Played	3	2	1	3	1	0/5
	Reported	Unheard	Unheard	Unheard	Unheard	Unheard	

3.7 Song Differentiation Test

The completed prototype utilized two pairs of parallel motors. Each pair was connected to an independent channel of the motor driver. The driver’s voltage output for each channel was controlled by the Arduino which transmitted the amplitude mapped PWM signal to each channel’s signal input pin. One channel only transferred the PWM signal when the sound’s frequency was above 1 kHz. The driver drew current from the lithium polyester battery to drive the motors in accordance with the signals transmitted by the Arduino. The microphone remained on a separate board for testing purposes but was attached to the appropriate Arduino pins with long wires as shown in Fig. 4.

The three test subjects were not deaf or hearing-impaired, and were able to hear sounds in their daily life. However, during the haptic tests they could only feel the vibrations generated by the LRAs in a headband they wore. They wore noise canceling headphones to prevent being able to directly hear the song being played. Before testing procedures began, the test subjects were introduced to the three songs to familiarize them with their respective tempos, rhythms and tones. In this test, each subject wore the headband and a pair of active noise canceling headphones to simulate impaired hearing, so that they would not directly hear the song. In the control test, the music was played from a smartphone and the subject was asked to guess which of the 3 selected songs was currently playing. If the subject could discern the music without the influence of the

headband, the music volume was reduced. When a volume at which the subject could not discern the song at least 4/5 times was identified, the vibration program's maximum volume was adjusted to that volume. The subject would then be asked to guess the song being played at that same volume with the assistance of the active headband. By chance alone, a subject under these conditions was expected to guess the correct song 1.6/5 times. After the tests were conducted, the subjects were asked for suggestions on how to improve the comfort and appearance of the prototype (Table 3).

With the assistance of the headband, test subject 1 was able to guess the correct song 3/5 times while test subject 2 was able to guess the correct song 2/5 times. Songs 2 and 3 were most often confused for each other and as noted by the test subjects, felt similar or too similar to each other to consistently distinguish through vibrations. The similarity in vibration patterns between these two songs could be due to the similarity of the input parameters noted Table 2. When asked for suggestions on improving the comfort and appearance of the band, subjects 1 and 2 noted that the wires were obstructing their faces and were more comfortable when they put on the headset with the motors and wires against the back of their heads. Test subject 3 was unable to distinguish any of the songs correctly claiming that the motors were experiencing high levels of noise and did not vary in intensity. This could be the result of the sensitivity changes that were made to cater to subject 3's ability to hear which greatly differed from that of subjects 1 and 2.

4 Conclusion and Future Directions

The prototype system produced mixed results during the pilot test for assistance with discerning music songs. A more dynamic user experience would be required to accurately represent music, thus, the inputs and outputs of the system should be developed more. The primary testing had the vibration band worn on the head, but other locations were not yet tested, such as around the chest or arms. Future designs could incorporate improved filters to separate frequency components of the music. Motors with a wider range of vibration frequencies, such as Piezo actuators could be utilized. Reorientation of the components within the wearable band would also improve comfort and practical aspects of the system.

Further development on mapping of aspects of live music with haptic vibrations is necessary toward wider application. Such systems could enhance the ability of hearing impaired and deaf individuals to experience aspects of live music. Such experience might improve feelings of community with others listening to the music and potentially allow for other benefits of music on mental health.

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