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Aurora: Embodied Sound and Multimodal Composition

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satisfaction of the requirements for the degree
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by

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ABSTRACT OF THE DISSERTATION

Aurora: Embodied Sound and Multimodal Composition

by

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Dr. Paulo C. Chagas, Chairperson

This dissertation explores vibrotactile and vibroacoustic sensation as a mode of communication due to my own experience as a hard-of-hearing individual and musician. As a practicing audio engineer, I recognized a need in the industry for a more direct method of sound reproduction. Studios using near and mid-field audio monitors heavily rely on pure acoustics, and as a result incorporate the room as a function of frequency response which can vary wildly—even from studios within the same facility. Piecing together my experiences as a DJ, audio engineer, and music producer, I began to understand the relationship to music and vibrations, namely how certain synthesis and processing activities within the digital realm can have dramatic effect on the loudspeaker in the physical realm.

Manufacturers of transducers, and audio reproduction equipment have also recognized this relationship, and have created tools and instruments to help composers and end-users feel the unique relationship between sound and vibrations; however, composers are ultimately limited by which reproduction format the end-user chooses to experience the

work and the limited adoption of physical sound reproduction tools to allow end-users to experience the strange sensation of feeling sound.

This dissertation details five separate experiments to understand how specialized actuators (device that help perform mechanical action) called tactile transducers function. The experiments explore refining elements a of vibrotactile system to provide a more reliable acoustic and vibrational representation of a sound source. The experiments realized an enclosed purely-vibrotactile device with specifications that are comparable to a traditional loudspeaker design. This realization triggered an entrepreneurial journey that culminates in the creation of startup EDGE Sound Research.

Through this applied experimentation, I create three scales of embodied audio technology, the largest of which is the presentation of *Aurora*—a three-movement multimodal installation that demonstrates several compositional techniques to include embodied audio. These experiments are to help illustrate a scalable method of sound reproduction that engages the spectrum of hearing and hard-of-hearing participants by enhancing micro-vibrations that naturally exist when reproducing higher-frequency sounds via vibrotactile and vibroacoustic methods.

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Dissertation Framework

This dissertation shall explore physical sound, my own personal relationship with sound, and new contributions in the form of experiments to create a multimodal tactile-audio technology. Capabilities of this technology were necessary to perform *Aurora:* a three-movement multimodal installation that demonstrates several embodied audio compositional techniques. The experiments in this dissertation detail intense skill acquisition over the course of several prototypes in pursuit of the large-scale installation. As such, the dissertation is broken up into four distinct chapters:

1. "Introduction" explores existing research in the field of sound interaction including physical, philosophical, psychoacoustic concepts from both a hearing and hard-of-hearing perspective.
2. "Development of Embodied Sound Technology" details the outcomes of curated experiments. These experiments were used to develop electrical engineering, mechanical engineering, and industrial design skills necessary to build embodied audio devices capable of performing *Aurora*.
3. *"Aurora* - Multimodal Embodied Installation" shares build challenges, logistic challenges and the resulting creative compromises. The assessment is a self-review on the stated objectives from the Dissertation Prospectus, and notated program notes illustrate key moments of the piece.
4. Conclusion and Next Steps summarizes prior chapters of the dissertation and describe plans for future experimentation and research.

Chapter 1: Introduction

Sound as Radiation

Sound is pervasive in our everyday life, and careful observation allows us to realize how much sound actually interacts with almost every physical action. An audible ‘click’ can signify a successful impression of a selection on a machine, a deep and single ‘thud’ of a door indicates quality of workmanship, and little ‘beeps’ indicates a successful connection of two digital devices. After pitch training, an ear can hear discrepancies of oscillations of an instrument that are slightly faster or slower than other similar instruments within an ensemble, and even further, if harmonics of a performer's timbre are too excited and clash with the harmonics of another performance within a summed mix. This ubiquity of sound quickly places the sonic sensory experience into great importance and consideration - not unlike other research involving the senses, as even a minuscule change can have significant impact.

Even though we already face a nearly constant exposure of this stimulus, we still willingly subject ourselves to sustained exposures of sounds in the form of music. For the purposes of this discussion, I will define music as a collection of pre-determined vibrations (notes, sounds, etc.) that interact (harmonize) consonantly or dissonantly with each other. It is also the performance and organization of these vibrations to serve an effect on both a direct and indirect observer. A direct observer has intent and expectation to subject their senses to the vibrations, while an indirect observer does not. Consider a large-scale musical event, where a large group of direct observers (audience) are engaging in their expected experience, but the several neighborhoods surrounding the venue are also experiencing the sonic impact with or without explicit consent to receive the experience. This is also true of personnel that work within the venue—janitorial staff, concession staff, administrative staff, and security staff who work in the proximity of the stage and loudspeakers to prevent fans from interfering with the performance. Several smaller examples can be made from music within a store at a shopping center, a modified car sound system that is audible to a passerby, even headphones being audible beyond the listener's direct sensory area.

However, not all bodies share the same mechanisms to recognize and react to sonic stimulus and rely on different modalities for interpreting the sonic information of our world - which has a direct consequence on the quality of a shared experience. While this dissertation is not focused on discussing the experience of the hard of hearing population, some experiences and approaches can be shared with hearing populations. Different modalities of detecting sonic information might seem odd at first, but interpreting sound as a form of radiation can assist with creating a model of interaction that can be scaled to both hearing and hard of hearing populations, creating a pathway towards a more equitable 'listening' environment.

One model refers to sound as a sort of radiation.[1] Since sound waves can be thought of as radiating spherical ripples from an oscillating source, this 'radiation' perspective seems to fit most of the connotations involving our understanding of the sonic 'source'. In the 'traditional' method: a loudspeaker generates a series of pressure waves, allowing a

1. Anahid Kassabian, "Ubiquitous Listening," in *Ubiquitous Listening: "Affect, Attention, and Distributed Subjectivity"* (University of California Press, 2013).

microphone or other sensory receptor to pick up on the variance of pressure waves to interpret the source oscillation. However, consider the amount of sonic information created and the ubiquitousness of consumption through nearly every environment—some sort of synthetically generated or re-created sound is almost always present in our common areas. For example - shopping in a supermarket with the business's own music tracks creating an intended 'atmosphere', or individual shops at a mall trying to diversify and separate themselves with distinct musical choices, or even phone calls and watching television is not interacting with the authentic origin, but a facsimile of the source. With this omnipresence of synthetically designed or naturally occurring acoustic information, we are constantly interacting with some sort of sonic signature—forcing our consciousness to either adopt, adapt, or contend with its presence.

However, what if the normative or traditional pathway is compromised? Radiating energy is only effective if there is a way to transfer that energy or information—a radio frequency can only be picked up if the receivers' antenna is resonating and sympathetic to the frequency of the transmitter's antenna, otherwise the energy and embedded information is not transferred and lost to the invisible handshake. For this reason, it is worthwhile to consider that while our ears constitute an effective pathway to pick up sonic information, other senses also give us information of a source's oscillation patterns.

To this end, another model has described normative sound studies as 'earcentric'[2,3] where considerations involving sound are primarily focused on human ears as the sole or at least the main sensory pathway, incorporating the limitations they contain. However, a sound experience interacts with many modes of sensation outside of hearing including, but not limited to: visual, tactile, muscle memory, proprioception, and movement—all modes of interaction cochlear implant (CI) users employ due to the effect of their implant on their main sonic sensory pathway.[4] The CI modes of auditory compensation do not challenge and are consistent with our traditional understanding of the physical properties of sound: oscillations of energy that transfer through a substrate—with air as the historically sole substrate to be addressed.

It is no secret that sound travels differently when the substrate is affected: dense materials like water allow certain frequencies to travel further, whereas the vacuum of space is effectively a perfect absorber. It would logically follow that we should expand considerations of materials when considering factors that impact a sonic experience. For example, when presenting a pre-recorded performance such as a DJ set, concert, or live event, considerations should be taken as to what material is present in the environment that

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2. Douglas Kahn, "On vibrations: cosmographs," *Sound Studies* 6, no. 1 (2020/01/02 2020), https://doi.org/10.1080/20551940.2020.1713509, https://doi.org/10.1080/20551940.2020.1713509. referring to Sophia Roosth's criticism of Jonathan Sterne's approach to human sensory input regarding sound.

3. Sophia Roosth, "Nineteen Hertz and Below: An Infrasonic History of the Twentieth Century," *Resilience: A Journal of the Environmental Humanities.* 5, no. 3 (2018), https://muse.jhu.edu/article/702677.

4. Kate Gfeller et al., "Practices and Attitudes That Enhance Music Engagement of Adult Cochlear Implant Users," Community Case Study, *Frontiers in Neuroscience* 13 (2019-December-24 2019), https://doi.org/10.3389/fnins.2019.01368, https://www.frontiersin.org/articles/10.3389/fnins.2019.01368.

may affect the signal. Often, the signal was painstakingly generated within a specific controlled environment to have a specific effect on the listener, and any alterations to the environment will result in changes to the listener's experience of the piece. For example: a highly harmonically complex piece of music (like a song from several Metal genres) which was created in a highly treated studio environment will likely not fare well when played back within highly reflective surfaces of a museum. Assuming the museum has hard walls and floors, harmonics and overtones from the signal will continue to resonate between the surfaces, overlapping the continuous new complex harmonic information of the music. The same piece may sound much better in a velvet-lined room of a treated acoustic listening home studio, or a small venue with curtains lined around the audience to absorb latent reflections.

When considering a signal even in a typical acoustic earcentric environment, several alternate transmission methods are available in order to capture a faithful representation of the source signal. Take the example of two people speaking to each other: when the first person speaks, there are visual body cues, detectable tactile vibrations of their chest cavity expansion as they laugh, appendage motion, facial emotional cues, body temperature, textural sensation of skin/clothing, etc. All of these senses help determine authenticity of the experience - there is indeed a person trying to convey information to another person, using the modes available to them.

With the increase of digital availability, I believe there is a growing case to claim that we are losing authenticity of source; the old 'quality vs quantity' argument. Reflecting on the rise and cultural adoption of video calls during the coronavirus crisis: the *quantity* of virtual meetings can increase, but the communication is not rich with *quality*. Instead of two or more people meeting within a certain distance of each other with rich multimodal interaction, a virtual meeting is an equal distribution of rectangles featuring visual facsimiles of the other persons, with an acoustic facsimile of their voice using the bare minimum needed to communicate since the transmission is also heavily compressed.[5]

Considering this, one could therefore classify this research as simply studying energy transference. Studying energy transference allows us to understand the physical mechanisms of how an idea can be transmitted or communicated via various modes of sensation. I would like to understand how to leverage these mechanisms to increase the perceived authenticity of a transmitted source.

In this dissertation, I propose a multimodal composition exploring the relationship between modes to allow the observer to become closer to the idea I wish to communicate. I have written such a composition about the global warming crisis called *Aurora* that relies on multiple modes to fully express my emotional relationship to the subject matter. While current technology exists to blend visual and acoustic modes, I discover that the current state of the art with regards to vibrotactile and vibroacoustic technology falls short to blend the acoustic and tactile modes necessary for my piece.

To address the current state of the art, I propose alternative use-cases and configurations for specialized actuators called tactile transducers as a method of transmitting signal directly to a body. This is to improve reliability of sonic transference

5 Compression in this case means loss of information vs lossless signal transfer rather than volume control of a dynamic signal.

and introduces the ability to create tactile perception in higher frequencies. This approach is based on understanding of how energy (and therefore vibration) is transmitted through substrates and perceived in the body. Through the combination of at least three modes communicating this energy to the audience's senses, I hope to present *Aurora* with the impact I imagined during the compositional process.

Douglas Kahn describes seasons as the natural human experience of oscillation: hot, cold, hot, cold.[6] This oscillation is "dependent upon a tropospheric stability that no longer exists".[7] The dichotomy of temperature extremes affects the substrate that most people rely on for sonic transference. *Aurora* advocates to face our actions, while exploring the adaptation to a new modality of sonic perception.

6. Kahn, "On vibrations: cosmographs," 11. Referring to Marxist sociologist Henri Lefebvre's comment in *Rhythmanalysis*

7. Kahn, "On vibrations: cosmographs," 11.

Background Research

Personal Motivation

The motivation to explore research vibrotactile and vibroacoustic sensation is due to my experience as a hard-of-hearing individual, musician, and audio engineer. As a practicing audio engineer in Los Angeles, I recognize a need in the music industry for a more direct method of sound reproduction. Engineers use near and mid-field audio monitors which heavily rely on the room's acoustics, and as such, incorporate the room as a function of frequency response which can vary wildly—even from different rooms within the same studio. *What if there were a way to couple the sound directly to the user, bypassing the effects of the room?*

Growing up as a hard-of-hearing child, I had a lot of difficulty perceiving higher frequencies—roughly 2kHz and above—causing me to miss out on certain sibilant phonetics[8] and location-specific information. Perhaps this is the reason that lower frequencies have appealed more to me. Regardless, the discrepancy is observable in my life, as I noticed myself gravitate towards tactile, non-pitched percussion instruments, and bass-focused music like electronic dance music (EDM).[9]

I have been fascinated with audio since my father would play his New Order and Eiffel 65 CDs in his cars that featured premium sound systems. These 80s electronic artists had (to me) a noticeable and tactile bass presence, with newer artists in the late 90s/early

8. Any sound that makes a 'hissing' sound, including 's', 'z', 'sh', and 'zh' sounds.

9. My somewhat conservative environment veered me away from hip hop or R&B at the time.

2000s like Lou Bega and Madonna expanding on that frequency bandwidth, embracing bass frequencies that would require subwoofers or a large format speaker system to perform the intended experience.

As I transitioned from listening to creating my own music in the early 2000s, my mixes would be rather 'muddy'[10] and unclear, or 'too harsh'[11] which can be heard in my works created between 2008 and 2012.[12] There was a noticeable issue of *translation* from my idea to car or other consumer-available speakers. When I was consciously trying to avoid these issues, my mixes would then have *intelligibility*, but lacking in *articulation* of individual elements. Two components of my informal education contributed to my applied learning:

1. Professional DJ activities, which taught me about the properties and uses for different types and brands of loudspeakers.
2. Music production activities, where I developed digital audio recording and synthesis skills while observing their response on meters and other visual plots.

As I experimented, I began to piece together an understanding of the relationship to music and vibrations, namely how certain synthesis and processing activities within the

10. 'Muddy' is a colloquial term used in music engineering that describes an instrument or sound that lacks high frequency information to allow important timbral information to come through to distinguish from other instruments at the same volume.

11. 'Harsh' or 'harshness' is another colloquial term used in music engineering that describes an instrument or sound that has too much high frequency or harmonic overtone information in relation to the fundamental frequency, which decreases intonation confidence of the performance.

12. A frequency analysis would show that I focused on bass and high-end sounds too much, and over-compressed my mid frequencies, creating a Phil Spector-esque wall of sound response.

digital realm can have dramatic effect on the loudspeaker in the physical realm. The results from these learnings can be observed in my works completed between 2013-2016, with 2017 and beyond seeing commercially competitive properties in my own music. [13]

Major Players

Others have also recognized this relationship and have already begun to create tools and instruments that help people feel the relationship between sound and vibrations. There appears to be continued interest and compelling projects that are being produced with respect to both excitation and tactile audio technologies. Companies using tactile-audio technology are growing rapidly, as both startups and early adopter organizations. Key players as of 2019 were Subpac, Woojer, Lofelt, and Drown Audio. As of April 2023, only Subpac and Woojer remained on this list. Drown Audio saw early reviews in 2020, but nothing since.[14] Lofelt has pivoted from selling a discrete hardware product—Basslet[15]—to providing an open API software solution for other companies such as Qualcomm[16] and

13. Properties such as dynamic range, frequency response, and perceived loudness

14. "Drown Tactile Earphone Review," Game Rant, September 4, 2020, accessed 27 April, 2022, https://gamerant.com/drown-tactile-earphone-review/.

15. "The 'basslet' puts a haptic subwoofer on your wrist," Engadget, May 13, 2021, accessed April 27, 2022, https://www.engadget.com/2017-01-06-the-basslet-puts-a-haptic-subwoofer-on-your-wrist.html.

16. "Qualcomm's new partnership aims to improve haptic feedback on Android devices," The Verge, February 23, 2021, accessed April 27, 2022, https://www.theverge.com/2021/2/23/22297285/qualcomm-lofelt-haptics-vibration-snapdragon-888-api-software.

Android.[17] Lofelt was acquired by Meta (formerly Facebook) September 2nd of 2022.[18] Each of these companies were formed within five to ten years, seemingly to indicate that founders, investors, and the public are optimistic and betting about the future of wearables/tactile audio.

Human interaction researchers like Dr. Maria Karam have assembled a chair called Emoti-Chair that features rows of transducers traversing the length of the spine. Each pair of transducers covering a specific frequency band, with the lowest frequencies being produced near the base of the spine, and the highest frequencies closest to the upper back/neck.[19] The Emoti-Chair was developed in 2010 to be an interactive Tactile Music Exhibit embodying the research of Karam's 'Model Human Cochlea' (MHC) which translates sound to skin perceiving audio information. Meanwhile Composer/performer Dr. Lauren Hayes has explored the relationship between computer and electronic performer by using custom haptic feedback interfaces in a myriad of live performance situations.[20]

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17. "Lofelt's new haptics framework is ready to bring good vibrations to Android," The Verge, May 19, 2021, accessed April 27, 2022, https://www.theverge.com/2021/5/19/22440206/lofelt-vtx-ax-wave-haptic-framework-qualcomm-7-8-series-snapdragon.

18. Crunchbase, "Lofelt," (2023: Crunchbase, April 30, 2023 2023). https://www.crunchbase.com/organization/lofelt.

19. Maria Karam et al., "The emoti-chair: an interactive tactile music exhibit" (CHI '10 Extended Abstracts on Human Factors in Computing Systems, Atlanta, Georgia, USA, Association for Computing Machinery, 2010).

20. Lauren Sarah Hayes, Michael Edwards, and Martin Parker, "Audio-Haptic Relationships as Compositional and Performance Strategies" (dissertation, 2013).

Compositional Significance

As a composer, having a new technique for musical expression is like learning a new language: if your expression does not come across the way you want in one language, then you would attempt to use another. Likewise multi-instrumentalists began to develop techniques for one instrument, while learning other methods to perform an idea on another. Soon a performer can combine these modalities and methods to create a new sensation that can only be generated by cross-pollinating techniques together. [21] With the advent of digital synthesis, the limits of timbre virtually evaporate, as almost any sound and any timbre could be generated from layering small voltages.[22] Furthermore, all sounds can also be recorded and processed to deliver the desired timbral effects due to modern digital signal processing (DSP).

However, composers are ultimately limited by the reproduction format the end-user chooses to experience the work through. Consider the compositional feedback process during the analog era.[23] one of the only options to experience a large format work composed for a full symphony orchestra was in an auditorium that was painstakingly designed to deliver a certain acoustic performance to the audience. If a composer was fortunate enough to have access to the full orchestra while they were rehearsing at that specific auditorium,

21. Joanne Armitage and Ng Kia, "Multimodal Music Composition," Electronic Workshops in Computing, January 2013, https://doi.org/10.14236/ewic/eva2013.7.

22. "An Introduction To Additive Synthesis," Sound On Sound, 2004, accessed April 27, 2022, https://www.soundonsound.com/techniques/introduction-additive-synthesis. This is the foundational premise of additive synthesis.

23. Before recording capabilities became commonplace in the late 1800s/early 1900s.

only then the composer would have an idea of how the audience would receive the end result. Otherwise, the composer would have a skewed perspective of how the written notes would potentially impact the audience once the piece is premiered in the auditorium.

The history of recorded music and the effect on composition is thoroughly documented through complaints and comments by both players and composers during the late 18th-early 19th centuries as phonographic technologies were developed.[24] It is not a question of if, but of how much music perception changed over this time, as players could now confirm their performance, and overwrite their mistakes. A conductor could capture the perfect performance and share the captured signal with others who may have no way of ever attending the event.

Today, the same piece could be delivered in a multitude of digital formats, each more compressed and condensed than the last. For example, a composer can send an entire orchestra performing the grandest piece for you to experience right now in your own house via a streaming service, or even on a little device in your pocket via smartphone, or even on your wrist! An entire symphony orchestra—Mahler's Symphony of 1,000—right on your wrist—on demand. The scale of condensed convenience would have rendered composers of yesteryear speechless. However, the question must be asked - *is that going to be the same experience?*

24. Leonard M. Marcus, "music recording," in *Encyclopaedia Britannica*, ed. The Editors of Encyclopaedia Britannica (Britannica Group, October 09 2020). https://www.britannica.com/topic/music-recording.

While digitization has brought an element of consistency to the delivery method of the mastered file, there is still a similar concern for those who would have otherwise engaged in the traditional compositional journey. For example, in this age of digital distribution, the end-user experience is almost always unknown, and a composer[25] has almost no way of truly knowing how the end-user will consume the piece. There is no consistent method beyond metering tools at the digital source for a composer to know or understand how an audience may be exposed to the performance and must trust their own estimation of how the emotion will survive the digital reconstruction at the point of consumption.

To aid with uncertainty, recent guidelines from the Recording Academy,[26] mastering guidelines from streaming services.[27] and other broadcast standards[28] have helped to give targets to producers, composers, and engineers alike. Popular streaming services like Spotify, Apple Music, YouTube, and TIDAL processing playback to allow a

25. For this argument, I mean "composer" to include "music producer" which, in my own definition, is a composer who also programs sound design elements into the composition.

26. Leslie Ann Jones et al., *Recommendations for Hi-Resolution Music Production*, Recording Academy - Producers and Engineers Wing (Los Angeles: Recording Academy, September 28 2018), https://www.recordingacademy.com/sites/com/files/recommendations_for_hires_music_production_09_28_18.pdf.

27. "Help - loudness normalization – spotify for artists," Fans Make it Possible – Spotify for Artists, Spotify USA, Inc., 2021, accessed Aoril 28, 2022, https://artists.spotify.com/help/article/loudness-normalization.

28. EBU, "Operating Eurovision and Euroradio," (June 2021 2021). https://tech.ebu.ch/docs/r/r128s2.pdf.

normalized experience to ensure loudness between contrasting genres/creators is not vastly overwhelming.[29]

With the new standard processing to comply with regulations, how can I make sure *all* of the elements I program in my composition will be present on my audience's devices when they access my composition? After all, how could I control if someone is listening on their smartphone or watch device, with speakers that are not ideal to reproduce the frequency information necessary to accurately perform the piece? Other than changing every consumer's behavior, there must be an alternate method for the average consumer's body to interact with audio, so that even small devices can deliver the full range of frequencies and provide a better audio experience than a traditional acoustic speaker of a similar size.

There is also the perspective that the composer is not responsible for the end-user experience. Since the invention of the loudspeaker, the high-fidelity (Hi-Fi or HiFi for short) speaker industry has emerged in pursuit of an 'ideal' sound experience, regardless of the composer's intended vision. In fact, this spirit and intention outlined in H.A. Hartley's Audio Design Handbook[30] is the reason behind the 1950s High-Fidelity movement in the first place. Consumers were encouraged to change components from their systems to other components that would bring new 'colors' to the sound.[31] This often meant

29. Ian Stewart, "Mastering for streaming platforms: Normalization, LUFS, and loudness myths demystified," (June 24, 2014). https://www.izotope.com/en/learn/mastering-for-streaming-platforms.html.

30. H.A. Hartley, *Audio Design Handbook* (New York: Gernsback Library, Inc., 1958).

31. Hartley, *Audio Design Handbook*, 127.

using different materials in cabling or circuitry that would impede or improve electrical flow, causing efficiency gains or losses in certain frequency bands.

HiFi originally came about because mass-produced speaker technologies found in radios or television sets simply could not reproduce music in the full dynamic range, full frequency spectrum, or both in most cases. This was typically due to concessions made during the design for manufacturing process, as higher-quality elements are difficult to source at the cost needed for mass adoption.

As audio technologies have improved over the decades, the performance gap between mass-produced and HiFi speakers has significantly decreased. However, we are approaching a similar platitude in audio innovation, as consumers settle into the form factors of speakers as the only option for sound reproduction, limiting expectations of creative form-factors. Essentially, 'small' speakers are expected to either have a wide frequency band, and quiet volume (studio reference monitor), or a loud volume, but very narrow frequency response (megaphone/public address system).

By directly coupling to a user, even the smallest device can reproduce the entire acoustic range through combining acoustic and vibrotactile modes of reproduction. My contribution to this field shall be the evaluation of a proposed system of technologies that enhances existing haptic/tactile and acoustic technology to ensure not only low-end bass response, but an extended broadband tactile frequency response that also allows a reliably consistent embodied acoustic response among myriad reproduction scales. I will attempt to create a small system and a large-format system to evaluate frequency response at vastly different scales. Ideally, Mahler on the wrist would feel more similar to Mahler in a concert hall (or at least that part of the wrist will feel like it!).

'Feeling' Sound

The concept of feeling sound is fairly simple at first glance - you feel what you hear. The actual practice of obtaining information from another sensory organ besides your ears yields a much more difficult practice. For example, when you feel something while you hear something, the two experiences are intertwined, and your brain associates the distinct senses into a single sensory experience.[32] Possibly the most common understanding of 'feeling sound' is when someone experiences bass/sub frequencies during a music concert or performance. This concept is even more critical for the Deaf and Hard-of-Hearing (D/HH) community, as one of the primary ways of interacting with music or sound is through feeling.[33] Percussionist Evelyn Glennie is known for performing barefoot on stage, as the typical wooden floor of a concert stage can transmit vibrational sound energy into her feet where she can keep time with the other performers. Glennie reflects on her relationship with her sense of hearing:

> Hearing is basically a specialized form of touch. Sound is simply vibrating air which the ear picks up and converts to electrical signals, which are then interpreted by the brain. The sense of hearing is not the only sense that can do this, touch can do this too. If you are standing by the road and a large truck goes by, do you hear or feel the vibration? The answer is both. With very low frequency vibration the ear starts becoming inefficient and the rest of the body's sense of touch starts to take over. For some reason we tend to make a distinction between hearing a sound

32. Joanne Armitage and Ng Kia, "Multimodal Music Composition," *Electronic Visualisation and the Arts (EVA 2013)* (2013): 40-41, https://doi.org/10.14236/ewic/eva2013.7.

33. Michele Friedner and Stefan Helmreich, "Sound Studies Meets Deaf Studies," *The Senses and Society* 7, no. 1 (2012/03/01 2012), https://doi.org/10.2752/174589312X13173255802120.

and feeling a vibration, in reality **they are the same thing…If we can all feel low frequency vibrations why can't we feel higher vibrations?** It is my belief that we can, it's just that as the frequency gets higher and our ears become more efficient, they drown out the more subtle sense of 'feeling' the vibrations.[34]

Glennie's experience as a musician may contribute to her questioning the possibility of feeling higher frequencies. As a musician, the tonal relationship between vibrations is heightened versus non-musicians as the desire to stay in tune in relation to the rest of the ensemble is paramount for accurately recreating the composed work.[35] Hopkins et al. share several studies that show how the musical tonal relationship, enhanced with vibrotactile stimuli, can facilitate musical interaction between other musicians.[36] The article suggests a limited bandwidth of detectable frequencies on the fingertips (up to 400Hz), the authors also highlight that vibration at the fingertips trigger activity in the auditory cortex representative of hearing the same frequency. Glennie's experience as a musician and background as a hearing individual before losing her hearing corroborates the relationship observed between tactile perception and triggers within the auditory cortex. This is a possible reason why Glennie believes she can perceive a much wider range of frequencies via tactile perception than what the existing literature suggests.

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34. Evelyn Glennie, "Hearing Essay," (2015). https://www.evelyn.co.uk/hearing-essay/. **Emphasis added**.

35. Carl Hopkins et al., "Perception and learning of relative pitch by musicians using the vibrotactile mode," *Musicae Scientiae* 27, no. 1 (2023), https://doi.org/10.1177/10298649211015278.

36. Hopkins et al., "Perception and learning of relative pitch by musicians using the vibrotactile mode."

There are several instances of D/HH children, teenagers and young adults listening to music on big loudspeakers, blasting loud or bass-heavy music to create vibrations they can feel.[37] I can personally relate since I used to rest my legs and fingertips against the large woofers and subwoofer drivers of my father's loudspeakers and in-car audio system to achieve the same end. While not all D/HH people are completely deaf, most cannot rely on their ears as a reliable method to engage with the source audio, so feeling sound is one of the common compensation methods used. The same goes for those who have elected to receive a cochlear implant.[38] For my own experience, after contextual clues and reading lips/captions, trying to feel sound is my next most reliable compensation method to understand speech, and even more so when trying to understand detailed information of a complex audio source like music.

In the age of web conferencing during COVID-19 pandemic, I found myself having trouble understanding others unless I was almost entirely focused on reading their lips—since I lost the body-vibration aspect of someone speaking. To help regain that sensation, I used either a tactile transducer or a large speaker while asking the person to use 'original sound' mode (which allows a higher fidelity audio stream to be sent to me) to re-train my body to understand the nuances of zoom's compression algorithm as it relates to the reproduction of the human voice. When people were on the go and meeting from their phones while out and about with masks on, it was virtually impossible for me to understand

37. Friedner and Helmreich, "Sound Studies Meets Deaf Studies," 75-78.

38. Gfeller et al., "Practices and Attitudes that Enhance Music," 6.

what people were saying in the early days, since I couldn’t read lips and the phone microphone processing appeared to engage severe frequency cuts with strong compression to the source signal in order to decrease background noise and isolate the speaker’s voice. After about a year, my senses adapted, and my contextual compensation ability has become more capable to allow calls via web conferencing; however, I still employ Google Meet’s live captions whenever possible to help me follow a conversation.

There are also those who may not fall into a deaf/hard of hearing category but still rely on vibrations to obtain reliable communication, these can be musicians, mechanical engineers, automobile drivers, pilots, and more.[39] Continuous vibrational feedback can indicate, for instance:

1. Performing in time with each other
2. A machine is operating at optimal efficiency
3. The amount of resistance in an automotive engine - informing gear shifts
4. Analyzing intensity or speed of a thermal gust, informing whether to latch onto the thermal or stall and allow it to pass.

These are all examples of physical vibration-body interaction of sound, which is one of the earliest interactions we have with the physical world as human beings e.g., experiencing our mother’s voice and heartbeat in the womb.[40]

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39. Yoren Gaffary and Anatole Lécuyer, "The Use of Haptic and Tactile Information in the Car to Improve Driving Safety: A Review of Current Technologies," Review, *Frontiers in ICT* 5 (2018-March-26 2018), https://doi.org/10.3389/fict.2018.00005.

40. Alexandra R. Webb et al., "Mother’s voice and heartbeat sounds elicit auditory plasticity in the human brain before full gestation," *Proceedings of the National Academy of Sciences* 112, no. 10 (2015), https://doi.org/doi:10.1073/pnas.1414924112.

Limitations of 'Feeling' Sound

Gfeller offers a unique insight into how those with limited 'hearing' (via Cochlear Implant surgery) compensate by relying on other senses to fill in the gaps lost from the procedure. These compensation methods include visual, tactile, muscle memory, proprioception, and movement[41]—not unlike those in the D/HH community who shared their own compensation methods with me. Cochlear Implant (CI) users, and more specifically—musicians with a CI—are a unique set of persons who have a larger dependence on hearing through touch than a hearing-normative person, and can be representative of the learning and translation process to alternative modalities of sonic perception.

One researcher studying how sound is perceived in CI users is Dr. Raymond Goldsworthy of University of Southern California. Goldsworthy is a former drummer and Associate Professor of Research Otolaryngology, specializing in Head and Neck Surgery from the USC Keck School of Medicine. As of April 2022, he was spearheading a grant from the National Institutes of Health (NIH) in support of the Sound Health Initiative to restore music to CI users.[42] We have discussed in length about the support tactile information can give to someone with abnormal hearing function, using both of our individual backgrounds and colloquial conversations with others as informal data points.

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41. Gfeller et al., "Practices and Attitudes that Enhance Music," 6-8.

42. Raymond Goldsworthy, "Cochlear implant advancements to include music recognition capabilities." https://medresources.keckmedicine.org/news/cochlear-implant-advancements-to-include-music-recognition-capabilities.

He showed me some of the research his team is doing, particularly from Biomedical Engineering doctoral student Susan Bissmeyer and Interdisciplinary Media Arts and Practice program PhD Candidate Juri Hwang. I met with Bissmeyer and Hwang and participated in some of the exercises they had set up for their subjects[43] who were CI users with a musical background.[44]

My performance in one of the study activities surprised me, as the experiment involved being sound masked with noise reduction headphones while depressing a fingertip on a bone-conduction transducer held within a box lined with acoustic foam and being tasked with identifying the higher of two pitch tones emanating from the transducer. While I performed well in lower frequencies (40-80Hz), my sensation of the frequencies began to drop over 100Hz, even though I am comfortable feeling those frequencies when I place fingertips on my speaker drivers when mixing music. Based on my prior experience of other transducers, one of the possible explanations of my poor performance was that the bone conduction transducer did not efficiently deliver higher-frequency vibrations well beyond the resonant frequencies of the device.

For instance, during my preliminary explorations of distributed mode loudspeakers (DMLs) at UCR's Experiential Acoustic Research Studio (EARS), I was certain I detected higher frequencies from the panels. I wondered if introducing more power or signal to the

43. Susan R. Bissmeyer, Juri Hwang, and Raymond L. Goldsworthy, "Pitch perception conveyed by cochlear implant and tactile stimulation," *The Journal of the Acoustical Society of America* 146, no. 4_Supplement (2019), https://doi.org/10.1121/1.5137567.

44. Goldsworthy, "Cochlear implant advancements to include music recognition capabilities." under “Bringing implant users together for a common purpose”

system at the point where the vibration drop-off occurred would enable me to more accurately detect even higher frequencies.

Gfeller indicates while strong problem-solving tactics are among CI users, there is still an immense struggle to acquire the necessary skills to interact with complex harmonic representations of sound.[45] While Gfeller doesn't necessarily indicate a relationship with speakers, an intuitive dissection into the results along with the work from Dr. Goldsworthy's team can begin to unravel the reason why the disassociation with existing sound infrastructure exists, and an opportunity that it creates.

Perceived Sonic Authenticity of Events

Traditional speakers are not designed to reproduce the vibrations that we expect from sounds created in the physical world. Generally, speakers appear designed to connect with the inversely designed acoustic receptors to our body's natural pathway—the small tympanic membranes in our ears. However, the multimodal pathways in which we experience real-life sound sources are not always emanating from a single point or cannot be faithfully reproduced with stereo configurations.

There's an immediate and pressured response when a physical-world sound happens nearby that even a high-fidelity sound system with a subwoofer cannot faithfully reproduce. Of course, the truest way to reproduce the sound would be to reproduce the event. However, the state of the art does not include a way to faithfully re-execute an event

45. Gfeller et al., "Practices and Attitudes that Enhance Music," 6-7.

without significant financial and logistical burden, so we look to recordings to faithfully capture acoustic pressure waves created by the event for exact reproduction at a later moment. ***However, do current recording and reproduction technologies contain the fidelity necessary to faithfully reproduce an event?*** And even beyond that - ***how would the event be perceived by the listener?***

There is a very interesting relationship between reality and perception of a sound event that has become increasingly ever-present in my research. For example, if I created a sound event—it could appear to sound extraordinarily different to me, a hard of hearing musician, as compared to someone with a much more sensitive hearing system, or a non-musician CI user. The field of psychoacoustics, a subsection of psychophysics, attempts to understand this relationship, and attempts to quantify the shared perception of acoustic events.

For example, the Fletcher-Munson equal loudness contours (and resulting phon scale) quantified perceived loudness across all audible frequencies.[46] By capturing the results of several test subjects, the researchers were able to calculate a reasonable average baseline for threshold of hearing (quietest), and the threshold of pain (loudest). This eventually led to our existing International Organization for Standardization (ISO) standard

46. Willian A. Yost, "Psychoacoustics: A brief historical overview," *Acoustics Today* (2015). https://acousticstoday.org/wp-content/uploads/2015/08/Psychoacoustics-A-Brief-Historical-Overview.pdf.

226:2003.[47,48] However, while quantifying perceived loudness across all frequencies helped to consistently calibrate acoustic systems, that information by itself does not remedy the missing information to faithfully recreate the sound event so that the event is perceived to be more realistic.

'High'-Fidelity

The attempts to achieve sonic realism of sound events come in the form of increased resolution of acoustic sound events reproduced with acoustic systems. However, when analyzing the total pathway of an acoustic signal—consider the following:

Current recording industry standards for high-fidelity recordings rely on signal-to-noise ratio (signal:noise), as well as a high sampling rate to capture the widest broadband frequency range as possible.[49] A high-fidelity microphone can boast a very wide signal-to-noise ratio (SNR) (the difference between the loudest sound a microphone can record, and the point where the signal would be indistinguishable from noise), and a wide usable frequency bandwidth of at least 20Hz-20kHz (the 'full' bandwidth of human hearing). For example, the premium M50 microphone by Earthworks Audio, costs $1,299 and features a signal-to-noise ratio of 140dB SPL, and an effective bandwidth of 3Hz-50kHz.[50]

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47. ISO, "ISO 226:2003(en) Acoustics — Normal equal-loudness-level contours," (2003). https://www.iso.org/obp/ui/#iso:std:iso:226:ed-2:v1:en.

48. There's a whole saga about how the Robinson-Dadson's curves were temporarily considered more accurate than Fletcher-Munson before the ISO determined that Robinson-Dadson's curves were the odd one out. One can only imagine it was quite the scandal.

49. Jones et al., *Recommendations for Hi-Resolution Music Production*, 6.

50. "M50 - 50khz measurement microphone," Earthworks Audio, accessed April 28, 2022, https://earthworksaudio.com/measurement-microphones/m50/.

Even a microphone of this caliber still must be fed into an analog to digital signal converter (ADC) before it can store the signal. This can have a limitation on bandwidth and the ratio between signal and noise. For example, one of the most well-known audio interfaces was made by UK brand Focusrite and uses the Cirrus Logic CS4272 ADC converters.[51] The integrated circuit (IC) features a stated signal-to-noise ratio of 114dB on the manufacturer's website, even though the interface is marketed with an effective dynamic range of 111db and a bandwidth of 20Hz-20kHz.[52,53] This discrepancy could be introduced by subpar materials or intentionally designed filtering into the circuit board. Furthermore, the ADC chip within audio interfaces may have been upgraded to a higher sample rate, but other digital hardware may limit the whole system to 48kHz sampling rate, which most other budget or cheap audio interfaces/CODECs use as a maximum sample rate. One can start to understand how layers of signal degradation occur just within capturing the sound event to a computer.

The digital signal would then be brought into one of the many digital audio workstations (DAW), or other software that would expect an unbiased signal, at the sample rate that the recording device can handle. Depending on disk speed, disk space, processing power, and connection throughput, this may limit the session to import all audio files at a

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51. Chagalj, "Audio interfaces and their AD/DA chips LISTED," December 14, 2021 2021, https://gearspace.com/board/showpost.php?p=5913037&postcount=1 (April 28, 2022).

52. "CS4272," https://www.cirrus.com/products/cs4272/.

53. "Scarlett 2I2," Focusrite PLC, https://focusrite.com/en/usb-audio-interface/scarlett/scarlett-2i2.

lower sample rate or bit-depth.[54] For example, even though I have a fast processor and SSD storage drive powering an audio interface capable of 192kHz multitrack recording, I still record at 48kHz since I don’t have very much disk space on my notebook (2018 MacBook Pro) nor on my desktop studio computer (2013 ‘trash can’ Mac Pro), forcing me to choose between high quality (96kHz+) and huge project files, or much smaller files with decent quality (48kHz). My workflow may change as the Los Angeles internet infrastructure improves bi-directional internet transfer speeds that can support faster large uncompressed sound files streaming from network drive options like Google Drive.

Without even considering digital to analog converters (DAC) on the way back out towards reproduction for the listener, nor the amount of distortion present in reproduction methods, one can begin to understand how improving acoustic fidelity has multiple potential pitfalls across the *entire signal chain* of capturing, processing, reconstructing, and ultimately ***reproducing*** the signal to maintain a faithful execution of the event—in just the acoustic space. I maintain the position that even ***if*** ultimate acoustic fidelity is met, acoustic pathways alone will not faithfully recreate an authentic sonic event, since true reproduction will need to include some element of tactile capture and reproduction.

While more research is needed in these fields, any efforts towards capturing and converting purely acoustic signal will see negligible improvements unless a major innovation in sound reproduction is introduced first. Otherwise any effort towards any aspect earlier in the acoustic chain would not be faithfully evaluated. A high-fidelity

54. Bit depth determines how many available discrete steps of volume there are available for a single-point position of a sound wave.

reliable tactile reproduction method is a contender to serve as an solution for many more consumers to have the same response of high-end studio/lab equipment, where improvements to aspects of sound capturing and conversion will become more relevant.

Current Actuation Methods and Driver Technologies

The state of the art, at the time of writing, observes several similar actuation methods which cover the perceivable sonic magnitudes (2-20-200-2,000-20,000Hz). Infrasonic/subsonic/super low frequencies (~2-40Hz) use linear actuation drivers such as those used in simulation racing setups which are used for positioning and large-haptic movements. These tend to have a long throw (excursion distance), but very limited bandwidth from 1-10Hz, such as the PA-15 High Speed Linear Actuator sold by Progressive Automations.[55] Servo subwoofers and transducers allow for precise control of frequency and amplitude up to 150Hz, such as the M-Force 301P02 by Powersoft.[56] Traditional subwoofers and other low frequency drivers driven by traditional voice coil technology overlap around 20-200Hz depending on diaphragm diameter and maximum excursion distance. Smaller diaphragm-based speakers (woofers, mid bass, full-range,[57] soft-dome tweeters) cover various magnitudes with slight alterations to compensate for limitations that become problematic due to size constraints. These drivers usually do not cover more than two magnitudes of frequency ranges very well unless heavy signal processing is introduced, which can introduce unintended artifacts. On the very high frequency range (2,000Hz - 20kHz and beyond towards ultrasonic), piezo crystals and

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55. "High Speed Linear Actuator," Progressive Automations, accessed April 28, 2022, https://www.progressiveautomations.com/products/tubular-high-speed-linear-actuator.

56. "M-force 301P02 - powersoft," Powersoft, accessed April 29, 2022, https://www.powersoft.com/en/products/transducers/m-system/m-force-301p02/.

57. While claiming full-range, often these drivers just cover most of the audible range with large biases towards one side or the other.

MEMS tweeters can be used instead of traditional voice-coil ‘tweeter’ offerings. There are other niche methods of creating sound, such as the HyperSonic Sound system or Holosonics' Audio Spotlight that uses modulated ultrasonic waves to disrupts the air around a user's ears—creating audible vibrations,[58] but I would not consider this as a viable general speaker alternative due to the price to performance ratio and niche use cases where it would out-perform a traditional speaker.

Exciters and bass shakers are examples of tactile transducers that share the same foundational actuation methods—often using voice coil technology sometimes paired with pistonic motion (usually with bass shakers) to emulate linear actuation sensation via inertial force. While I acknowledge the existence of haptic-motor and narrow-bandwidth actuators, I will limit the scope of investigation to transducers that are capable of wide-band reproduction of a complex input signal and therefore capable of musical performance.

A Brief History of Tactile Transducers.

Exciters are used to excite a surface or substrate in order to emanate sound from the surface plane.[59] Exciters are often the actuators of distributed-mode loudspeakers (DMLs), which is a common panel form. These systems attempt to create ‘invisible’ sound systems without visible/obvious traditional speaker drivers with large cones.

58. F. Joseph Pompei, "The Use of Airborne Ultrasonics for Generating Audible Sound Beams" (San Francisco, California, United States, 1998).

59. A. Dumčius and L. Bernatavičius, "The Research of the DML Loudspeakers Properties," *ELECTRONICS AND ELECTRICAL ENGINEERING* 88, no. 8 (2008).

The origin of excitation technology comes from Dr. Ken Heron's work for the Defense Evaluation and Research Agency (DERA) in the U.K., looking for ways to decrease cabin noise in upcoming fighter jets and air machines.[60] While the original objective was not achieved to the desired results, Farad Azima - chairman at loudspeaker company Mission Electronics - recognized the potential for audio reproduction, and brought the technology to Verity Labs, overseen by CTO and brother of Farid, Henry Azima.[61] After establishing viable prototypes, Verity Labs formed NXT after filing a patent for Distributed Mode Loudspeakers (DML). NXT did not appear to actualize their full potential, eventually falling from grace right around the 2008 recession, however not before filing the patent the DML's eventual apparent successor in 2006: the Balanced Mode Radiator (BMR),[62] albeit under the name "Audio Full Range" or "AFR".[63] Both exciter-based bending wave and BMR technologies are actively being commercialized by Tectonic Audio Labs as of April 2023.

Larger tactile transducers, or bass shakers, are to be used in conjunction or to replace a subwoofer. bass shakers are often designed to be inertial drive transducers,[64]

60. "NXT: When a Little Chaos is Good For You," Audio magazine, Davidson College, 1998, accessed April 22, 2020, https://www.phy.davidson.edu/FacHome/dmb/py115/NXTflatpanel/NXTflatpanel.htm.

61. , The Engineer, 2002, accessed April 22, 2020, https://web.archive.org/web/20200923122543/https://www.theengineer.co.uk/flat-hi-fi-speakers-in-performance-breakthrough/.

62. "About Tectonic," Tectonic, 2019, accessed April 22,, 2020, https://www.tectonicaudiolabs.com/about-tectonic/.

63. The Engineer.

64. "Tactile Sound 101: Technical Manual," White Papers, Clark Synthesis, 2018, accessed April 22, 2020, https://clarksynthesis.com/wp-content/uploads/2018/07/White-Paper-Tactile-Sound-101.pdf.

swapping the mechanically moving unit from the voice coil adhered to a plastic former (like in exciters) to a design where the magnet itself being suspended and moved.[65] Since the magnet is often heavier than the voice coil, the physical movement of the magnet is enough to experience a tactile sensation, without adding another moving weight to the system—although some still do. Bass shakers come in several sizes and power ratings from 10s to 1,000s of Watts, whereas only a few models of exciters are available above 50 Watts since normative applications (DMLs) would not be able to withstand a large pushing force (nor do they require it).

Due to the internal movement, bass shakers are often designed to be securely attached and felt, whilst exciters are designed to be heard via a substrate. Companies like SUBPAC and Woojer take advantage of the ability to feel the vibrations from moving magnets in their portable wearables that deliver a strong, subwoofer-like, frequency response felt when coupled to the body. Otherwise, their acoustic performance appears like a weak/small subwoofer—note the peak sound pressure level (SPL) just barely reaches above 100dB and only at the device's resonant bump at 40Hz:

65. The R&D team of EDGE Sound Research opened one of the 'puck' transducers to look inside.

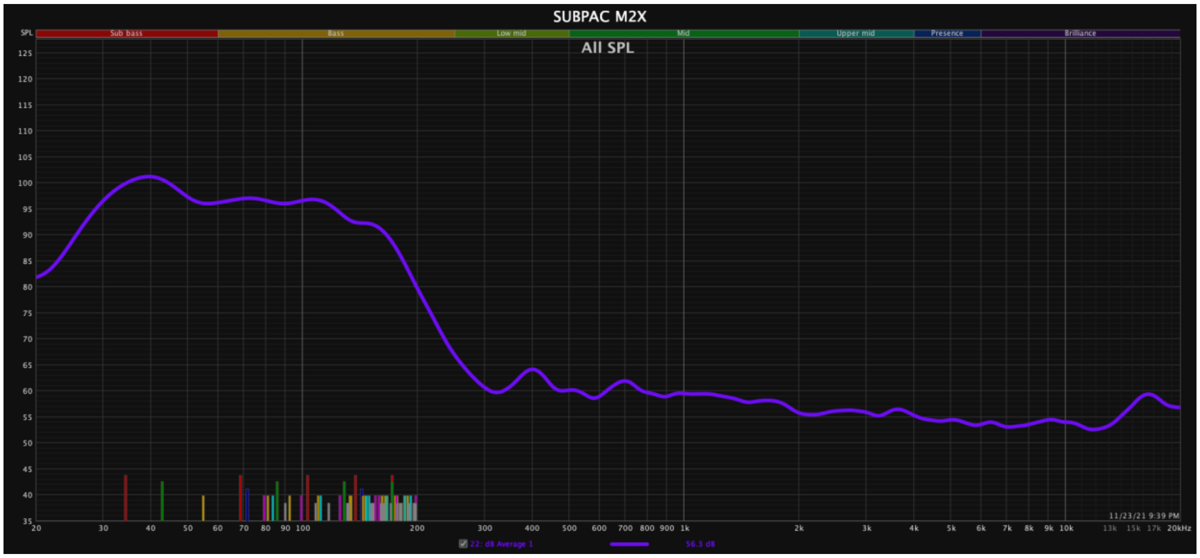

Figure 1: Frequency Response of Subpac M2X

I took this measurement and created this screenshot with Room EQ Wizard (REW) software, and a Dayton Audio OmniMic V2, which is a microphone designed for precise measurement of acoustic systems. Each microphone is calibrated at the factory, and the user is provided with the calibration file to use with software that can make use of the calibration.

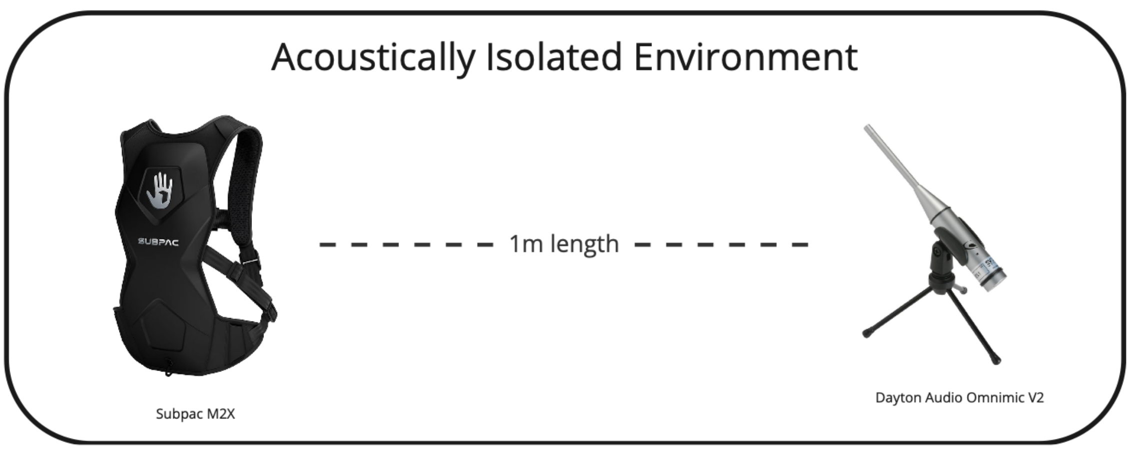

Figure 2: Measurement setup: OmniMic v2, 1m away from Subpac M2X to obtain frequency response

By contrast, here is a REW screenshot of the frequency response of the Sonos Move—a 'premium' full-frequency acoustic system showing a strong and stable frequency response from 40-20kHz:

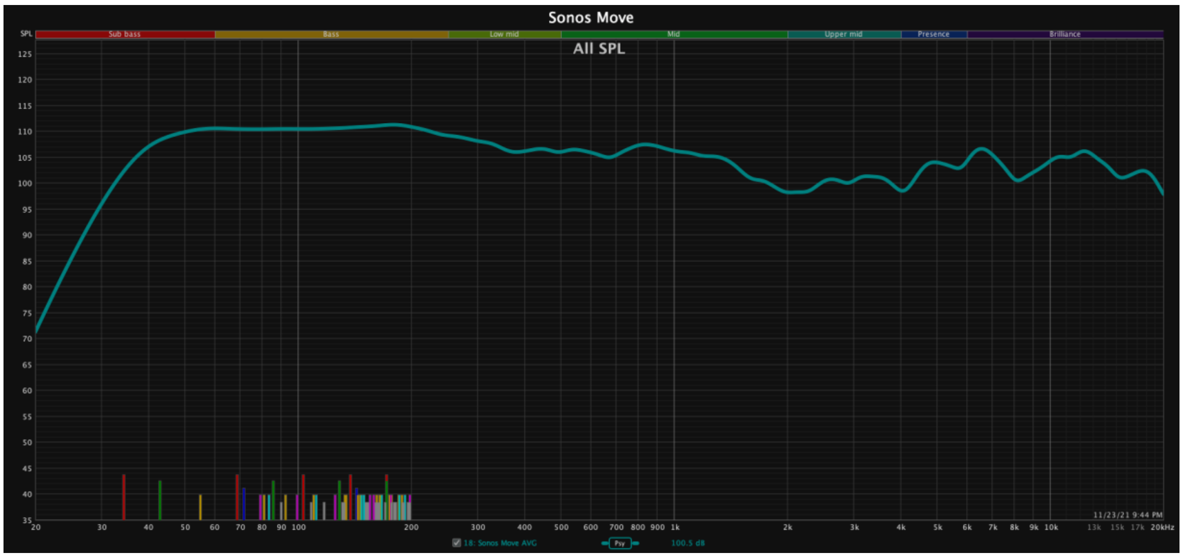

Figure 3: Frequency response of Sonos Move - contains one mid woofer and one tweeter

My Contribution to the Field

Why Not Tactile Transducers?

With my research, I sought to answer the question proposed in my prospectus: why are tactile technologies such as exciters and their larger bass-shaker brethren not seen in areas of professional or discerning audio spaces? The following is a preliminary position from discussions and observations from my time working in Los Angeles as an audio engineer:

Exciters are generally approached to create Distributed Mode Loudspeakers (DMLs) by attaching and exciting a panel of material. DMLs are intended to be used as dipole speakers, since the excited panel is designed to be suspended on all sides, causing both sides to emit sound. Because both sides emit sound, the sound reproduction method has extra emission directions to take into consideration when acoustically treating and planning within a studio space, which makes DML and dipole speakers less than desirable for studios or critical listening applications despite their cult-like following in the audiophile forum space, especially compared to the stable speaker box industry with ample research and industry knowledge.[66]

So far, I have not come across a critical listening that space seems to consider tactile technologies as a source of reliable sound monitoring. bass shakers are advertised towards home theaters, and effect-driven systems, but DMLs, or exciters for that matter, do not

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66. This opinion is sourced colloquially from peers and various studio technologists at their own studios and at the National Association of Music Merchants (NAMM) show between the years 2014-2019. Forums such as Sterophile.com and audionirvana.org

appear to be considered a primary driver to deliver physical sound. It is likely that the waveforms are not as noticeable to most as the intense larger bass and sub-bass variants delivered by the larger bass shakers. The original question about tactile audio technologies is perhaps better suited as a sub-question of a larger question I have been seeking to answer since my youth: ***Is there a way to have a more direct method to experience sound from a source?***

Exploring Methods of 'Direct' Signal Pathways

The revised question led me to explore ways of 'hearing' without ears, since assistive technologies such as hearing aids just amplify sound—essentially forcing more signal down a pathway that has already proven unreliable to transfer signal in the first place.

From my interviews with participants and researchers from Dr. Goldsworthy's lab, I learned about inherent foundational limitations of implants when dealing with harmonically complex sounds like music. To keep implants small, light, and long lasting, the device must be highly efficient. To keep such efficiency on such a small device, the processor must choose specific critical bands within the auditory nerve to excite, aiming to cover enough of the acoustic spectrum to make speech intelligible.[67] Speech frequency bands do not always correlate with music frequency bands, especially for small intervals

67. John C. Middlebrooks, Julie Arenberg Bierer, and Russell L. Snyder, "Cochlear implants: the view from the brain," *Current Opinion in Neurobiology* 15, no. 4 (2005/08/01/ 2005), https://doi.org/10.1016/j.conb.2005.06.004.

in higher registers, which makes some instruments and genres of music inaccessible for CI users.

Even closer to the auditory cortex, brainstem implants bypass the inner ear and auditory nerve completely to place an electrode at the mating location of the brain and auditory nerve, however the procedure remains particularly risky (brainstem damage results in active critical function impairment), and extraordinarily intrusive, while not restoring normative hearing.[68]

Tactile Audio

The balance between a direct connection of sound vs invasiveness led me to non-auditory pathways of causal listening with the intention of investigating a reliable method to receive semantic information from a digital source, such as a digital recording. I decided to try one of the other compensatory methods that Evelyn Glennie and I share as hearing-impaired percussionists - tactile perception via touch. I remember playing percussion in a symphony orchestra, using the timpani as an extension of my own tympanic membrane—but through my fingertips. I would be able to feel the pitches of the low brass instruments and tune to them through measuring the beats coming from the timpani via my fingertips, meaning I could tune without having to listen to the timpani how I was taught. After exploring DMLs and bass shakers within UCR's Experimental Acoustic Research Studio (EARS), I wondered if artificially recreating the sensation of the timpani's resonance

68. This was explained to me by Dr. Goldsworthy - the distance of travel for the auditory nerve within the cochlea is crucial for understanding resonance and temporal information. If the data comes straight to the brain, it's sort of like seeing the whole world in 2D.

against my fingers was possible, but with **any** substrate—using some sort of vibrotactile device.

A vibrotactile device supposedly delivers vibrations directly to a substrate with the express purpose of delivering those vibrations to a person in contact with the substrate. In certain cases, the substrate can be directly attached to a user in the form of a backpack like with SUBPAC, or a vest like with Woojer. Lofelt produced (for a time) a wrist worn bass transducer, while Buttkicker and others have chair-stem mounted and screw-mounted bass transducers. Like Glennie and others from the D/HH community, I pondered as to why it is comparably difficult to perceive higher frequencies through touch.

Karam's research with the Emoti-Chair indicates that the body can perceive accurate tactile information purely through skin, which is consistent with my own experience touching speakers/timpani to obtain more information. However, there does not seem to be a central consensus on the bandwidth limit. For example, Mahns et. al provides an indicator of Theo body's vibrotactile response of up to 1,000Hz,[69] but Glennie believes she and others can perceive higher frequencies through practice becoming sensitive to those frequencies.[70]

From my own experimentation with bone-conduction headsets, I can confirm my own observations that around 2kHz from the devices—my left ear then seems to dominate perception of the higher frequencies coming from the transducers within the headset rather

69. D. A. Mahns et al., "Vibrotactile Frequency Discrimination in Human Hairy Skin," *Journal of Neurophysiology* 95, no. 3 (2006), https://doi.org/10.1152/jn.00483.2005.

70. Glennie, "Hearing Essay.".

than being perceived solely from my bones. However, upon plugging my ears, my main acoustic sensory method for higher frequencies was inhibited, so it appeared that my skin-hearing pathway compensated and became more sensitive to higher frequencies from the bone conduction headset, allowing me to perceive above 2,000kHz, albeit faintly.[71]

The bone-conduction test brought forth the main issue with tactile audio and alternative forms of sound perception - ***there is no recognized or standardized way to know how a signal will carry from the source to the listener through the body***, like we have in acoustics. Ultimately, there are more tools available for traditional acoustic speakers—for example, a calibrated microphone to help alert disparities in frequency fluctuations at various points in the room. To the best of my knowledge, I am not aware of any branded microphones or specific DSP/psychoacoustic tools for tactile sound interaction.

Embodied Sound

There is much to explore about moving away from understanding sound as an acoustic experience, towards an *embodied* experience with ***acoustic input seen as one of many possible inputs to the body***. In their book, *Sonic Virtuality*, Grimshaw and Garner explore the concept of the "*sonic aggregate*".[72] They describe this as all non-auditory, non-physical, and perceptual modes of understanding a sonic event—plus the actual physical sound wave itself—to be considered together. The sonic aggregate helps to understand the

71. As of July 2022, the EDGE Sound Research team and I performed several frequency sweeps on a ResonX prototype model 503 and informally determined that I can perceive somewhere just above 5,000kHz from my fingertips.

72. Mark Grimshaw et al., "Embodied Acoustic Ecology," in *Sonic Virtuality: Sound as Emergent Perception* (Oxford University Press, 2015).

perspective of an embodied experience of sound by considering the body as a singular entity and the sound source as an external entity—with the intent to be received by the body. As the sound signal emanates from the source, there exists an expectation and anticipation of the sound via visual cues, actions, and the optional receipt of the sonic vibrations from the air that can also be felt through the body. [73,74] This meshes with the idea of *multimodality*—using multiple sensory methods to experience a singular idea or event—as a way to understand a method of experiencing sound with the body. The culmination of all modes of communicating the sonic event coalescing to the body is described by Grimshaw and Garner as a singularity event that "…is dependent on a host of factors, temporal, spatial, environmental, psychological, and physiological."[75] For example, an embodied sound experience could involve sight + sound, sound + feel, sound + taste, visual + feel, or any combination of senses that inform the transmission of a sound event.

Understanding the embodiment of sound is critical, but does not help with *creating* a truly embodied experience. Theoretically, a *true* embodied experience of sound introduces the same signal via the available modes equally and simultaneously. Speakers, while having *an* effect on the embodied experience, is not an *equal* embodied experience in most cases (unless you find yourself held in the cone of a speaker!). This is to say: just

73. Kassabian, "Ubiquitous Listening," 7-8.

74 In defining embodied sound experience, it is important to disembody sound into multiple aspects as to include the experience.

75. Grimshaw et al., "Embodied Acoustic Ecology."

because you touch a speaker and feel the vibrations from it, doesn't mean that you are getting *useful* information from it.[76]

To investigate how to create a balanced embodied experience, we must understand the nature of both embodied and acoustic perception. As mentioned by Stefano Papetti et. al from NIME 2015: "In order to design audio-tactile interactions, systematic knowledge is needed of psychophysical mechanisms related to the integration of the auditory and haptic channels."[77] With my piece *Aurora*, I created super low frequencies, as well as extraordinarily tactile and transient mid and high-frequency information that can be used to explore how the audience will respond to receiving auditory, tactile, and visual information of a series of events simultaneously. One step beyond, the audience will receive a relatively equal embodied experience of sound, which I hypothesize will impress the subject matter into them more than having simply the typical embodiment of traditional loudspeakers. One small problem: ***devices that can create an equally embodied sound experience do not currently exist.***

Vibrotactile + Vibroacoustic Multimodal Embodied Sound System

In such spirit, I propose a novel multimodal embodied sound solution for *Aurora*: a vibrotactile + vibroacoustic system emitting high fidelity physical vibrations of all audible frequencies, that will also radiate high fidelity vibrations in the air to achieve a true

76. To be fair, I used this method for years, any information is better than no information.

77. Stefano Papetti, Sébastien Schiesser, and Martin Fröhlich, "Multi-Point Vibrotactile Feedback for an Expressive Musical Interface" (Proceedings of the international conference on New Interfaces for Musical Expression, Baton Rouge, Louisiana, USA, The School of Music and the Center for Computation and Technology (CCT), Louisiana State University, 2015).

embodied acoustic + tactile sound experience. The combination introduces the body as a relevant acoustic sensory pathway so we can begin investigations into the relationship between the body's physical perception of vibrations and how it is translated to perceived acoustic information. The ears, if available and accessible, will be able to pick up a normative, substrate-corrected frequency response, with the body compensating for the limited acoustic range of substrate which is being sonically excited. The combination of the two sensations should trick the brain into a smooth crossover of the threshold between feeling high frequencies through the body vs perceiving high frequencies through the ears. Papetti warns in a separate paper that "tactile sensation can be biased by the spectral content of auditory cues" and in my case, my proposed system leans into the bias as a strength instead of a possible weakness.[78]

It is important to recognize that the system must be both vibrotactile and vibroacoustic since feeling is as significant to hearing—as hearing is to feeling. The bidirectional importance as a standard makes the negotiation happen at the point of the user's faculties, where the user will bias towards whichever sensory pathway is most developed for their body, defaulting the remaining senses to a supportive role. For example, a hearing person may default to listening with their ears, and appreciate the accompanying

78. Stefano Papetti, "Design and perceptual investigations of audio-tactile interactions," *Proceedings of AIA DAGA* (2013), https://www.researchgate.net/profile/Stefano-Papetti/publication/260436820_Design_and_Perceptual_Investigations_of_Audio-Tactile_Interactions/links/0deec5314ce1cf2dfe000000/Design-and-Perceptual-Investigations-of-Audio-Tactile-Interactions.pdf.

vibrations, while a hard-of-hearing person may rely on the vibrotactile information more than the vibroacoustic response that interacts with the room.

Therefore, an ideal listening system for professional or discerning audio spaces should be a vibrotactile device capable of producing wide bandwidth vibroacoustic frequency response, paired with either headphones or an external speaker system using complimentary technology. Complementary speaker would ***not*** include point-source traditional speakers found on most bookshelf or studio monitor systems, but with drivers that create a smooth emanative response across critical frequency bands such as the Balanced Mode Radiator (BMR).

BMRs—a cousin technology to DMLs—are a parallel hybrid technology between excitation and traditional pistonic design and offers the benefits from exciters at high frequencies, while also providing pistonic motion of a traditional woofer for low frequencies.[79] BMRs can be seen as a miniaturization of exciters panels, which otherwise have to be quite large to radiate low frequencies into an audience. Using the large pistonic motion that naturally occurs from the lowest note of a voice coil, the BMR uses the panel material as a 'cone' which pushes air from the resonating surface—just like a traditional pistonic driver in order to reproduce low frequencies.[80] Higher frequencies are delivered from exciting the panel material like a traditional DML, with both modes of acoustic transmission evenly covering the full frequency range.[81]

79. Tim Whitwell, *The Balanced Mode Radiator (BMR)*, (Woodinville, WA: 2016).

80. Tectonic Audio Labs, *TEBM35C10-4 Miniature BMR® Driver*, (Woodinville, WA: 2019).

81. The Engineer.

The ResonX + *Aurora*

While the BMR is a very promising technology, and effective in subjective tests, the technology lends itself poorly to touch-based experiences as its traditionally pistonic brethren, so the technology needed to demonstrate my proposed hybrid solution still needed to be created and tested before attempting to perform *Aurora*.

After submitting a Record of Invention (ROI) disclosure form to the school, Dr. Chagas and I were given the opportunity to either allow UC Riverside to pitch the technology for license or create a startup company that would license the technology from the university where we could have more control over the development and implementation of the invention. Teaming up with co-founder and then MBA student Valtteri Salomaki, we began raising funds and adding members to our team to create the first proof of concept, then prototypes, that would eventually lead to the creation of the ResonX™ - a smart, active, transducer array embodied in a single, attachable enclosure. The ResonX™ would be a proof of concept for the potential scaling of the technology to a large form-factor, suitable for an audience of 10-15 at a time to experience a near-true embodied sound experience.

Alongside the R&D team at EDGE Sound Research, I developed a performance platform that produces a wide frequency range: ~7Hz-17kHz, on which to perform *Aurora*, the three-movement multimodal piece that demonstrates the function and ability of a high-fidelity vibrotactile + vibroacoustic multimodal embodied sound system for multiple audience members at once.

Chapter One Conclusion

This chapter began with a discussion of my personal relationship with sound, and how that has shaped my own past works, commercial and concert. I introduced the major players involved with tactile reproduction of sound (or claim to be able to do so).

"Compositional Significance" questions whether composers can ever have a monitoring system that shows them the truest representation of their audience's perception of their composition. What if a composer creates a piece for subwoofer, but someone tries to play it on their phone, which cannot recreate those frequencies? Would we compose differently if everyone had a reliable and high-fidelity way of perceiving every frequency? I propose the utopian version of a novel broadband vibrotactile technology that could make this a reality.

In "Feeling Sound," I share stories of individuals who rely on their sense of touch to interact with sound. I also draw on my own experiences to shed light on the challenges that the world's earcentric design has introduced, particularly in the realm of web conferencing, for individuals with hearing loss. While this section acknowledges the current limitations of achieving an ideal experience, I highlight the past research by Kate Gfeller and ongoing research at the University of Southern California (USC), which offer a glimpse of the practical possibility for this ideal to exist.

To introduce the proposed novel technology, I broke down what was contained in a sonic event by following the impulse through the resulting pressure waves that are interpreted as vibrations. I followed the mechanistic pathway from impulse to perception, emphasizing the importance of each component of the mechanical system involved in perceiving a realistic representation of the original impulse.

To demonstrate how our pathways are affected by reproduction, I provided an illustration of the tools necessary for capturing sound and all the opportunities for corruption that may arise along the way. I concluded that any efforts to capture and convert purely acoustic signals would yield negligible improvements unless a major innovation in sound reproduction is introduced first.

After conducting a comprehensive review of available sonic reproduction technologies across five magnitudes (2-20-200-2,000-20,000Hz), I focused my attention on tactile transducers as the most suitable candidates for providing a wide bandwidth frequency response. Systems of tactile transducers require the fewest amount of drivers, have the lowest cost, and offer the simplest setup process since they are compatible with existing acoustic infrastructure.

In the final section, I contributed my thoughts and experience as an audio engineer and music producer to the discussion around using tactile transducers as a solution to common issues faced around critical listening with near-field monitors. I reviewed existing methods of direct signal transfer to the body and highlighted the invasiveness of the most direct methods that we had to date: Cochlear Implants and Brainstem Implants.

I then discussed using tactile transducers to directly monitor signals by compensating for the body's natural filter of higher frequencies that could mask critical frequencies. This idea was inspired by my own experience, but it was also supported by Mark Grimshaw and Tom Garner's concept of the *sonic aggregate* in "Defining Sound".

Using vibrations to stimulate multiple senses simultaneously could help confirm the perception of other senses and significantly increase confidence in accurately interpreting the source signal.

I proposed a vibrotactile device that can produce a wide bandwidth vibroacoustic frequency response. This device can be paired with either headphones or an external speaker system, making it an ideal listening system for critical listening. I proposed composing a large format multimodal installation experience called *Aurora* to demonstrate the effectiveness of wideband tactile frequency response. *Aurora* would require several critical experiments to confirm the performance of such a system, requiring new technologies to be developed to successfully perform the composition.

The next chapter will detail five experiments undertaken to explore the environment that led to the ROI, as well as the necessary steps to achieve the stated performance requirements. The following chapters will also include reasons for starting the startup, as well as implications to my own research and others.

Chapter 2: Development of Embodied Sound Technology

Overview

This chapter will examine five distinct experiments to assess the feasibility and limitations of developing a vibration-based sound device capable of producing interpretable signal across the entire acoustic frequency range (20Hz-20kHz). The resulting experiments were designed to test the feasibility of creating such a system and identify which elements—if any—are hindering the translation from the theoretical realm to reality. Traditional speaker designs use voice-coils to create a piston motion to drive a membrane to vibrate air which acts as a coupler to our ears.[82] Speaker driver designs are reflective of the human hearing range, with several types of drivers that specialize reproducing certain frequency bands such as tweeters for high registers and woofers for low registers.[83] Variants of small drivers are then light enough to reproduce a midrange and treble frequency range, while larger drivers called subwoofers reproduce very low bass to subsonic frequencies.[84]

Common enhancements to traditional speaker systems generally fall into signal processing, room design and planned acoustic treatment, unique enclosure designs (folded

82. Jay Mitchell, "Loudspeakers," in *Handbook for Sound Engineers (Fourth Edition)*, ed. Glen M. Ballou (Oxford: Focal Press, 2008), 597-8.

83. Mitchell, "Loudspeakers," 597.

84. The Editors of Encyclopaedia Britannica, "loudspeaker," in *Encyclopedia Britannica* (2020). https://www.britannica.com/technology/loudspeaker.

horn, transmission line, etc.), various styles and approaches of driver arrays, and simultaneous multichannel (stereo and object-based like Dolby Atmos).[85,86]

Advanced uncommon acoustic systems include technologies such as planar electrostatic speakers, distributed mode loudspeakers (DML) also known as bending wave or flat panel speakers, array beamforming, ambisonic systems, rotary woofers, ultrasonic acoustic systems, and other niche systems like plasma arc or thermoacoustic speakers.[87,88,89]

Certain advanced technologies, such as the aforementioned flat panel or ambisonic systems, can operate on conventional audio pathways including pre-existing signal cables and amplifier technologies. However, others, like beamforming, electrostatic, and plasma arcs, necessitate specialized and frequently proprietary amplification technologies to translate incoming signal and produce audible sound.

Alternative methods of perceiving sound information rely on representing certain temporal and spectral elements of a signal, such as an FFT graph visually representing spectral information, or an oscilloscope visually representing a short temporal history.

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85. "Active Vs. Passive Crossovers," Elliott Sound Products, 2004, accessed April 18,, 2022, https://sound-au.com/biamp-vs-passive.htm.

86. "The New 8260A Three-Way DSP Loudspeaker System," Technical Paper, Genelec, 2009, accessed March 26,, 2023, https://web.archive.org/web/20101230170304/http://www.genelec.com/documents/other/Genelec%208260A%20Technical%20Paper.pdf.

87. "Loudspeaker types and how they work," The Absolute Sound, 2020, accessed May 1, 2023, https://www.theabsolutesound.com/articles/loudspeaker-types-and-how-they-work/.

88. Lin Xiao et al., "Flexible, stretchable, transparent carbon nanotube thin film loudspeakers," *Nano Lett* 8, no. 12 (April 6, 2009 2008), https://doi.org/10.1021/nl802750z.

89. "The Art of Speaker Design," 2002, accessed March 26,, 2023, http://www.nutshellhifi.com/library/speaker-design1.html.

Recent years there have been more emphasis on tactile technologies to help deaf and hard of hearing audiences ‘feel’ sound, including Karam’s Emoti-chair and Subpac. Other approaches include encoded haptics such as CuteCircuit’s SoundShirt,[90] TeslaSuit’s Suit,[91] and bHaptics’ Tactsuit X40.[92] While these haptic options are certainly novel and interesting, they would be more likely considered as a modal representation on-par with visual graphs, as they are unable to create both temporal and spectral information necessary for an accurate representation of sound signal.

This means that tactile transducers are the only technology specifically designed to enhance a multimodal experience of sound. While other speaker technologies can be felt to some extent, they are primarily designed to deliver acoustic rather than tactile sensations.

Tactile audio systems may help include those whom communication is hindered from traditional acoustic modes, such as those in the d/Deaf and Hard of Hearing community (D/HH)[93] and those with intellectual and developmental disabilities (IDD).[94] However, while panel-based speaker systems created with excitation technology seem to

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90. "The SoundShirt," CUTECIRCUIT, 2020, accessed March 26, 2023, https://cutecircuit.com/soundshirt/.

91. "Full body VR haptic suit with motion capture," Teslasuit, 2022, accessed March 26, 2023, https://teslasuit.io/products/teslasuit-4/.

92. "Tactsuit x40," Bhaptics.com, accessed March 26, 2023, https://www.bhaptics.com/tactsuit/tactsuit-x40.

93. "How a person who is hard of hearing listens to music," HuffPost, 2015, accessed April 29, 2020, https://www.huffpost.com/archive/ca/entry/hard-of-hearing-music_b_6595252.

94. Eadric Bressel, Mandi W Gibbons, and Andrew Samaha, "Effect of whole body vibration on stereotypy of young children with autism," *BMJ Case Reports* (2011), https://doi.org/10.1136/bcr.02.2011.3834.

answer many concerns for media enthusiasts and engineers,[95] they do not address all critical use-cases, even though they use similar driver technologies.

The strong and reliable reproduction of all acoustic frequencies is not present between other tactile solutions such as Emoti-Chair, Subpac, Woojer, Flexound, Lofelt, etc., but before blindly experimenting, it is first needed to identify parameters and define what an 'ideal' full-frequency multimodal sound system would be:

Based on the subjective experience of existing solutions, and conventional aims of the high-fidelity community shared in 'High'-Fidelity, the theoretically 'ideal' sound system would be able to produce vibrotactile and vibroacoustic modes, with a frequency response +/- 3dB between at least 20-20kHz where the user can perceive most or all frequencies equally from acoustic and physical senses, or a combination of them both. This theoretical system should eliminate most acoustic issues arising from room interference or interaction and would be much more compact than a comparable traditional speaker system with the same performance specifications.

The following experiments were designed to test the feasibility of creating such a system and identify which elements—if any—hinder the translation from the theoretical realm to reality. The experiments also assist to determine whether the technological landscape of the time could support the development and potential commercialization of such a technology.

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95. Dumčius and Bernatavičius, "The Research of the DML Loudspeakers Properties," 47-50.

Introduction

Deaf percussionist Evelyn Glennie performs barefoot on stage, feeling the sound vibrations through her feet to keep time with other performers. While the concept of 'feeling sound' is easy to grasp, relying on this sensation practically is not. As mentioned in "Feeling Sound" section of Chapter 1, cochlear implant (CI) users, especially musicians with a CI, rely more on touch to perceive tonal sound than those with normal hearing. They can teach us about learning to perceive sound through alternative ways. Feeling Sound shares an example by researcher Kate Gfeller explains how CI users use visual, tactile, muscle memory, proprioception, and movement to compensate for the lack of sound perception, similar to Glennie and other hard-of-hearing individuals.

As discussed in "Current Actuation Methods and Driver Technologies" section of Chapter 1, both hard-of-hearing and normal-hearing individuals can take advantage of tactile transducers' electromechanical ability to convert sound signals into physical sensation. Examples of tactile transducers include exciters and bass shakers, which use electromagnetic actuation methods similar to conventional loudspeakers. Bass shakers and exciters are inverse designs, with the former moving a weight using the voice coil, and the latter exciting the surface to create audible frequencies directly with the voice coil attached to a substrate.

As mentioned in "Current Actuation Methods and Driver Technologies", even though bass shakers have a similar actuation design to exciters-based sound systems, they are currently used for tactile perception of sound. Meanwhile, exciters-based sound system designs are primarily used for acoustic modalities and not for their motion energy. This is because most conventional acoustic solutions deliver larger low-frequency waves compared to high-frequency content to keep their system balanced according to equal-loudness contours and how humans perceive the acoustic frequency range.

On the application side, Dr. Maria Karam's Emoti-Chair project is one of the first instances where exciters are used to deliver information to the body. As previous described in "Tactile Audio" section of Chapter 1, Karam's Emoti-Chair features rows of transducers traversing the length of the spine. Because each pair of exciters provides a specific band of frequencies to the user, the project requires both complex proprietary signal and amplification hardware and embedding of the custom transducer array into a specific seat. This approach does not provide full vibrotactile range due to the limited range of the exciter transducers, and the complex and custom nature of this form factor limits scalability and commercial reach.

By combining both vibrotactile and vibroacoustic experiences together, it is possible to create a full-range sonic experience driven entirely by vibrations, with no traditional loudspeaker technology other than the voice-coil—functioning to excite substrates instead of carefully crafted speaker cones which transfer sonic information through the air. By correcting the response of an excited substrate that a user is coupled to, a purely vibration-based system can deliver a wider bandwidth vibrotactile response directly to a user's body, potentially including the critical bands of human speech.[96]

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96. Jont B. Allen, "Harvey Fletcher's role in the creation of communication acoustics," *Acoustical Society of America* 99, 1, no. 4 (1996): 1825-26, Acoustics Research Department, AT&T Laboratories, https://acousticstoday.org/wp-content/uploads/2016/03/Allen96.pdf. As defined from Fletcher's research at Bell Labs on articulation index for speech reproduction over the early telephone network from 1920-1933

Distributed Mode Loudspeakers and Tactile Stage

Objective

It was the hypothesis that even small acoustic waves associated with higher frequencies can be detected by the body with varying degrees of success. It has been understood that frequencies up to 1kHz are detectable in the Pacinian corpuscles mechanoreceptors in the fingertips.[97] However, it has been noted both colloquially via artists such as Glennie and in literature[98] that hard of hearing individuals may challenge the expected limit and feel frequencies higher than any individual mechanoreceptor.

It was therefore the hypothesis that different tactile transducers—such as exciters and bass shakers—can be used together to expand total tactile frequency range that is detectable by the human body from a single source, by allowing each transducer to perform in its optimal range, expanding the effectiveness of the transducer array.

Experimental Design

Materials

We made a series of Distributed Mode Loudspeaker panels by using 24" x 24" x 1" end grain balsa wood panels and similar-density materials like acoustic ceiling tile and polystyrene (StyroFoam) following the instructions from *Tech Ingredients*'s video on DML

97. Julia C. Quindlen, Victor K. Lai, and Victor H. Barocas, "Multiscale Mechanical Model of the Pacinian Corpuscle Shows Depth and Anisotropy Contribute to the Receptor's Characteristic Response to Indentation," *PLOS Computational Biology* 11, no. 9 (2015), https://doi.org/10.1371/journal.pcbi.1004370.

98. Lonce L. Wyse and Suranga Nanayakkara, "Perception of vibrotactile stimuli above 1 kHz by the hearing-impaired" (2012).

panels titled "Fantastic DIY Speakers for Less than $30!". The Distributed Mode Loudspeaker (DML) is a method of creating a loudspeaker by attaching a transducer to a membrane in order to excite the membrane, creating sound as a result of the vibrations resonating from the substrate. We also tested faux resonant tonewood from a budget-series acoustic guitar. We placed a single 40mm 40 watt (at 4Ω) tactile exciter on the lower third grid intersection (one-third from either left or right and one-third from either top or bottom) of each material. [99]

Figure 4: DML panels created to explore tactile perception. Left to Right: Keith Hussein, Mark Lopez, Andrew Lvovsky

99. "Dayton Audio DAEX32QMB-4 Quad Feet Mega Bass 32mm Exciter 40W 4 Ohm," Parts Express, accessed April 29, 2022, https://www.parts-express.com/Dayton-Audio-DAEX32QMB-4-Quad-Feet-Mega-Bass-32mm-Exciter-40-295-264.

We repeated the same orientation and placement of a larger bass shaker called I-BEAM that theoretically produces a wide-band frequency response according to the manufacturer. The larger bass shaker was attached to a cut of medium-density fiberboard (MDF) which was suspended on a large metal frame to allow the wood to vibrate.

The stage, as it was built was about 6’4” (about 193cm) along the length, about 4’6” (about 137cm) at the width, and about 5.75” (about 14.6cm) off the ground including some large square wooden blocks, 2.6” (about 6.6cm) without the blocks (although the bass transducers are larger than the depth of the system).

We powered both the large- and small-scale tests with a relatively inexpensive desktop amplifier capable of 20 watts/channel, and later, a repurposed 300 watt guitar amplifier that featured a line-in port for full-range auxiliary sound input, such as an mp3 player.

Figure 5: Ethan presenting the tactile ‘stage’ at the EARS 2018 winter showcase event.

Methods

To create a perceptual baseline, we first subjectively evaluated the frequency response of a tactile transducer. We decided to create a pair of DMLs for the transducer evaluation. There are published methods of creating DMLs that include attaching a single transducer off-center to a lightweight, somewhat rigid, thin square panel.

Theoretically: the larger the panel, the larger the resonant wave can exist, and therefore the panel should produce lower frequencies. To test this, we created a larger, scaled up version of the DML panel, to evaluate the perceptual differences between the two.

Later, we would merge the two systems into one. The new system would include the low-frequency-focused IBEAM transducer, which would be attached to the tactile 'stage' platform, and two exciter-driven DML panels suspended by string. The platform and DMLs would not be crossed over, and only the DMLs would be adjusted with a low shelf based on the capabilities of the amplifier.

Since there was not a physical equivalent to the equal-loudness contours for quantifying the perceptual loudness or power of physical audio, we used a subjective analysis based on an approximated equivalence to acoustic power, determined by seasoned interpretation of an audio engineer's mechanoreceptors. The engineer coupled the substrate to the mechanoreceptors in his fingertips, and provided a subjective evaluation of the power and availability of frequencies or frequency bands that were detectable from the system.

Results

DML Panels

Upon testing, the DML panels resonated clearly, indicating that the frequency response was reasonable without any adjustments. By making minor adjustments using the high and low "tone" knobs included on the amplifier, which appeared to be high and low shelves, the falloff frequencies at the highest and lowest extremes appeared to be corrected.

The DML panels were capable of reproducing spectral and dynamic acoustic information of popular commercial genres of music including but not limited to electronic, hip hop, rock, and popular, with greater responsiveness for genres that featured compressed and complex acoustic mixes, as well as sparse mixes.

Among the materials tested, balsa tiles resonated with greater efficiency (more perceptible frequencies per watt) than the other materials. This is not to say that the other materials were ineffective at certain frequency ranges, but they were not as efficient overall in terms of perceived volume and accuracy.

During the dismantling of the DML system, it was observed that the audible vibrations could also be felt through fingertips. Even higher frequencies, previously thought to be undetectable, were faintly detected through the lightweight material.

Tactile Stage Prototype

Initially, the team encountered some difficulties in establishing a demonstrable setup. The IBEAM, which has a power rating of 250 watts RMS, was connected to an existing 20-watt/channel RMS amplifier. Although the low frequencies produced by the

IBEAM were detectable, they were quite faint. It was understood that a stronger amplifier in the range of hundreds of watts was required. A 300 watt guitar amplifier with a detachable speaker was used to deliver the amplified signal to the transducer. Upon testing, the IBEAM caused the workshop table to vibrate with incredible force as the bass elements became present within the music of the source test signal. The IBEAM was then attached directly to a large piece of MDF wood, which was supported by a stage-like metal frame.

The tactile stage was tested without the use of any digitally applied filters and so it was found that the natural unprocessed response of the transducer affixed to the wood panel was proficient in bass frequencies under 100Hz. The strongest response was observed around 45Hz, with a consistent decrease in observed frequency response until around 10kHz. With a frequency response focused on bass, genres that naturally emphasize bass such as electronic, hip-hop, and rock elicited the most vibration response from the system and were subjectively preferred.

Figure 6 is a screenshot of a video capturing a phone-based spectrogram displaying the frequency response of a tactile stage module. The team used a bass-heavy song by artist Mr. Bill to capture this video. A water bottle about $1/10^{th}$ filled with water demonstrated the tactile vibrations present in the material, since the vibrotactile vibrations are too small to see at this scale. The bottle would bounce around the stage when bass frequencies below around 60Hz were present.

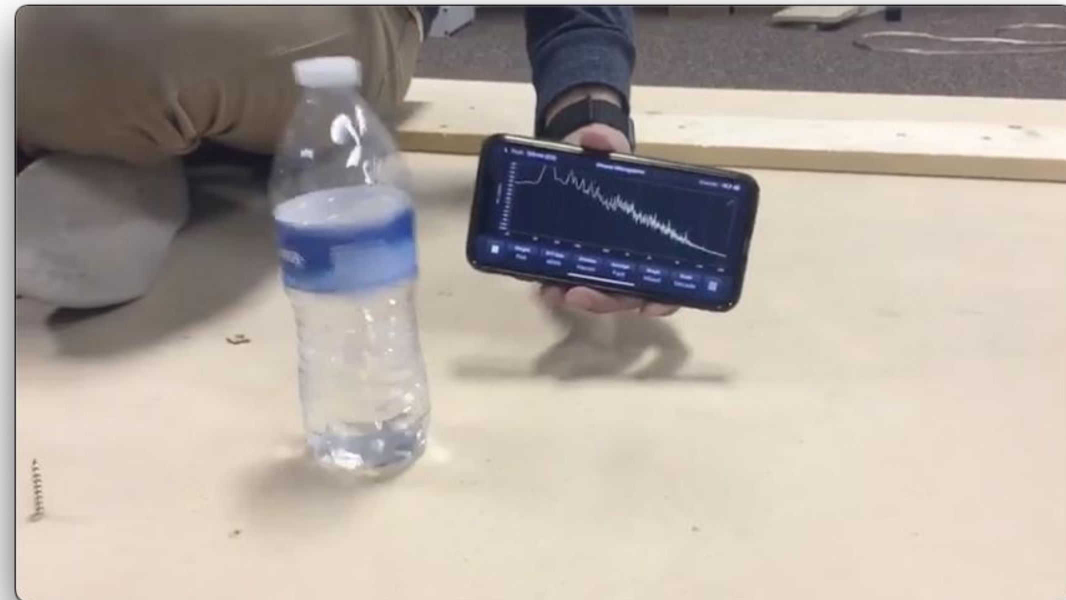

Figure 6: Water bottle responds to tactile stage, while FFT plot shows vibroacoustic response.

Discussion

For the DML experiment: It is important to note that while the acoustic bandwidth was sufficient, there may be other factors that need to be taken into consideration when determining the overall quality of the sound produced by these systems. For instance, the listening environment, the quality of the source material, and the placement of the speakers can all have a significant impact on the sound quality. Therefore, it is recommended to conduct further testing in a variety of environments to fully evaluate the performance of these systems.

It is also worth noting that most measurements and observations are largely based on comparative perception. For comparison, a perceptual mapping of audio experience was created in the practical field during music creation or audio engineering. Additionally, a reliable mapping of visual cues was created from: meters, the feeling of the speaker membrane vibrating, and acoustic information from studio monitors. Comparing prototype and commercial studio monitors to the physical response of research prototypes was used as a pseudo-measurement due to lack of availability and access to relevant tools. Although limitations exist, current research seeks to correct this perceptual bias. Interpreting higher-frequency vibrations appears to be more akin to an art than a science until some sort of standard for physical-perceptual limits is established for higher frequencies.

For the tactile stage experiment: It is important to note that the range of frequencies lacking in the system is particularly important for the human auditory system and that the responses observed in this study may have implications for the design of tactile systems that seek to simulate auditory experiences from the same system. Further research is needed to fully explore the capabilities of the tactile stage, and to determine how they might be applied in practical applications such as virtual reality or haptic interfaces.

Conclusion

Our experiments have shown that tactile transducers such as exciters and bass shakers can expand the range of frequencies that are detectable by the human body from a single source, through certain substrates. This is achieved by allowing each transducer to perform in its optimal range, expanding the effectiveness of each transducer. We have also found that the use of Distributed Mode Loudspeaker (DML) panels in conjunction with a bass-focused tactile stage showed promise in reproducing spatial and temporal perception of various genres of music.

However, it is important to note that while the acoustic bandwidth was sufficient, there may be other factors that need to be taken into consideration when determining the overall quality of the sound produced by these systems. For instance, the listening environment, the quality of the source material, and the placement of the speakers can all have a significant impact on the sound quality. Therefore, we reiterate the recommendation to conduct further testing in a variety of environments to fully evaluate the performance of these systems and how they may be useful in practical applications.

Based on our research and observations, it is suggested that it would be possible to detect higher frequencies as well as low frequencies through the body, if there was a way to wrap the user in a material to allow for constant contact to both sets of transducers providing high and low frequencies.

Since wrapping a person or colleague in wood seems rather invasive, we therefore proposed an additional experiment to embed the technology into a chair form factor. This form factor was hypothesized to provide a more immersive experience, as the user would be able to feel the vibrations throughout their entire body. Such an experiment could also have implications for practical applications such as virtual reality or haptic interfaces.

Chair Proof-of-Concept and Prototype

Objective

A previous experiment with tactile transducers embedded into wood demonstrated the potential for gathering acoustic information through a person's sense of touch at higher frequencies, possibly extending the frequency range previously believed to be possible.

The goal of this experiment was to optimize the previous experiment by increasing the maximum surface area of a user's interaction with a substrate that delivers vibrotactile and vibroacoustic signals. This would allow the user to passively interact with the substrate and focus on other tasks.

It was hypothesized that using a chair embodiment would provide a natural position for a user to interact with vibrotactile and vibroacoustic signals, maximizing the surface area of the body in contact with the signals.

It was unclear whether a user would be able to detect higher vibrations through padding or coverings in a seat, as Karam's experiment used a super thin and flexible membrane to minimize substrate loss between transducer and user. A successful outcome would include a user reporting detecting higher frequencies through their body or experiences a positive perceptual difference when using a known source with the setup (e.g. a movie trailer, or favorite song first experienced elsewhere).

Experimental Design

Materials

Proof of Concept

We chose a stackable chair with a wooden seat, which is covered with fabric padding where the user would sit. It was hypothesized that it is ideal for the user to sit on the same substrate to which the transducers are attached.

The proof of concept used four 40mm 40-watt (at 4Ω) tactile exciters placed on each corner of the wooden chair bottom, and a single IBEAM bass-transducer in the middle of the seat bottom, equidistant between each exciter.

Each pair of exciters were amplified by a 20 watt/channel RMS amplifier, while the bass shaker was powered by a 100 watt/channel amplifier, which could provide 200 watts of power when both channels are bridged to mono. Each amplifier contained a 3.5mm jack to receive line-level signal. This signal was fed by a 3.5mm splitter, which in turn received signal from a dedicated Bluetooth receiver. Each amplifier had minimal filtering capabilities in the form of ‘tone’ knobs, affecting both a high and low shelf.

Prototype

This experiment used a 2020 series ergonomic racing style gaming chair from OFM LLC as an example of a typical selection that a gamer might choose. The chair, as of May

2023, has 4.5/5 stars on amazon, with 23,025 ratings on the Amazon product page.[100] The chair was made of a sort of plywood, wrapped in foam, breathable fabric, and imitation leather. A quick survey of several similarly priced offerings on the website indicated that most constructions were similar in design.

The chair prototype used four 40-watt RMS (at 4Ω) tactile exciters, arranged in series of 80 watts RMS. It also used two IBEAM bass shakers, each rated at 100W RMS. The exciters were placed near the top of the chair back, and the bass shakers at the bottom of the chair back, in line with learnings from Emoti-Chair.

To power the exciters and bass shakers, two identical amplifier models capable of producing 100 watts per channel were used. Since the IBEAM bass shakers have a 4Ω impedance, we connected them in series with 4Ω 100 watt resistors to achieve a total impedance of 8Ω for the amplifier channels. This was necessary to match the expected load for the amplifier, which can only deliver the full 100 watt power to an 8Ω load, while providing only 76 watts to a 4Ω load.

The amplifiers received a processed signal from a digital signal processor (DSP), capable of 10 bands of parametric EQ, high and low shelf EQ, delay, phase adjustment, and custom signal path routing. The DSP device also functioned as a Bluetooth sink for a Bluetooth-enabled source, such as a phone or laptop, to connect to and provide audio data.

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100. "OFM Gaming Chair Ergonomic Racing Style PC Computer Desk Office Chair," OFM, 2016, accessed November 19, 2020, https://www.amazon.com/Essentials-Racing-Style-Leather-Gaming/dp/B01M1E96WX.

The exciters, bass shakers, DSP, amplifiers, resistors, and all associated cabling were affixed onto the chair back.

Methods

To determine whether future experiments should avoid padding or having soft materials touch the body, we tested this in a proof of concept. By placing the transducers on the wooden side of a folding chair, the seat of the chair was allowed to absorb and enhance the amplified vibrations of the transducers:

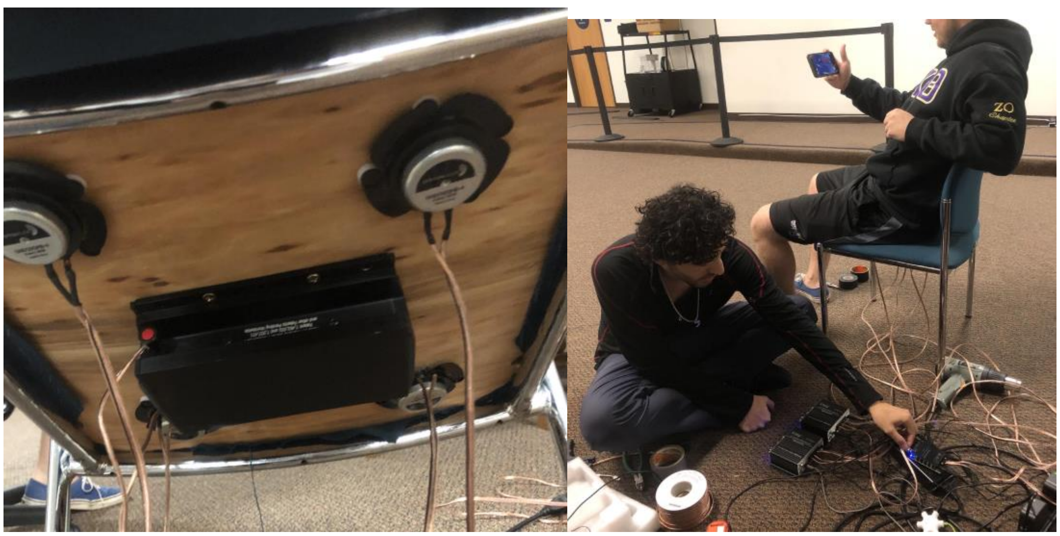

Figure 7: Ethan (left) creates first embodied sound POC for colleague Valtteri Salomaki (right)

A series of commercially available and works-in-progress were used to determine the ratio of vibrations present from exciters and the bass shaker. With a quick confirmation that light material such as padding was inconsequential to the preliminary tests, we moved to create a larger scale embedded chair prototype.

To address the early acoustic FFT measurements showing a roll-off at 17kHz, we decided to incorporate a pair of tweeters into the original system diagram.[101]

This block diagram reflects the initial proof of concept setup (alpha), but adding tweeters:[102]

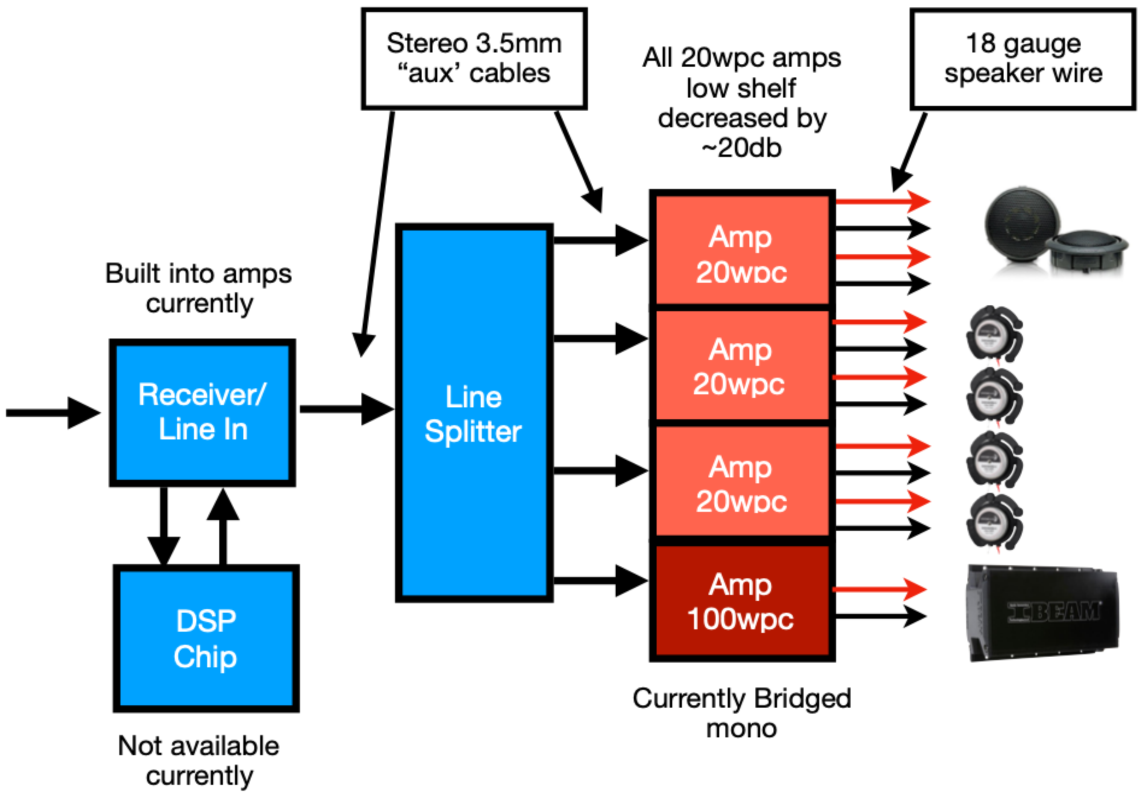

Figure 8: Initial high-level block diagram of embodied audio system

For the DSP, we initially proposed a method to detect and separate transient and sustained information from the source signal. Then, we considered processing each signal

101. “Tweeters” are the colloquial term for acoustic transducers in loudspeakers that are optimized for higher frequencies.

102. Note that the diagram refers to “currently” referring to the configuration at the time of the experiment in Winter 2019-2020.

pathway separately before they were separated into four frequency bands: High, High-Mid, Low-Mid, Low/Sub. Finally, dynamic processing could be applied to each frequency band before sending the signal out to discrete amplification channels.

After conducting thorough research and careful consideration of available components and requirements, we concluded that our algorithm and system design may have been overly ambitious at that juncture. Therefore, we believed that it would have been more prudent to focus on developing a more reasonable solution for the purpose of this experiment.

The proposed schematic for the beta system is as follows:

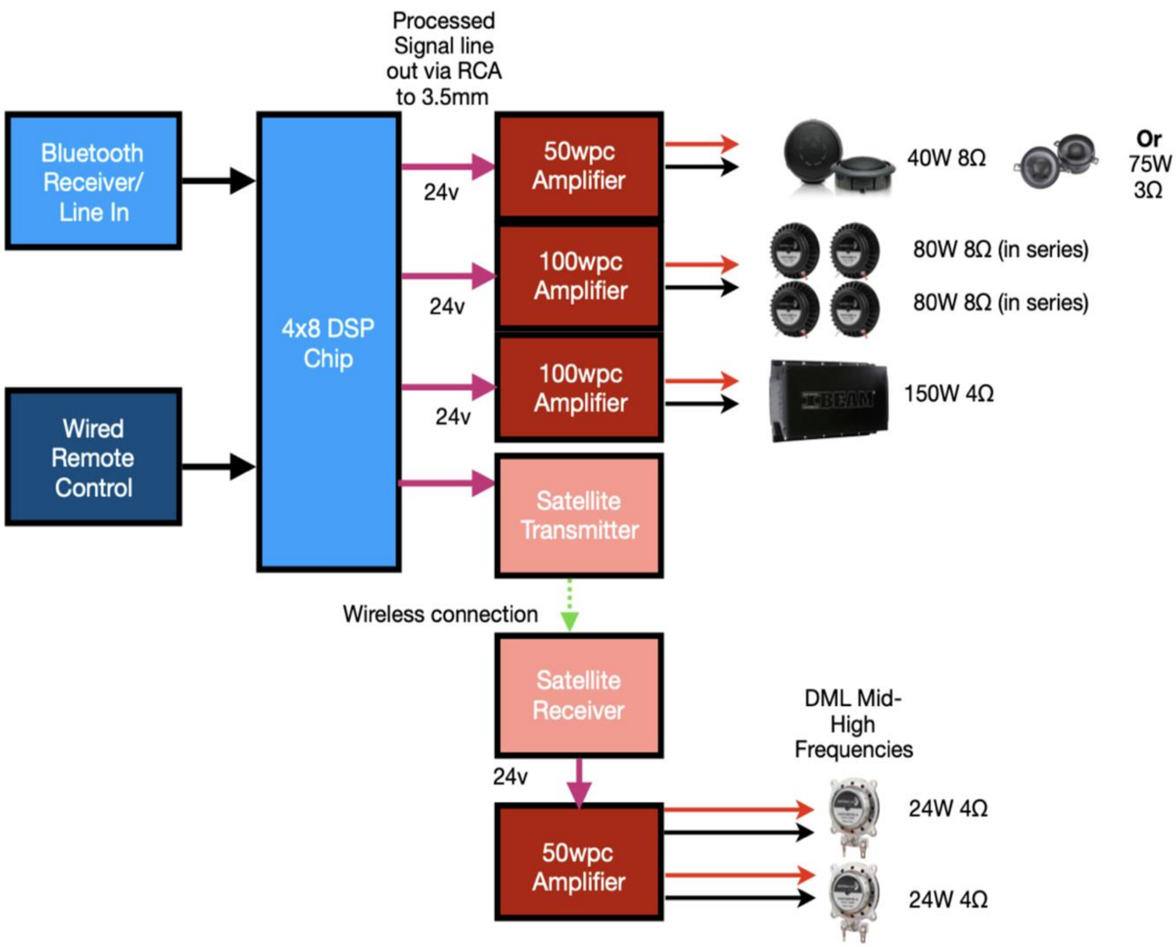

Figure 9: Updated high-level block diagram for proposed 'beta' system

The 'beta' system diagrams show the main elements:

1. Tweeters for high frequency fill
2. Exciters for Wideband tactile response
3. Bass shaker for low frequency tactile response
4. Satellite DML panels for 'rear' channels of 5.1 system.

While the system is not intended to fully express the processed signal, it should still deliver a sufficient full-frequency tactile audio experience to the user. We positioned the devices we used on the bare back of the chair with enough space for wire paths in between each one: 2 x IBEAMs, 4 x Dayton high-excursion speakers, 2 x 100W/channel amplifiers, and the Dayton Audio DSP unit with the Bluetooth dongle:

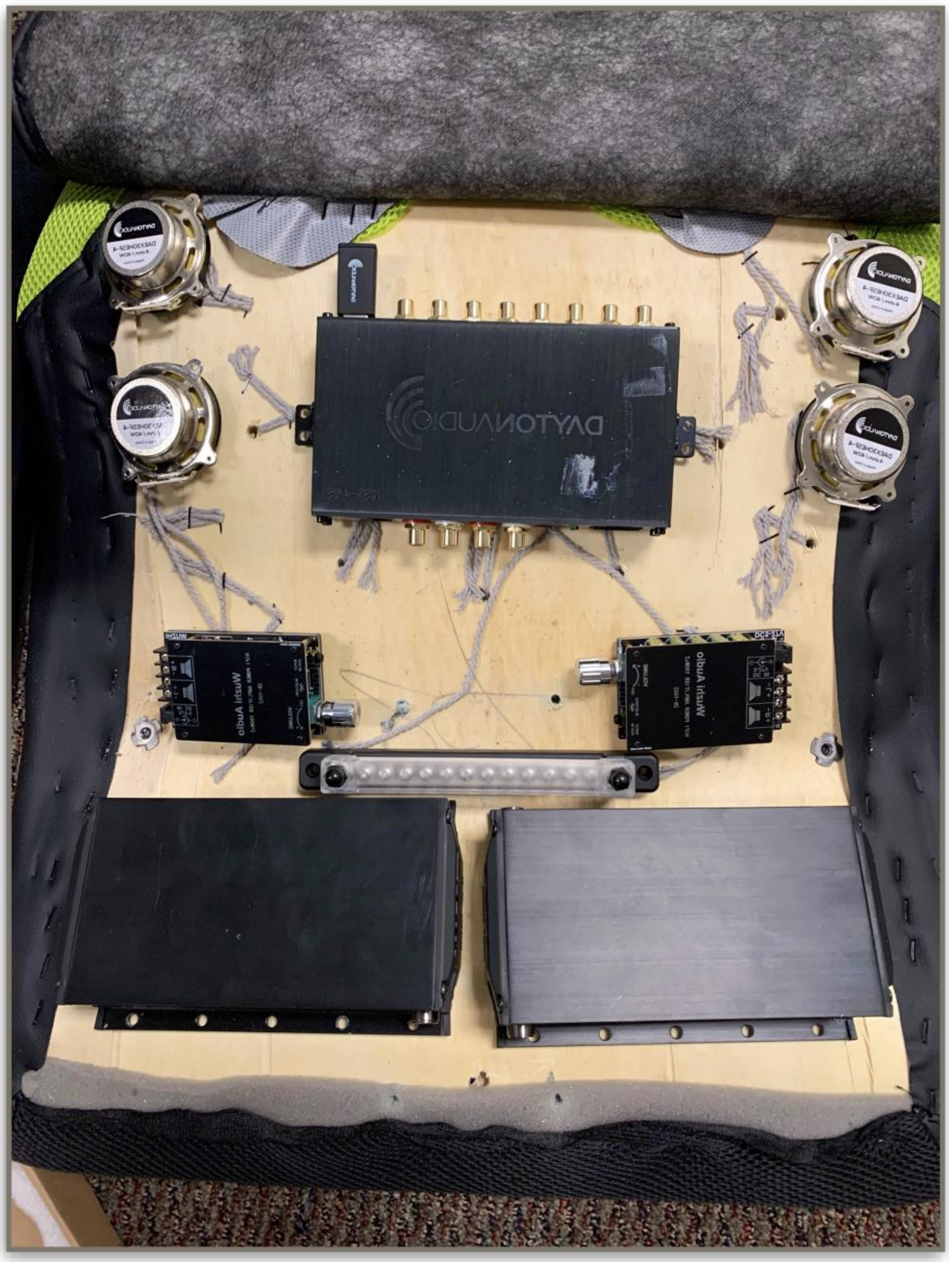

Figure 10: Layout of the components of the 'Beta' chair prototype

We tested a Bluetooth device with a strong signal and a DSP preamp set at -5dB (level 55 on the Dayton Audio DSP remote). The tests were conducted using familiar, subjectively well-produced, bass-heavy music that were regularly used to internally evaluate sound systems.

Since there is not a physical equivalent to the equal-loudness contours for quantifying the perceptual loudness or power of physical audio, we used a subjective analysis based on an approximated equivalence to acoustic power, determined by a seasoned audio engineer. The engineer coupled the system to his fingertips and body, and provided a subjective evaluation of the power and availability of frequencies or frequency bands that were detectable from the system.

Results

As the first proof of concept experiment was to determine whether high frequencies are perceivable through foam or soft material, the result was a perceivable affirmation - the three subjects present each reported the perception of higher frequencies. While not a randomized comprehensive sample, the subjective affirmation of the participants was significant enough to build the larger prototype.

The embedded chair prototype delivered subjectively reasonable results on-par with a series of entry-mid level studio nearfield monitors. While some higher-frequency vibrations were seemingly absorbed by the chair cushion, most lower frequencies were easily felt, and a subjectively balanced response was designed by applying a series of filters created by a DSP device.

While we did not collect frequency response measurement from this prototype, we collected the filters that resulted in an acoustically balanced response when measured from a spectrum analysis app on an iPhone XS from roughly below head-height in landscape mode, using pink noise and songs with known frequency response as the source material.[103]

The captured screenshots of the Dayton Audio DSP 408 are as follows:[104]

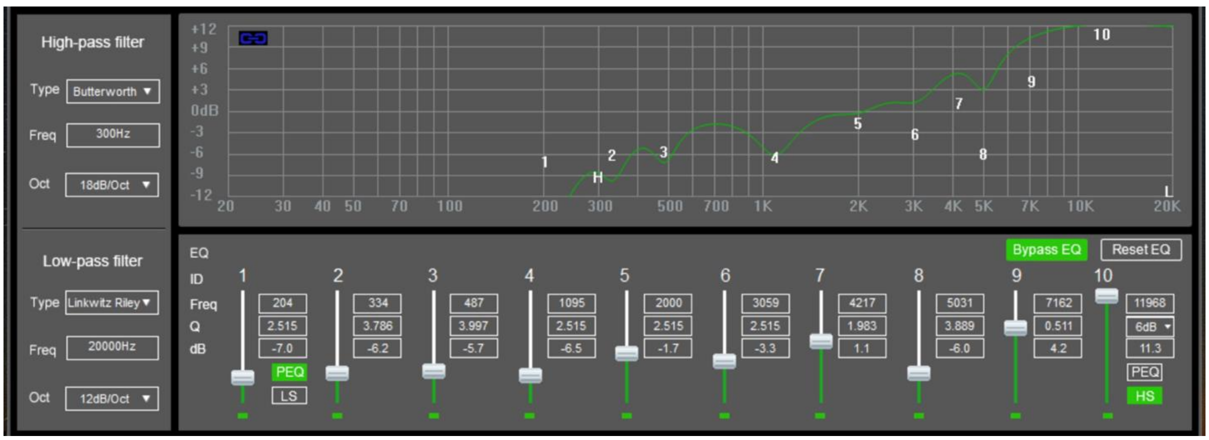

Figure 11: High frequency settings of chair prototype

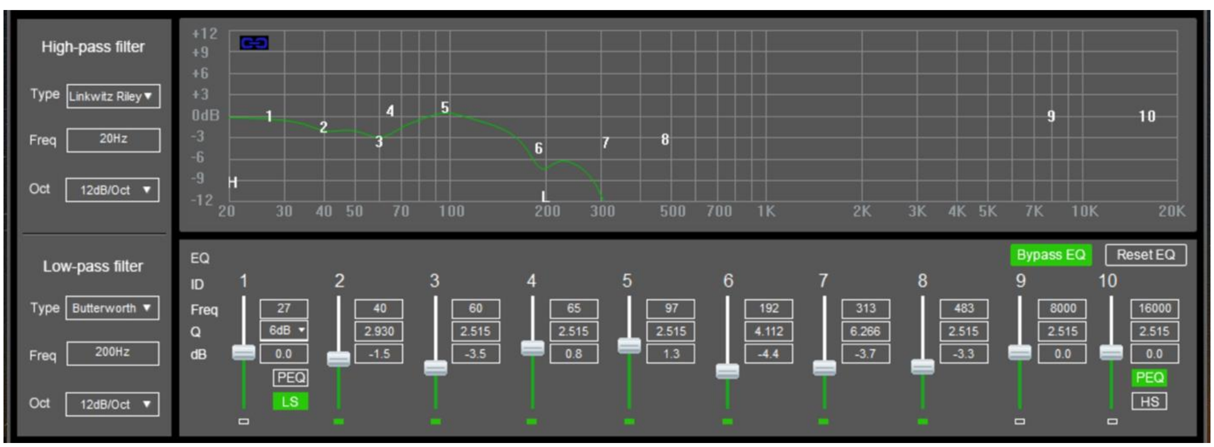

Figure 12: Low frequency settings of chair prototype

103. Pink noise is like white noise but biased towards lower frequencies.

104. The high frequency DSP channel had to compensate much more than the low frequency channel for extreme ranges of frequencies. This is thought to be due to the chair material absorbing smaller vibrations characteristic of higher frequencies.

Discussion

While all three subjects reported perception of higher frequencies in the proof-of-concept experiment, it is possible their biases of hearing the acoustic emission of the system while being reinforced by the tactile vibrations of complex harmonic material present in commercially available popular song samples.

During tuning of the gaming chair prototype, it seemed that splitting the entire audible frequency range between two sets of transducers allowed an increase in the number of filters to be applied to the signal before amplification. Granted, while more filters ≠ better quality, it did allow for more specific flexibility and addressability of the extra harmonics present when exciting a material, as any substrate would have naturally resonant substrate-dependent frequencies.

Adding the inverse of the filters to a pink noise signal, would show an excited substrate that overperforms in mid-frequency ranges of 200-500Hz, 1kHz, and slowly rolls off until 20kHz, as shown by the necessity of a high shelf filter with substantial positive gain to compensate for the lack of high-frequency information present in the prototype.

It is worth noting that most measurements and observations were largely based on comparative perception. For comparison, a perceptual mapping of audio experience was created in the practical field during music creation or audio engineering. Additionally, a reliable mapping of visual cues was created from: meters, the feeling of the speaker membrane vibrating, and acoustic information from studio monitors. We compared the acoustic frequency response of commercially-available studio monitors to the perceptual physical frequency response of the vibrotactile and vibroacoustic prototypes due to lack of availability and access to relevant analysis tools. Since perceptual measurements were used, further research will need to produce a system to accurately measure wideband vibration frequency response to mitigate perceptual bias. Interpreting higher-frequency vibrations appears to be more of an art than a science until some sort of standard for physical-perceptual threshold is established for higher frequencies.

Conclusion

This experiment demonstrated potential for a high-fidelity vibrotactile and vibroacoustic chair-based experience. The chair embodiment is a known and naturally ergonomic position for a user to interact with vibrotactile and vibroacoustic signals since the chair surface maximizes the surface area of the body in contact with the signals. By increasing the maximum surface area of a user's interaction with a substrate that delivers vibrotactile and vibroacoustic signals, a user can passively interact with the substrate and focus on other tasks.

The proof-of-concept tested whether a user would be able to detect higher vibrations through padding or coverings in a seat, and each team member reported the perception of higher frequencies through a chair with transducers attached to the bottom.

The prototype demonstrated even more robust performance than we anticipated—like a performance ceiling for a vibrotactile and vibroacoustic system, but the approach is not commercially sustainable as it would require custom building each chair by individually placing each transducer across the back of a chair. To be commercially viable and manufacturable, this technology must be miniaturized and modularized.

Miniaturization of Tactile-Audio Module

Objective

A previous experiment demonstrated potential for a high-fidelity vibrotactile and vibroacoustic chair-based experience. In the experiment, while the vibrotactile and vibroacoustic chair-based experience was powerful and immersive, we realized the difficulty in replicating the chair experience because custom considerations and placements would need to be taken per-chair. Therefore, it was our aim to miniaturize every component in the system to make the system more modular, allowing the experience to be applied to any chair. It was unclear if the experience would remain relatively consistent with a smaller size, or if the relationship between lower and higher frequencies would diminish and become indistinguishable.

Experimental Design

Materials

We searched for the most compact and affordable transducers commercially available at the time. Our search led us to the 15W Dayton Audio PUCK mini bass shaker and the 24W Framed High Efficiency exciter, both offered by Dayton Audio via Parts Express. To power both transducers, we planned to use a Bluetooth amplifier featuring 100W per channel that we have utilized in prior prototypes. Because this experiment took place in the height of the pandemic and stores had not enacted reopening protocols, the researchers could not acquire project wood for the experiment. Therefore the build was encased in remnant wood veneer flooring tile found in one of the researchers' homes. The wood flooring tile appeared to be a very dense sandwich of MDF wood fibers encased in a very thin wood veneer on both sides.

We also planned to implement a custom crossover and equalization (EQ) system for each frequency band, since the DSP408 used in a prior experiment was too large for a miniature solution. We designed both an analog crossover, and a digital DSP solution implemented on a Raspberry Pi 4B microcomputer.

Methods

The goal of this experiment was to determine if the performance of the large gaming-chair prototype would still be found in a smaller variant. We determined this by measuring frequency response and perceptual detection of available frequencies.

To create the smaller device, we laid out components on a wood flooring piece, arranging them in a compact pattern, with the transducers on one side, and the electronics on the other:

Figure 13: Components of miniature tactile audio module laid out on wood material

The intention was to stack the components on top of each other, to allow the most compact footprint on the back of the substrate the device is attached to. Not unlike the same shape of the I-BEAM transducer we used previously.

We then cut the wood, taking into consideration the height of all components, and the locations where they would be mounted:

Figure 14: Photo showing assembled prototype miniature full frequency tactile audio module

We discovered we needed another amplifier to have discrete control over high and low frequencies, so we added another amplifier, forcing us to reposition the DSP to the top of the module.

To determine if a complicated active crossover with DSP and multiple amplifiers was even needed, the team concurrently created a passive crossover circuit to separate the band-passed feeds from a single amplifier. The passive crossover was designed by graduate student and team researcher Julian Bell, who created the analog crossover network that would receive powered signal in via speaker cable and deliver a separate high frequency output to the exciters as well as a low frequency output to the bass shaker.

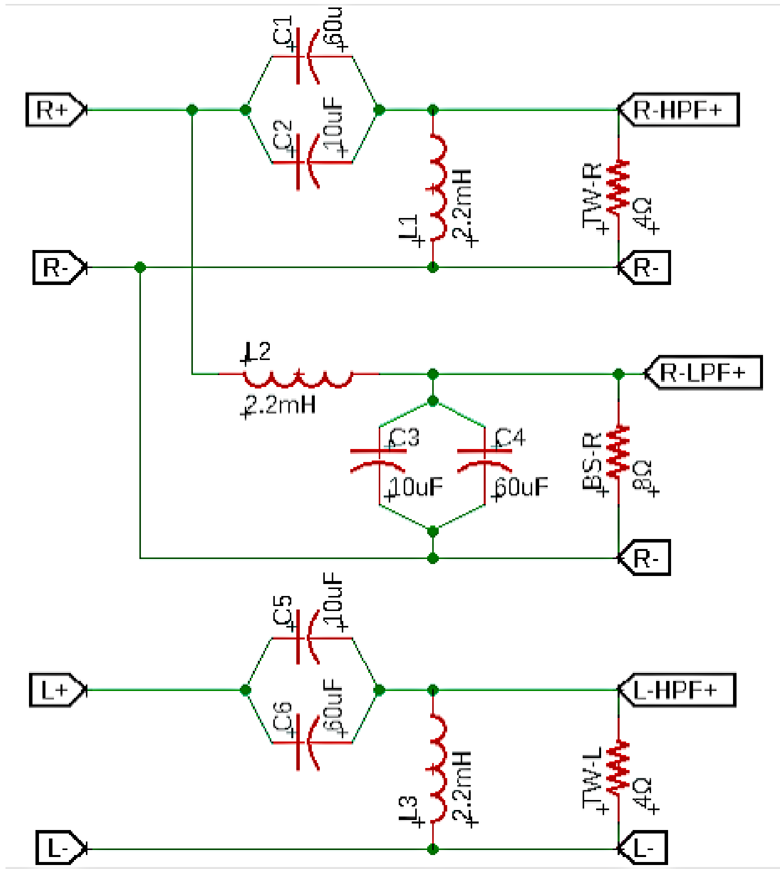

Figure 15: Hardware-based crossover schematic showing a 'right' and 'left' powered audio signal pairs (left), each passing through a filter circuit to deliver bandpass signal to the appropriate transducers (right)

Simultaneously, software engineer Winson Bi began to design a DSP series to be placed on the Raspberry Pi 4 module. After a bit of research, he landed on using Pyo - a dedicated Python module for digital signal processing.[105]

The module after mounting and wiring all the components:

105. "PYO - dedicated Python module for digital signal processing," Ajax Sound Studio, 2021, accessed April 20, 2023, http://ajaxsoundstudio.com/software/pyo/.

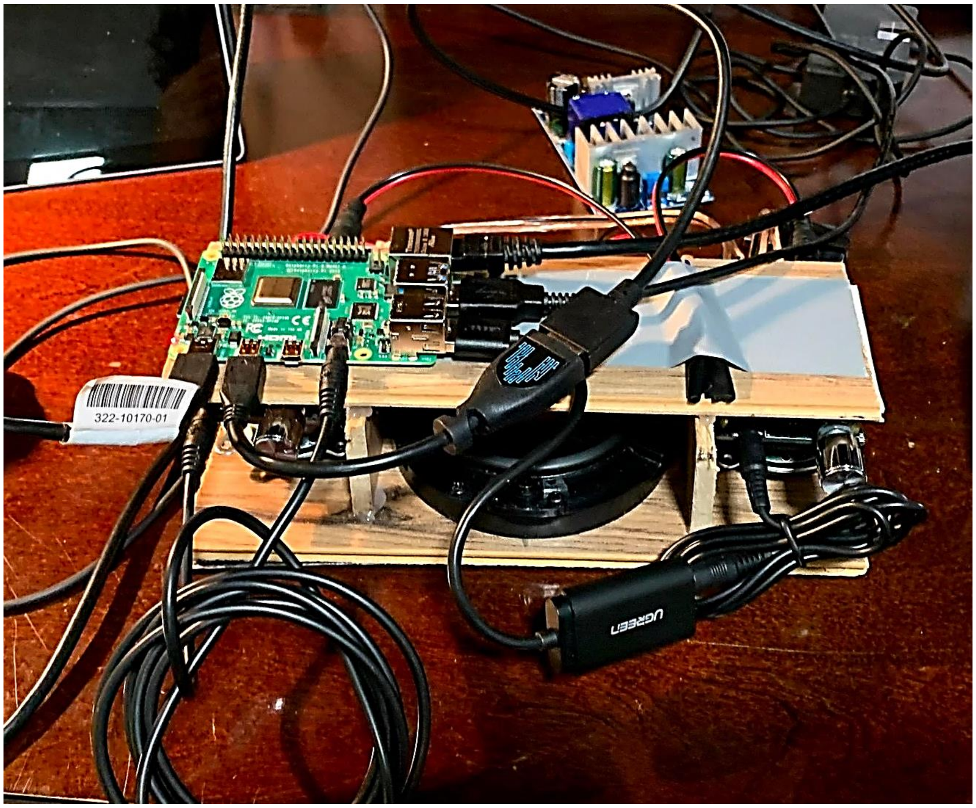

Figure 16: Tactile audio module with new software-based crossover and DSP device running on Raspberry Pi.

The final device consisted of a Raspberry Pi functioning as a digital crossover and DSP, sending a signal to two separate amplifiers responsible for low and high crossed over signals, respectively. The low frequency amplifier fed the single 15w RMS puck bass shaker, and the high frequency amplifier fed a 24W Framed High Efficiency exciter on each of the stereo amplified outputs.

Results

The final device did function well via perception of available frequencies present from the device, although the petite form factor was somewhat ambitious since the cables were somewhat unwieldy due to the angle of some connectors projecting outwards of the components.

The passive crossover circuit made did not pass on the intended frequencies well. When tested, we could not achieve a crossover at the expected 200Hz between the two amplified channels:

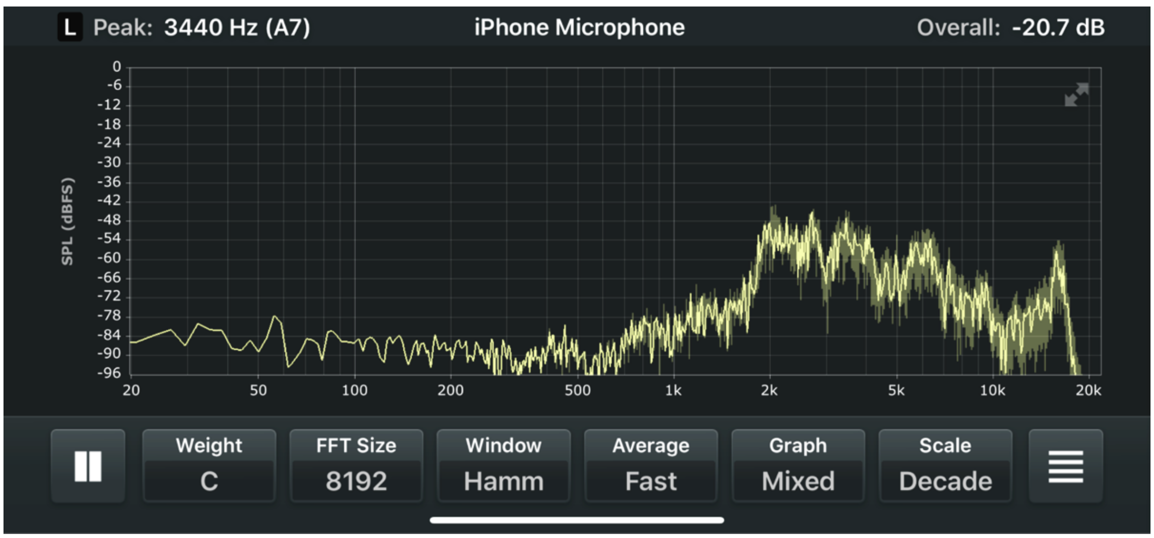

Figure 17: Pink noise through hardware-based crossover when connected via method 1: strong low cut at 2kHz

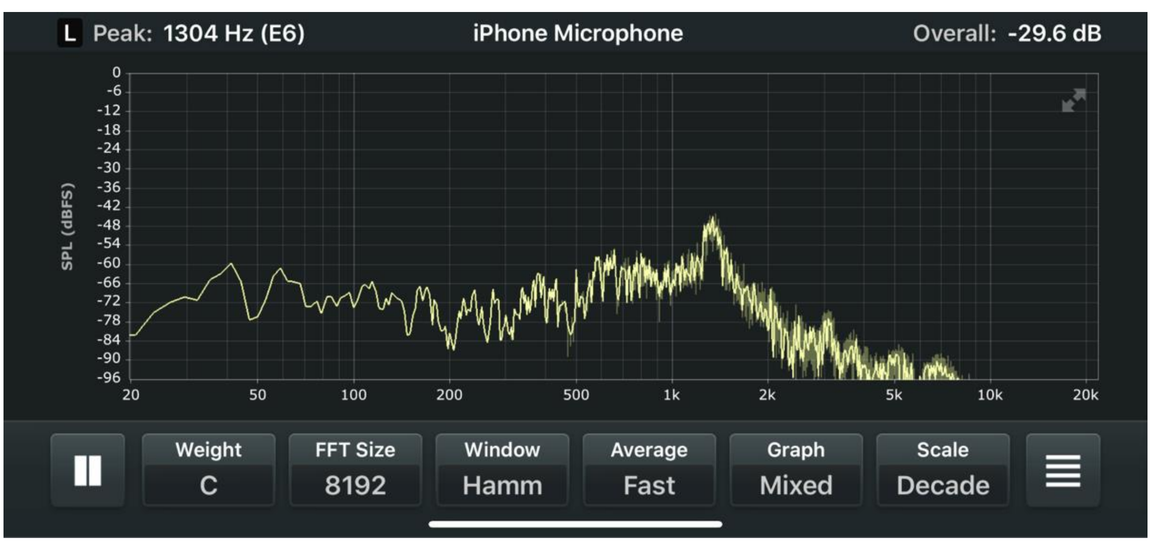

Figure 18: Pink noise through hardware-based crossover when connected via method 2: strong high cut at 1.5kHz

Not only was the crossover in the wrong place, but the signal was also heavily deteriorated, with a wide-band dip at 200Hz in one sample response (shown above), and another at 10KHz.

The digital DSP system fared a bit better, even though we did not take a sample measurement like with the passive crossover system, the device performed commercial popular music comparable to a commercially viable consumer sound device, indicating that the frequency response would likely have been more balanced than what the passive crossover indicated.

Overall, the design seemed to lack the perceptual 'punch' that the original chair had, even if the vibroacoustic response was present and similar. The noticeable gap between the vibrotactile presence indicated that there was a certain threshold of expectation of the vibrotactile experience vs how much vibroacoustic response was present.

Discussion

We ultimately could not figure out what went wrong with the passive crossover system, which illustrated the case against a large, physical device to function as a crossover in a vibrating device - many components would be at risk of becoming loose or faulty, causing a total collapse of system function.

While the digital DSP solution required multiple power supplies for both amplifiers and Raspberry Pi microcomputer (as well as several cables falling over the sides of the device), the active DSP approach seemed more flexible and capable overtime. The DSP was adjustable since it was easy to modify and tweak, as well as being easier to replicate on multiple places at once—a necessity whilst working remotely during the pandemic.

Conclusion

This experiment demonstrated the idea that a full range vibrotactile and vibroacoustic sound experience can be modularized in a miniature form factor, as compared to a previous experiment with components destructively embedded (with wood screws) into a gaming chair.

Digital DSP was determined to be the ideal candidate for signal processing the input signal for conditioning before amplification, but the overall size of the device with the limited transducer availability caused a noticeable lack of overall performance, hampering vibrotactile expectations compared to vibroacoustic sensation.

It is the hypothesis that further exploration should be around form factor and enclosure design so that a balance of transducer power and modularity can be found as the technology is prepared for commercial release.

ResonX RX100-200

Objective

Our miniaturization prototype demonstrated potential for a miniaturized modular full range vibrotactile and vibroacoustic experience. While the overall experience was deemed too weak to compare to the high-fidelity experience of our chair prototype, the system demonstrated scalability between sizes. It was the objective of this experiment to slightly scale up the experience of the module, so that the device would have enough power to pass its vibrations through to another large substrate such as a gaming chair, but small enough to be handled by a single person.

A successful experiment would yield in a device that is able to be non-destructively attachable to a gaming chair (also able to be non-destructively removed) by a single person, and produces a balanced frequency response from subsonic frequencies at ±10Hz from 20Hz to the critical bands of human speech around ±1kHz from 2kHz.

Experimental Design

During this experiment, the functionality of the module changed quite rapidly due to equipment failures, as well as iterative improvements on each component. While there was a clear change between generation 1 and 2 (RX100 and RX200), each variant will be indicated by adding an integer to the third digit (RX101, RX102, etc.) to keep track. In this section, materials and methods are combined under each variant, with a short overview of results that led to the next variant.

RX100

- Not enclosed, components embedded on plank of wood
- 1 x Dayton Audio BST-1 50W bass shaker
- 2 x Dayton Audio HDN-8 50W Weatherproof Sound Exciters
- 2 x 100W/Channel stereo Bluetooth amplifier boards
- 1 x Dayton Audio DSP-408
- 1 x Raspberry Pi Bluetooth sink
- 1 x USB soundcard
- 1 x piezoelectric ‘microphone’

Figure 19: Photo of the initial RX100 on Ethan’s desk

We faced an initial problem with the size of the HDN-8 exciter transducers. Despite their impressive 50W power output, they were quite large compared to the 40W DAEX30HESF-4 exciters used in the original chair prototype, which were nearly equal in power and sounded more balanced. While the HDN-8 exciters were great at reproducing sensitive frequencies between 1-5kHz, even after equalization, their frequency response still peaked at certain frequencies in the range as they could not be fully controlled.

Additionally, we encountered attachment issues with the HDN-8 exciters, as they were not fully secured to the wood during transit. The high-frequency transducers relied solely on a single narrow screw thread for energy transduction and attachment, which often became unscrewed during normal operation.

Another challenge was the size of the other components, which quickly became unwieldy. The DSP-408's size and the need for the Raspberry Pi to be our Bluetooth sink required a sound card for interaction between processing devices.

RX101

~~Strikethrough~~ text indicates that the element was changed and no longer used.

- Not enclosed, components embedded on plank of wood
- 1 x Dayton Audio BST-1 50W bass shaker
- 2 x Dayton Audio DAEX30HESF-4 40W 4Ω exciters
    - ~~2 x Dayton Audio HDN-8-50 exciters~~
- 1 x 50W+50W+100W 2.1 amplifier board
    - ~~2 x 100W/Channel stereo Bluetooth amplifier boards~~
    - ~~1 x Dayton Audio DSP-408~~
- 1 x Raspberry Pi Bluetooth sink
- 1 x USB soundcard
- 1 x piezoelectric ‘microphone’

We searched for any other method that would divide frequencies among transducers, and fortunately we discovered a 2.1 amplifier from the same vendor that also sells the other Bluetooth amplifier boards (DAMGOO on Amazon). The amplifier has a selectable crossover range of up to 200Hz, as well as a 100W mono output for bass and 50W/channel for the stereo hi-passed output.

This enabled us to swap out the large HDN-8 exciters and DSP-408 for much smaller alternatives, reducing overall complexity of this configuration. We still kept the Raspberry Pi as a source and calibration signal that worked with the piezo crystal to 'calibrate' the device.

This was the version that was sent to contracted industrial designer Vincent Zhang to enclose in a custom enclosure:

Figure 20: RX 101 being sent to industrial designer Vincent Zhang in Canada.

We met with Vincent several times to brainstorm various design concepts during the first phase of his design proposal. We explored several aspects of the design, including how the transducers would be attached, the ideal configuration and layout, and how the module would be non-destructively attached to the gaming chair:

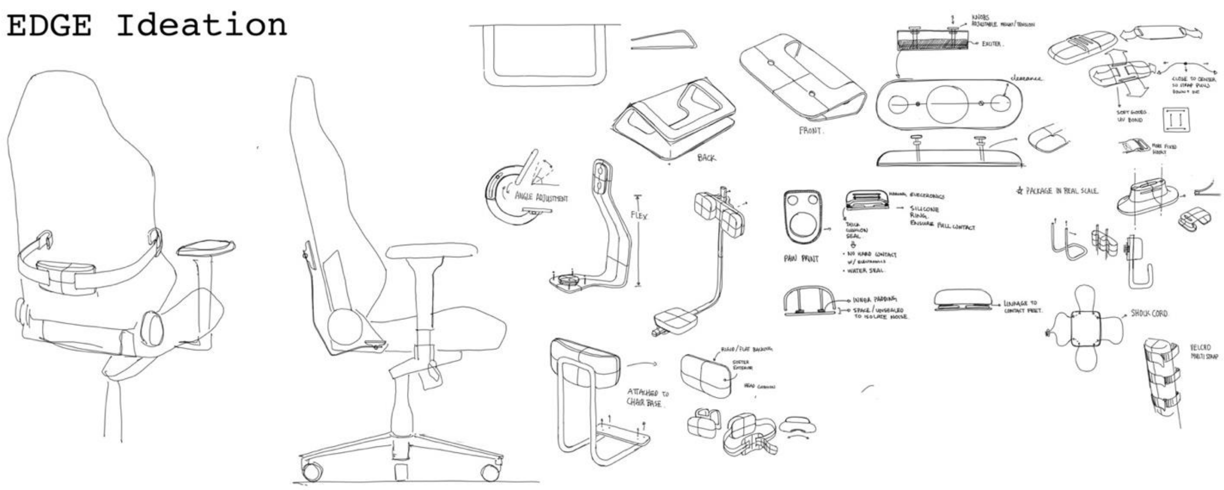

Figure 21: Sketches by Vincent Zhang of how to attach ResonX to gaming chair

RX200 - August 12, 2020

~~Strikethrough~~ text indicates that the element was changed and no longer used.

- Large 3-stage wooden enclosure
    - ~~Components embedded on plank of wood~~
- 1 x Dayton Audio BST-1 50W bass shaker
- 2 x Dayton Audio DAEX30HESF-4 40W 4Ω exciters
- 1 x 50W+50W+100W 2.1 amplifier board
- 1 x Raspberry Pi Bluetooth sink
- 1 x USB soundcard

● 1 x piezoelectric ‘microphone’

Vincent had already created a prototype enclosure based on the earlier measurements we sent him with the larger individual components, and quickly noticed that we had significantly reduced the internal volume needed to contain all the components.

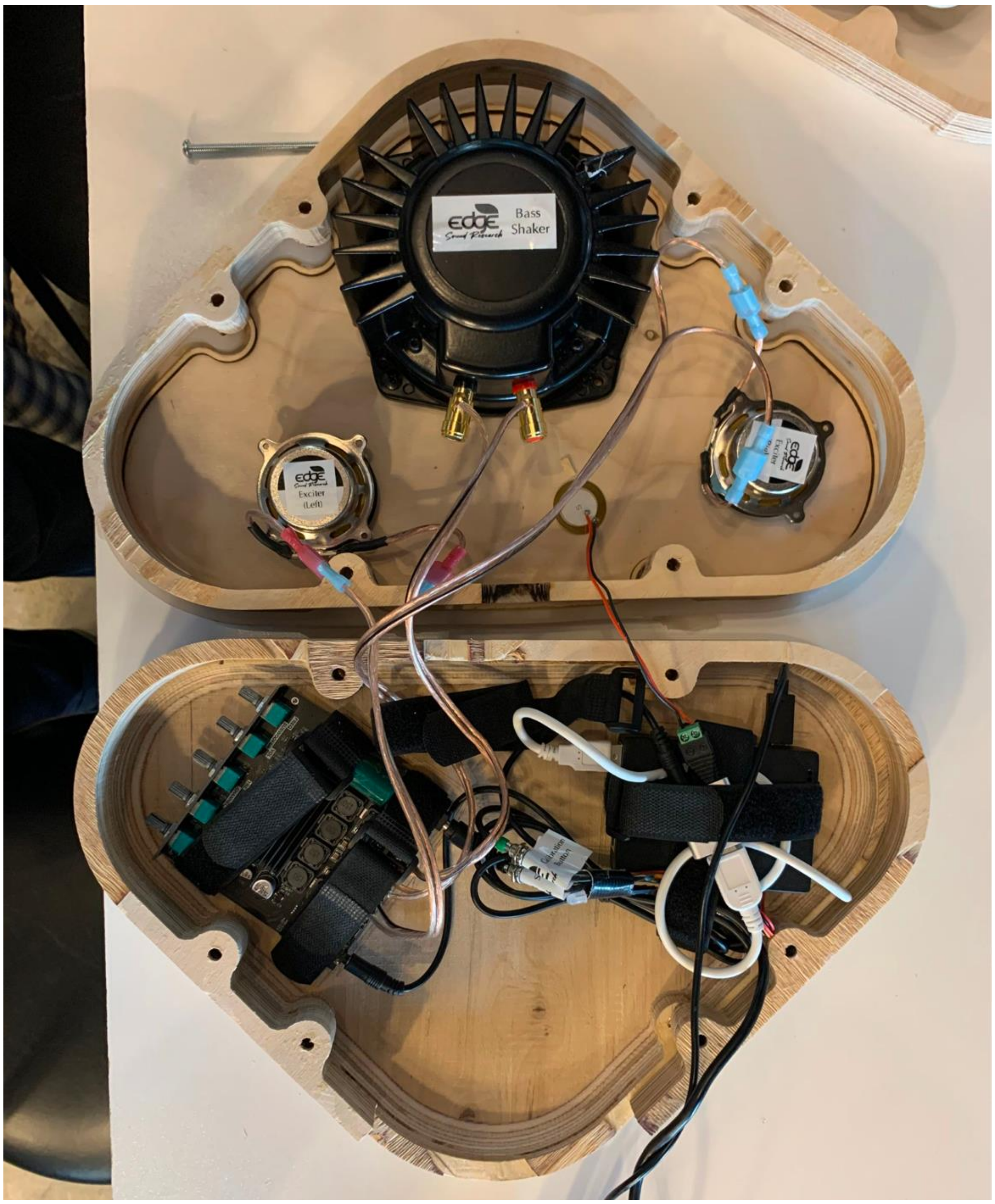

Figure 22: Photo by Vincent Zhang showing the large amount of unused volume in an early ResonX enclosure.

The enclosure was made of three solid, laser-cut plywood pieces - resonating plate, middle spacer section, and electronics housing. The idea was to separate the vibrating tactile transducers on the thin resonant plate from the electronics in the electronics housing.

RX201 - August 30, 2020

~~Strikethrough~~ text indicates that the element was changed and no longer used.

- Large 2-stage wooden enclosure
    - ~~Large 3-stage wooden enclosure~~
- 1 x Dayton Audio BST-1 50W bass shaker
- 2 x Dayton Audio DAEX30HESF-4 40W 4Ω exciters
- 1 x 50W+50W+100W 2.1 amplifier board
- 1 x Raspberry Pi Bluetooth sink
- 1 x USB soundcard
- 1 x piezoelectric ‘microphone’

Vincent decided to slim down the design before sending us the first prototype, since the components would not take up as much space as he initially thought. He created a slim resonant plate which would hold the transducers and suspended the resonant plate from the rest of the enclosure using a medium density silicone ring. Additionally, he experimented with mounting methods, including a compliant springless clamp for the headrest and a compliant clamp for the armrest of the proposed gaming chairs.

Vincent made a render of the design in Autodesk Fusion 360 before beginning to manufacture the prototype out of laser-cut plywood:

Figure 23: Autodesk Fusion 360 3D render of RX201 in a white void, also showing strap mounting mechanisms

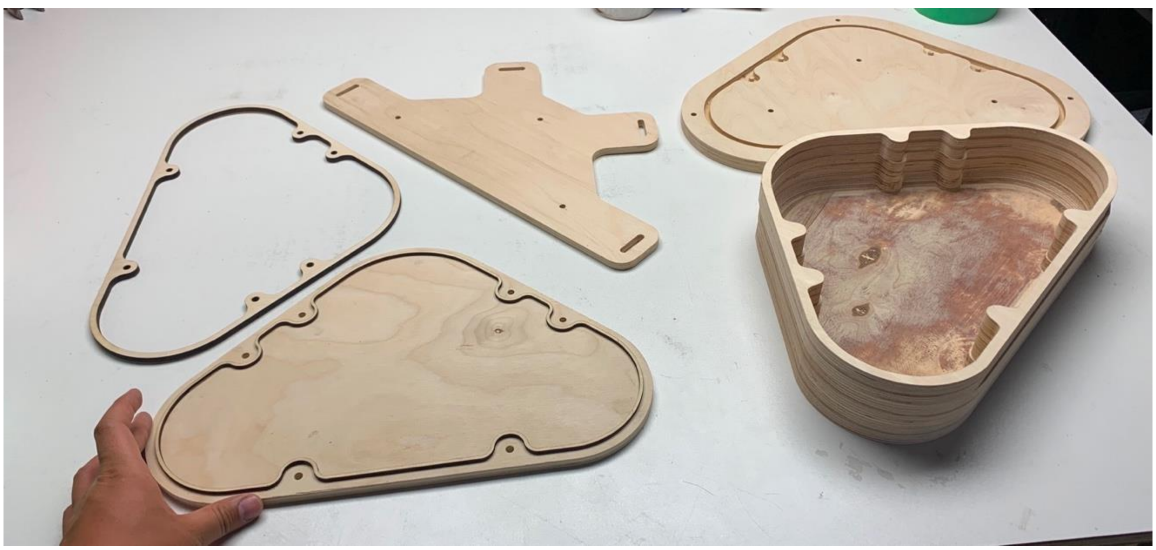

Figure 24: Laser-cut pieces of RX201 on a white project desk

Figure 25: Side views of RX201 strapped to an office chair

Figure 26: Rear view of RX201 strapped to an office chair

Vincent's thoughts in approaching the design:

> Our prototype—unlike traditional speakers—[is] for a complete[ly] different use scenario and requirement on internal space. Slimmer design will help with the portability and ease of attachment of the device. At the same time, going slimmer means less overall mass and overall loss of energy to the mass. It's also the first major constraint that helps to guide the necessary hardware selection to make sense of how to get the most performance out of the least amount of parts (again—mass reduction). Most electronics don't need to worry about vibration and have ways to make sure to dampen vibration, we are in a situation where we want vibration in [the] resonating contact surface and isolation from vibration for [the] chamber that contains electronics.[106]

Vincent touches on something quite crucial in his recollection: vibration is both the desired outcome, as well as the greatest threat in a vibration-based audio system. Most speaker systems have a dedicated design to contain vibrations from the transducer, with the electronics stored away in another section. From opening several consumer electronics and other speaker systems, we learned that companies also resort to securing electronic components that may rattle with a type of adhesive or putty that keeps components from vibrating against the printed circuit board (PCB) and making unwanted sounds. We did not put putty or extra adhesives in the unit since we wanted to ensure that we were not taking away desirable vibrations, which is the primary output of our device. This sometimes meant that the device would vibrate components undesirable, which we characterized as 'chatter'.

106. Vincent Zhang via Slack 04/19/2022 with minor edits in [brackets] for clarity.

Once Vincent put together the prototype, we scheduled a video call. From the call, it appeared to me that some of the electronics did not function properly after being transferred from the RX100 to the RX200. This resulted in the device not being able to generate the hypothesized frequency range, and improperly demonstrating the technology.

After Vincent returned the device, we tested a curated playlist of commercial songs with careful attention to sound design and transient details across multiple frequency ranges. We noticed that the normally loud and powerful acoustic performance of the device was significantly reduced. Upon inspection, we found loose screws in the block connector that held the wires to the board, resulting in weak or no signal in some of the transducers.

Additionally, the bass shaker appeared to be either damaged in transit or when connection shorted or suddenly connected with signal - causing mechanical components within the transducer to break.

While this unfortunate situation resulted in a poor demonstration and experience for Vincent, it presented an opportunity to further engineer the internal components.

RX202 - November 9, 2020

~~Strikethrough~~ text indicates that the element was changed and no longer used.

- Large 2-stage wooden enclosure
- 2 x Dayton Audio TT25-8 PUCK 15W tactile transducer
    - ~~1 x Dayton Audio BST-1 50W bass shaker~~
- 4 x Dayton Audio 40W 4Ω exciters (different but similar models)
    - ~~2 x Dayton Audio DAEX30HESF-4 40W 4Ω exciters~~

- 2 x 100W/channel stereo Bluetooth amplifier boards
    - ~~1 x 50W+50W+100W 2.1 amplifier board~~
- 1 x Raspberry Pi Bluetooth sink and DSP
- 1 x USB soundcard
- 1 x piezoelectric ‘microphone’

When the larger bass shaker broke, it presented an opportunity for us to gain a significant amount of real estate back within the device. After considering our options, we decided to use two smaller Dayton Audio PUCK™ bass shakers, which are extremely compact and have an RMS power rating of 15W and a peak power of 30W.[107] By putting two of them next to each other, we were able to introduce 60W of peak power (although only 30W of RMS power) in a slimmer, but wider form factor than the larger 50W RMS Dayton Audio BST-1. This decision allowed us to create a more compact product that fit inside of the enclosure, which was important due to our focus on making a device that could be non-destructively attached to gaming chairs.

By using smaller bass shakers, amplifiers, and foregoing an internal power supply, we were able to significantly increase the available internal volume inside the enclosure. This allowed us to easily route all necessary wiring with room to spare.

107. "Dayton Audio TT25-8 PUCK Tactile Transducer Mini Bass Shaker 8 Ohm," Parts Express, accessed November 19, 2020, https://www.parts-express.com/Dayton-Audio-TT25-8-PUCK-Tactile-Transducer-Mini-Bass-Shake-300-386?quantity=1.

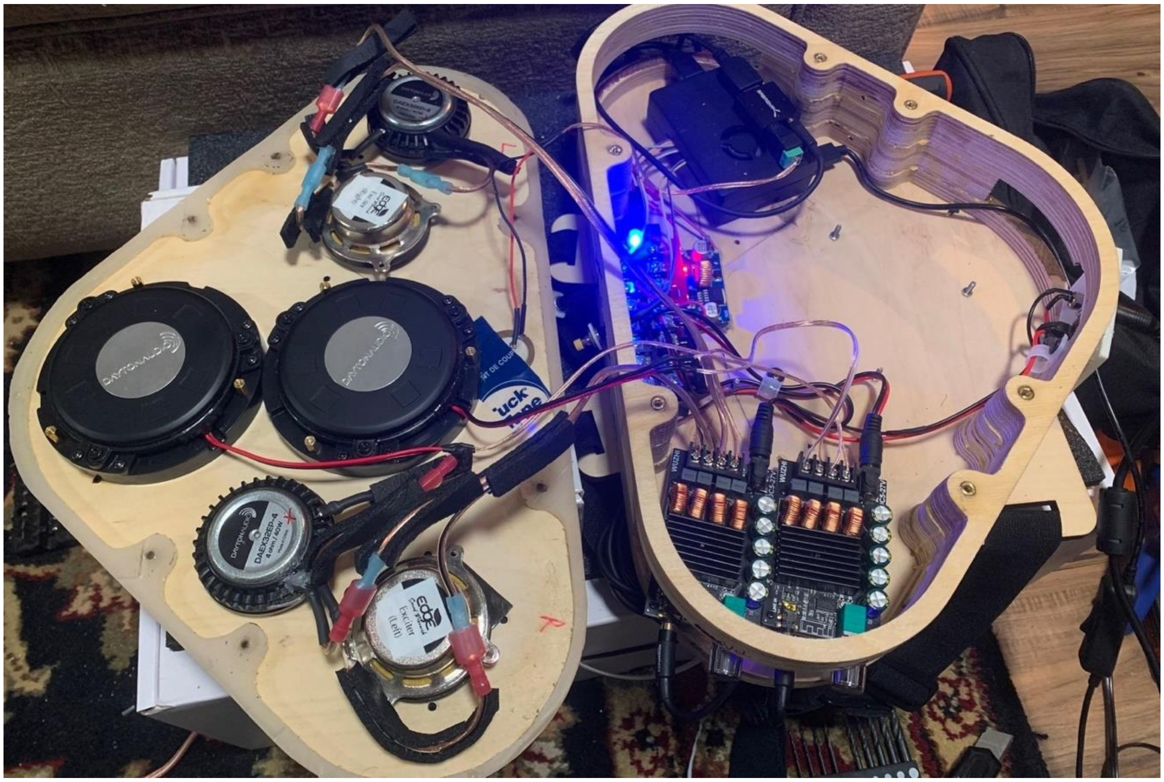

Figure 27: New internal components of RX202

We attempted to use the piezo crystal as an input method to determine the frequency response at the resonant plate and engage the calibration sequence that Winson had been working on. However, we were unable to achieve a consistent or desired outcome from the system. The calibration method was based on something similar to how Room EQ Wizard functions:

- play a known an impulse response on a system
- measures captured frequency response against a predetermined target curve
- creates a series of biquadratic filters to compile a summed filter curve
- applies the array of filters to 'correct' the incoming signal so that it matches the target curve before being passed along to amplifiers for playback.

Although the testing with Dayton Audio OmniMic V2 calibrated microphone demonstrated that we could match REW-style correction, when we used the piezo input method, the algorithm would return a highly skewed response.

We found that further investigation was needed to understand the signal chain between input devices and the interpreted signal received by the computer. It was also important to determine a method for evaluating the performance of our input method and/or identify a solution to correct for piezo frequency bias. While some preamplifier circuits claim to be capable of addressing this issue, our initial investigation has revealed that they are only effective for specific models or sizes of piezo pickups.

RX203 - November 29, 2020

~~Strikethrough~~ text indicates that the element was changed and no longer used.

- Large 2-stage wooden enclosure
- 2 x Dayton Audio TT25-8 PUCK 15W tactile transducer
- 4 x Dayton Audio 40W 4Ω exciters (different but similar models)
- 2 x 100W/channel stereo Bluetooth amplifier boards
- 1 x Raspberry Pi Bluetooth sink
    - ~~1 x Raspberry Pi Bluetooth sink and DSP~~
- 1 x USB soundcard
- 1 x Dayton Audio DSP-408
- 3 x piezoelectric ‘microphones’
    - ~~1 x piezoelectric ‘microphone’~~

Figure 28: RX203 with three piezo pickups (left) the Dayton Audio DSP-408 joins the design (right)

To try to increase the overall signal presented by the piezo microphone(s), we included two additional low-cost piezo crystals, and enveloped all three with a thick outer layer, mirroring some of the premium piezo options we observed on Etsy and other third-party marketplaces. This was designed to eliminate some of the resonant frequencies that exist due to the brass plate that most piezo crystals are attached to. We observed more of the existing bias, but we lacked another microphone or a calibrated method to test other input sources at the time. In short, this approach did not significantly change the unreliable outcome, and only served to complicate our build.

Without the necessary knowledge of how to calibrate our input source, we did not have a method to successfully implement DSP to correct the device's frequency response.

For this reason, we had to use the Dayton DSP-408, even though it didn't fit inside the enclosure. As a result, it remained as a "hump" on the back of the RX203 until we could get the Raspberry Pi to work as a functional calibration and DSP device.

RX204 - January 28, 2021

~~Strikethrough~~ text indicates that the element was changed and no longer used.

- Large 2-stage wooden enclosure
- 2 x Dayton Audio TT25-8 PUCK 15W tactile transducer
- 4 x Dayton Audio 40W 4Ω exciters (different but similar models)
- 2 x 100W/channel stereo amplifier boards
    - ~~2 x 100W/channel stereo Bluetooth amplifier boards~~
- 1 x Raspberry Pi Bluetooth sink and DSP
    - ~~1 x Raspberry Pi Bluetooth sink~~
    - ~~1 x Dayton Audio DSP-408~~
- 1 x USB 5.1 soundcard with 2 inputs
    - ~~1 x USB soundcard~~
- 1 x piezoelectric ‘microphone’
    - ~~3 x Piezoelectric ‘microphone’~~

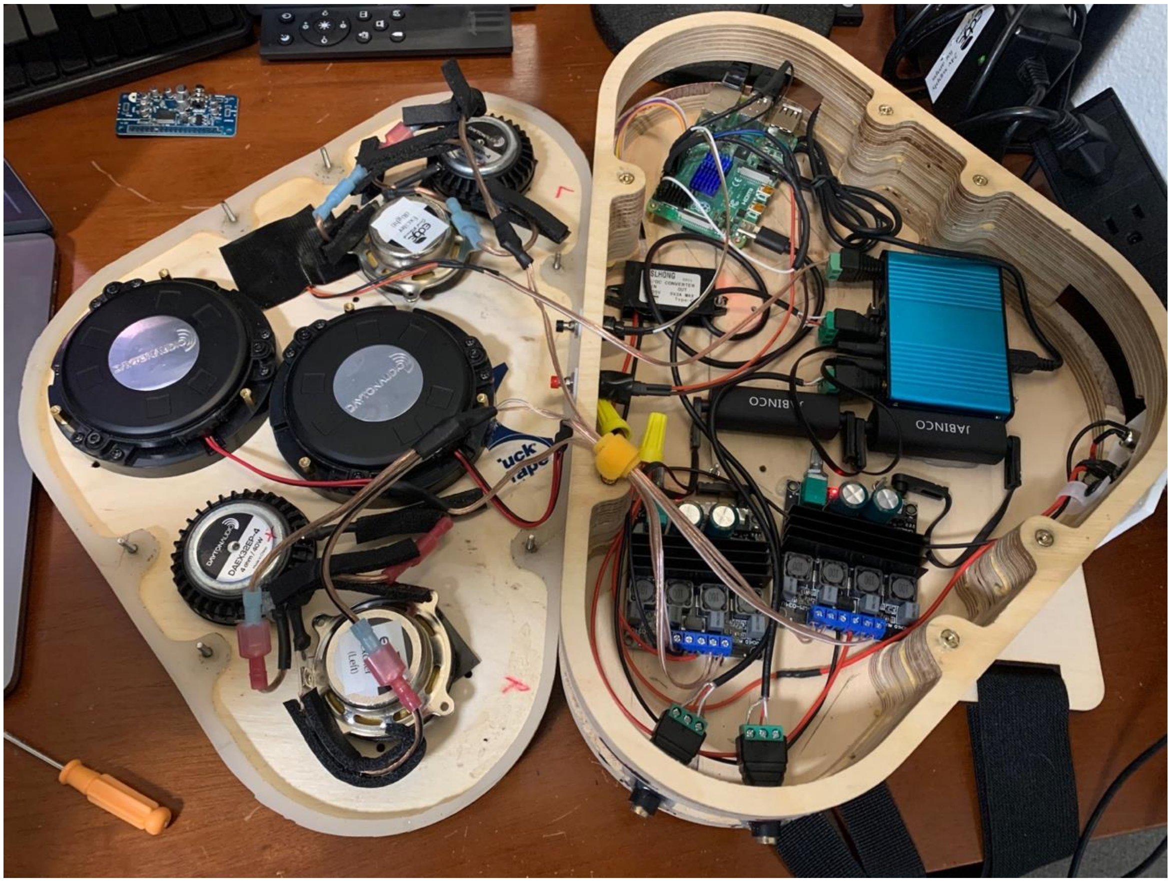

Figure 29: A photo showing the internal components of RX204 - the final prototype in this wooden form factor

We used a variety of software packages available for Raspberry Pi, such as PulseAudio, BlueALSA, Jack, Pyo, and an open source autoEQ tool, to transform the Pi into a multifunctional device that could serve as a programmable Bluetooth sink, crossover/DSP, and input/output method. To achieve this, we needed a dedicated USB sound card with multiple channel outputs and at least one pre-amplified input to enhance our passive piezo pickup. After some research, we found an affordable 5.1 channel USB sound card that allowed us to send uncompressed PCM audio to each of the amplifiers and offered a pre-amplified microphone and line-level input.

We also discovered that we needed to isolate the transmission of signal from the soundcard output to the amplifiers, since all devices were sharing the same ground, introducing a ground loop, producing undesired feedback.

The signal flow for the custom software imposed on the Raspberry Pi is as follows:

1. Raspberry Pi Bluetooth audio sink (via PulseAudio/BlueALSA) to receive audio stream
2. Jack for to route audio to autoEQ
3. Auto EQ sequence (generates filters for Pyo in next step)
4. Pyo for crossover, dynamics control, filter bank assignment (from previous sequence)
5. Back to Jack for routing to sound card
6. Soundcard outputs:
    1. 1,2 for exciter conditioned output
    2. 3,4 for headphone out port
    3. 5,6 for bass shaker conditioned output
7. Ground-loop isolators to remove ground feedback loops for Exciter and bass shaker signals to amplifier
8. Bass shaker and exciter 100W/channel amplifiers
9. 2 x Dayton Audio PUCK 30W bass shakers, 4 x 40W Dayton Audio exciters.

Results

RX202

We analyzed the frequency response of the device by taking an FFT sample using a spectrogram app which used the iPhone XS Max's built-in microphone:

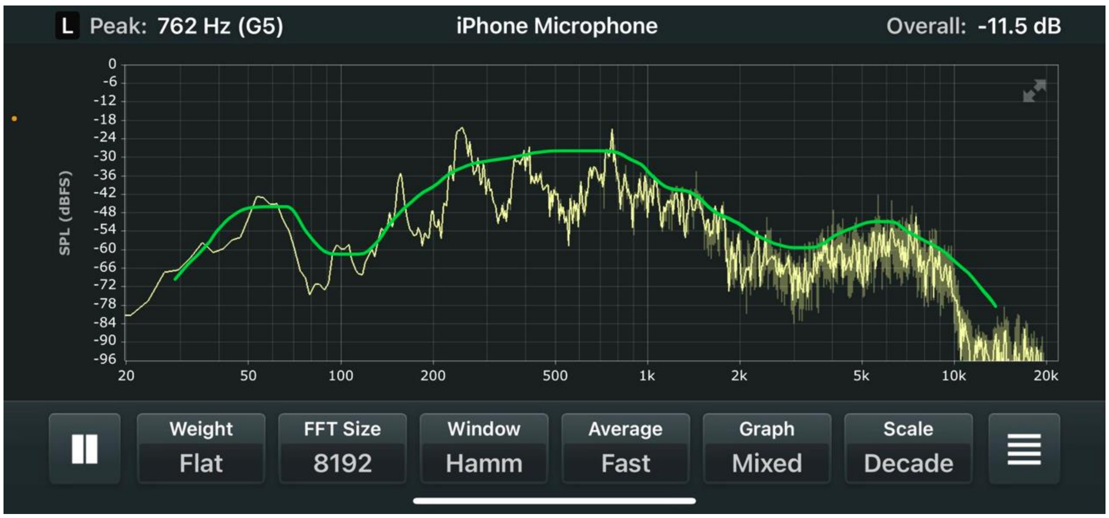

Figure 30: FFT plot capture of pink noise on RX202 device by iPhone XS Max microphone, with hand-drawn curve outlining frequency response of the device. Taken Nov 10, 2020

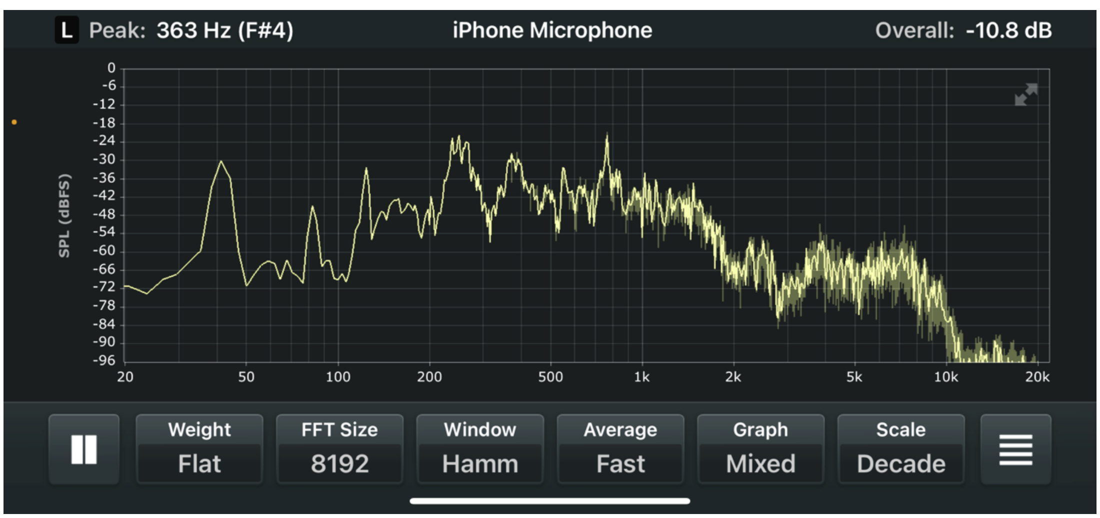

Figure 31: FFT plot capture of pink noise of RX202 device with bass frequencies increased, by iPhone XS Max Microphone Taken Nov 10, 2020

While the frequency response began to fade just above 1.5kHz, the fact that the acoustic microphone was able to pick up any significant frequency response from 40Hz - 1.5khz ±30dB marks a promising result for a prototype vibrational device.

While acoustic microphones were capable of interpreting the frequency response, we had significant trouble capturing a reliable signal from the Piezo pickup vibration microphone:

Figure 32: Room EQ Wizard Graph showing the combined frequency responses from the Piezo pickup, and the OmniMic V2 calibrated microphone

RX203

The DSP-408, while unwieldy and needing to be placed on the outside of the device, proved to be a very stable DSP device for crossover and EQ for each channel. With the DSP-408, we were able to take some measurements with the OmniMic V2:

Figure 33: Screenshot of Ethan Castro testing the frequency response of the RX203 with a calibrated microphone. Taken November 24, 2020

By holding the rear of the device, the silicone ring allowed the resonant plate (facing the microphone) to resonate without interference so the microphone would be able to efficiently pick up all produced frequencies. It is understood that placing the device at least a foot away from the calibrated microphone would produce less biased results, but the team was concerned that the microphone would be more biased to the acoustically present higher frequencies than the inaudible bass frequencies.

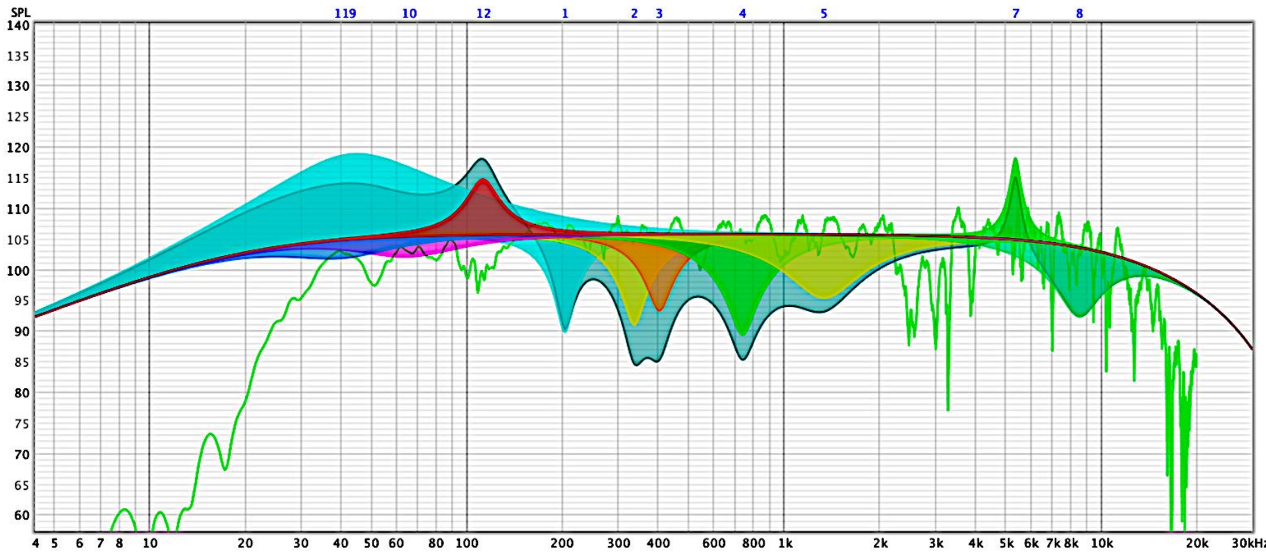

Figure 34: Screenshot from Room EQ Wizard (REW) showing the potential flat frequency response if the proposed filters were applied to the output signal. Taken November 20, 2020

The difference with and without the Pyo processing module can be seen via measurements taken with the processing module bypassed:

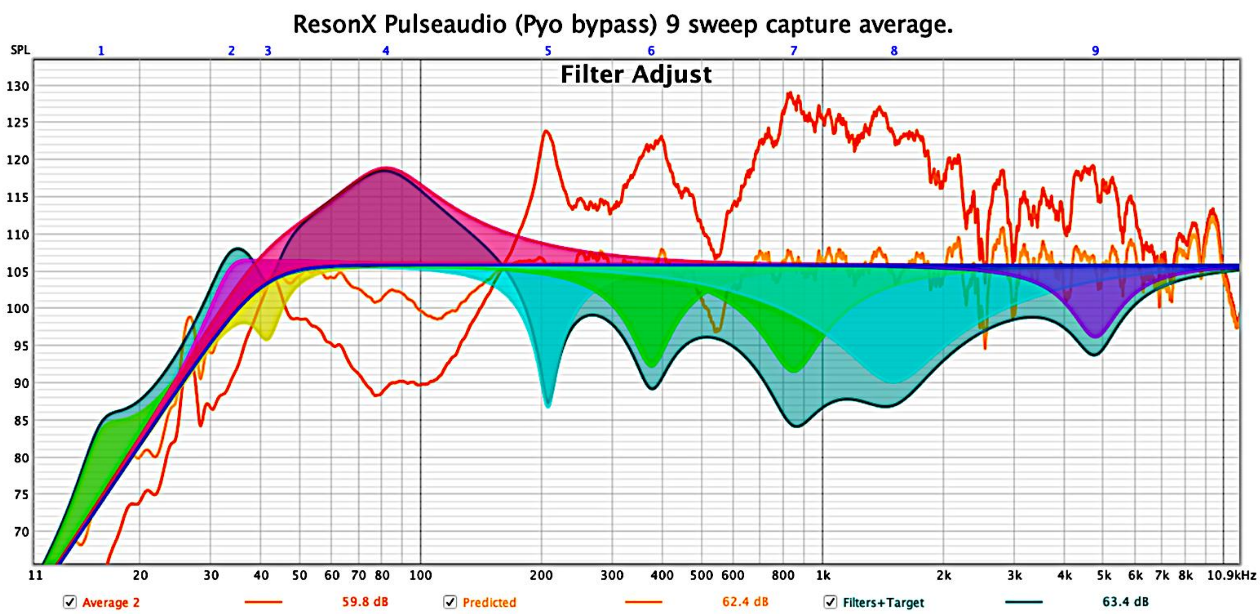

Figure 35: Screenshot from REW showing raw audio output (dark orange), and potential response (light orange) if the proposed multicolored filters were applied to the output signal. November 23, 2020

The frequency response of the RX203 and corresponding corrective EQ filters indicated a balanced post-processed frequency response from 30Hz to 10kHz, ± 10dB for the majority of the bandwidth (except a ~20dB dip at ~2.7kHz).

After attempting to use the piezo as a vibrational microphone again, we received the following result after multiple attempts:

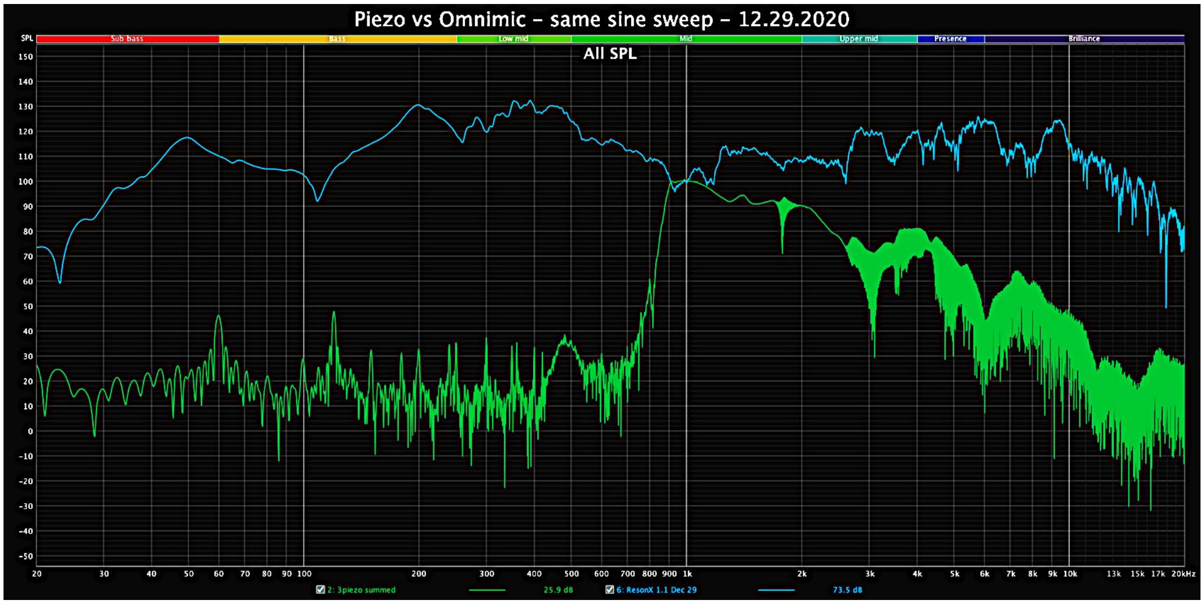

Figure 36: Screenshot from REW showing the difference between the calibrated Omnimic and the Piezo pickup capturing a sine sweep performed on the RX203

The calibrated OmniMic reported the same response that has been previously observed, with the piezo microphone only reporting a significant signal response from 1-5kHz, where the frequency response promptly begins to fall off.

Discussion

By this experiment, the team was quickly growing towards the startup direction, as research funds were found from grants dedicated to help student-startups, which meant that the team was exposed to other limitations besides acoustic performance: user interface/design, willingness to pay, and repeat manufacturability. These restrictions impacted this experiment, as obvious solutions to certain problems like material, shape, overall power, etc. were not implemented.

For example, it seemed that early customers would be gamers, hence the strong focus on attachment to gaming chairs, this meant that even though a larger, more robust version of the device could be made with professional audio components (rack mounted amplifiers and DSP), a focus on making a compact product limited us to consumer grade hardware that was compact enough to fit inside of the compact enclosure.

As far as measurements go, the OmniMic seemed to be the most reliable form of controlled comparable feedback of the device's performance. While we could not get the piezo microphone to function as expected, the perceptual tactile response of the researchers' bodies could suffice until a controlled calibrated physical vibration microphone solution could be achieved.

Conclusion

The goal of this experiment was to attempt to create a device that is able to be non-destructively attachable to a gaming chair (also to be non-destructively removed) by a single person, and produce a balanced frequency response from subsonic frequencies at

±10Hz from 20Hz to the critical bands of human speech around ±1kHz from 2kHz. The RX203 achieved the milestone, and even achieved a somewhat balanced acoustic frequency response from 30Hz-10kHz after post processing was applied.

This result supports the original hypothesis that combining vibrotactile and vibroacoustic experiences can create a full-range sonic experience driven entirely by vibrations through a substrate. Although the substrate used in this experiment is known and controlled by the research team, it is reasonable to assume that a successfully automated calibration algorithm can be applied to an unknown substrate and produce a similar frequency response.

ResonX RX300

Objective

Our RX200 series prototypes eventually achieved a balanced acoustic response from 30Hz-10kHz ±10dB after post processing was applied—a milestone in this line of experiments. Since performance parity with acoustic alternatives was achieved,[108] the goal of this experiment was to address potential customer usability to begin alpha testing with potential customer segments.

Mostly focused on design objectives, this experiment explored the following areas as directed by Vincent Zhang:

1. Size reduction
    a. Any mass reduced from the device means more energy is transferred from the transducers to the substrate that the device is attached to, and less of the vibrational energy is lost in the mass of the device itself or its housing.
2. Ease of iterative prototyping
    a. Creating prototypes out of wood was time-consuming, so we decided to prototype faster and evolve our hardware beyond a tiered laser-cut design strategy. We used 3D printing to quickly refine our designs. Although FDM printing with PLA material was less than ideal, it was forgiving in the

108. Not necessarily 'good' acoustic performance, as the extremities (20Hz, and 20kHz) of the acoustic range were lacking, and there was still significant deviation across the existing frequency range.

prototyping stage. We initially designed for easy 3D printing and assembly, while keeping in mind design for manufacturing.

3. Visual language
    a. In the early stage, we explored how stakeholders and users would perceive our new design, which was a rare opportunity for designers. Since no one had experienced this technology, we needed to explore how the design would explain what it did, how it could be used, and how it fit into different settings.

Throughout the experiment, we developed a total of five prototypes, each crafted to maximize our learning outcomes.

Experimental Design

During this experimental series, the design and structure of the module changed quite rapidly. As such, each new design will be indicated by appending an integer to the series indicator (RX300 Design 1, RX300 Design 2, etc.) and larger or hard changes like internal component swaps, or shape variations and assembly methods by adding an integer to the model number itself (RX301, RX302) to keep track. **Materials** and **methods** will be combined under each variant, with a short overview of results that led to the next variant.

RX300 - Design 1

During the initial planning stages for the first ResonX enclosure, Vincent explored some brutalist designs that involved tightly wrapping the larger block components that we had at the time. As we gained understanding of the internal components and the principles of vibration transfer, we experimented with shortening the triangle hard lines and wrapping the components more closely. We also considered the use of protruding bumps where the transducers would be placed to reduce the amount of material between the transducer and the chair.

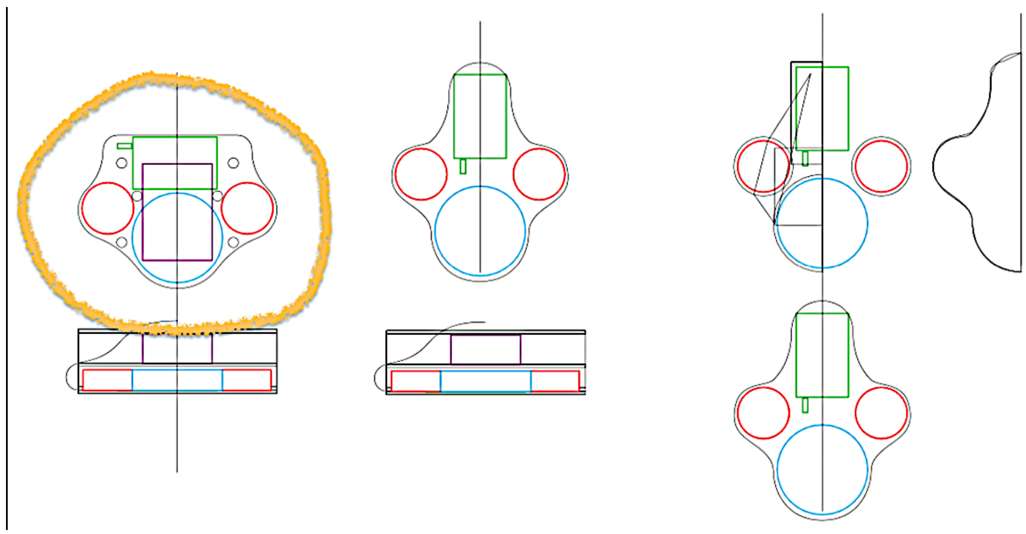

Figure 37: Vincent's Illustrator file for RX100 showing outlines of various enclosure designs around outlines of components.

The original RX300 prototype design featured an enclosure that tightly wrapped around the components, with the outline of the enclosure matching the outline of the internal components. Additionally, there were protruding bumps on the bottom of the enclosure that allow the transducers to make maximum contact with the substrate:

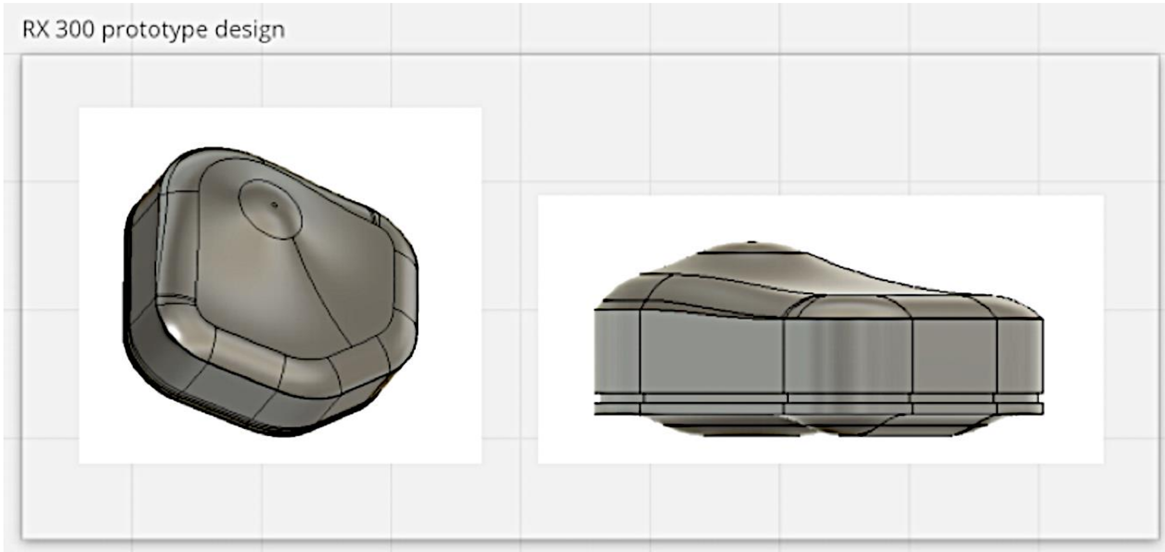

Figure 38: RX300 Prototype Design 1 – brutalist design with protruding bumps on bottom for better contact

RX300 - Design 2

Vincent proposed a radical design shift from wrapping enclosures with specific contours, which proved challenging to manufacture, to a simple shape design language that would be easier to manufacture and more amenable to user experience:

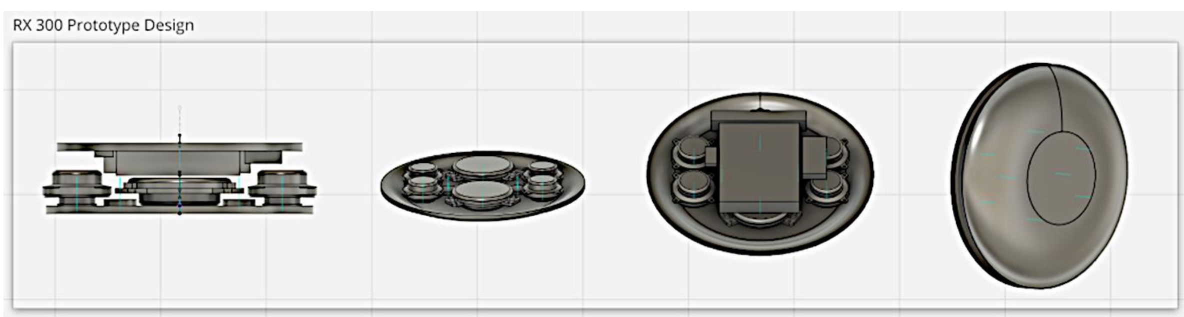

Figure 39: RX300 Prototype 'bowl' Design 2

The rounded shape, while retaining the same internal volume, handles the components in the natural curvature of the bowl-shape, while appearing much thinner at the edges, especially compared to the blocky RX200 design:

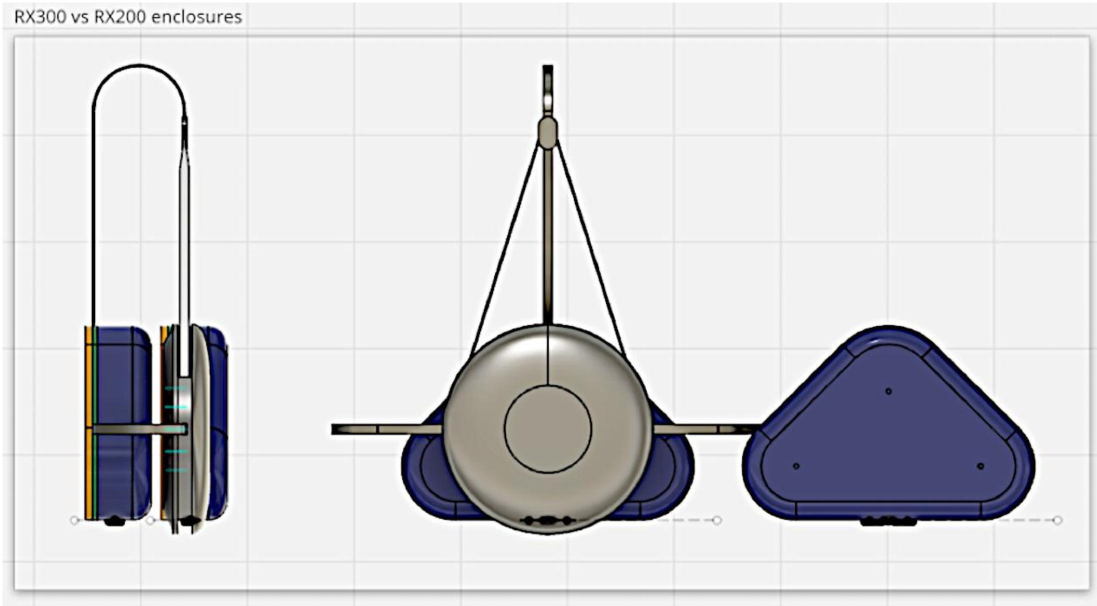

Figure 40: Proposed RX300 - Design 2 vs old wooden RX200 Design

RX300 - Flange Exercise

We then investigated different flange angles, and corner loudness to test internal sentiment on how the device would be perceived. Vincent created 10 different directions (see figure 41) that would still contain the internal components.

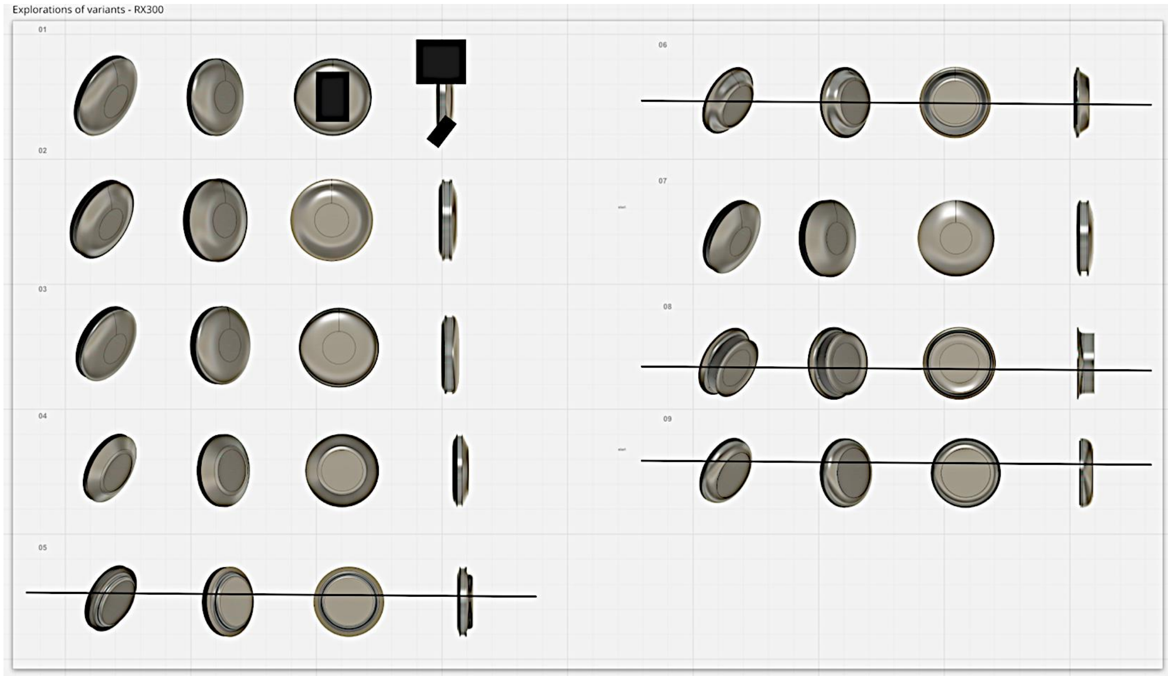

Figure 41: RX300 Variants showing different flanged designs.

Vincent Zhang shares his inspiration for this design direction:

> The circular design is meant to help reduce the visual size of the device. Reducing the design to a fundamental shape help[s] to reduce the layers of complexity we have to go through. It opens up the internal space for a variety of prototyping opportunities. It is a platform to help us develop clarity and simplicity on [the] best arrangement of hardware. It's a continuation in our effort to tame the complexity of the challenge and hits all 3 of our design criteria at the time.[109]

RX300 - Design 3

After thorough consideration and collaboration, we reached a consensus on a distinctive combination of design features for the ResonX RX300. The resulting design

109. Vincent Zhang via Slack, 4/19/2022

showcases a circular shape that resembles a resonant plate and incorporates a cover that can function as a lid. The cover has an increasing slope towards the edge, providing a visually appealing design to enhance the user experience while handling the device:

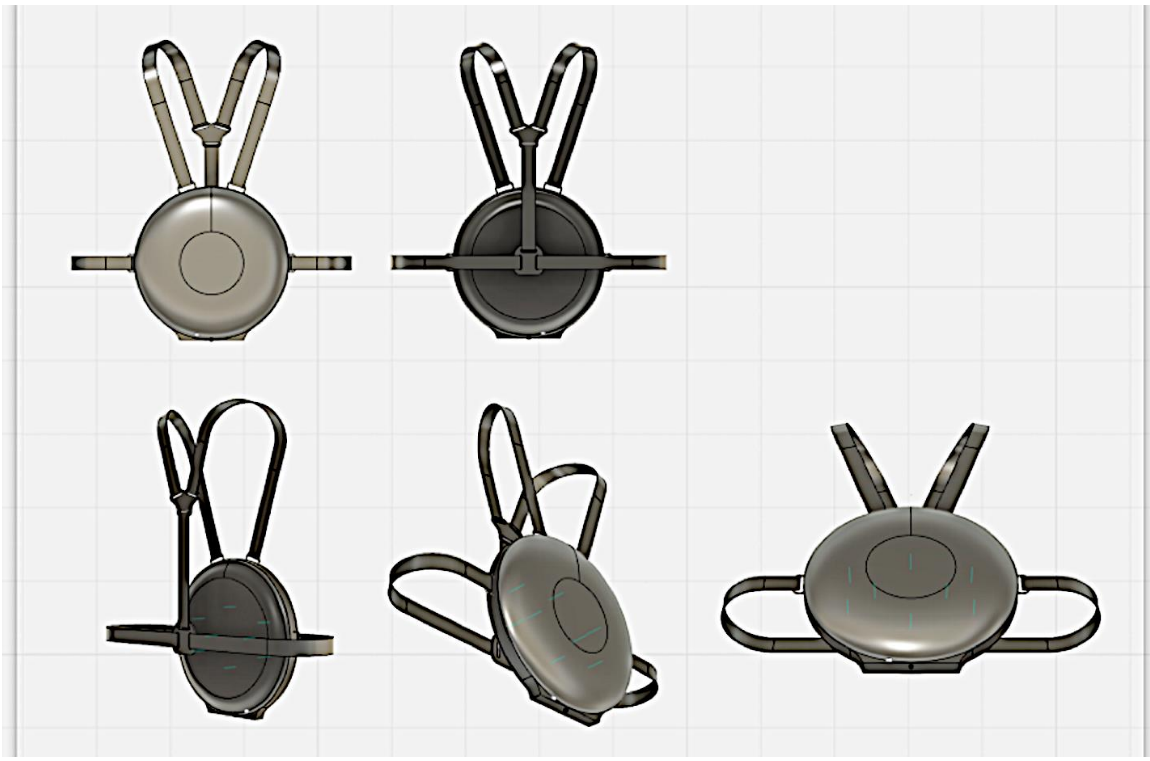

Figure 42: RX300 - Design 3 direction after design exercise

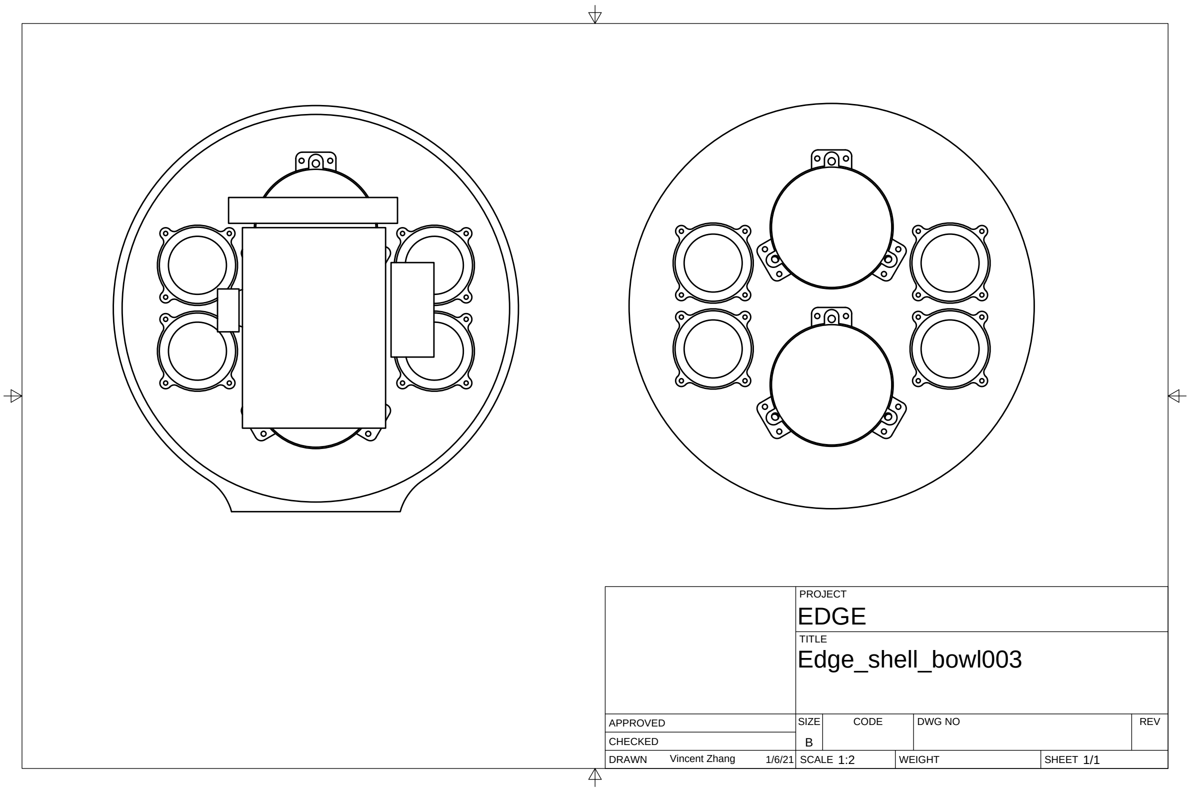

Figure 43: Schematic showing internal component layout of RX300 - Design 3

After conducting digital measurements and analyzing device specifications, we arrived at the conclusion that we needed a larger-form factor 3D printer to create our prototype. We chose the Snapmaker 2.0 A350 as our printer of choice. This particular 3D printer was selected because it was the right size to accommodate the specifications of our prototype. With this printer, we had the ability to quickly create and iterate a more accurate and precise prototype that was in line with our design objectives.

We used grant money awarded by the National Collegiate Inventors & Innovators Alliance (NCIIA), also known as VentureWell, and their E-teams program to purchase a device with modular construction. The device's ability to swap between CNC, laser etching, and 3D printing at an affordable price made it the go-to solution for all-in-one rapid iterative prototyping. We quickly learned Snapmaker's 3D print slicer software—Snapmaker Luban—enabling us to print the first resonant plate on the machine to test the fit of components:

Fortunately, all components were installed with a precise fit, albeit with minimal clearance between the bass shakers and exciters and the edge of the wall. In order to ensure adequate space around the bass shakers, we removed the bass shaker attachment ring, allowing the exciters to move more freely before securing them to the plate.

We then deliberated about how to arrange the I/O and control scheme via the I/O panel which would be place on the bottom of the device, when viewed from the back of the gaming chair it was designed for (see figure 44).

Figure 44: Renderings showing all the components that make up the RX 300 I/O schema

RX300 I/O panel

At this time, we also worked on the accompanying I/O panel that would allow the user to interface with the internal Raspberry Pi:

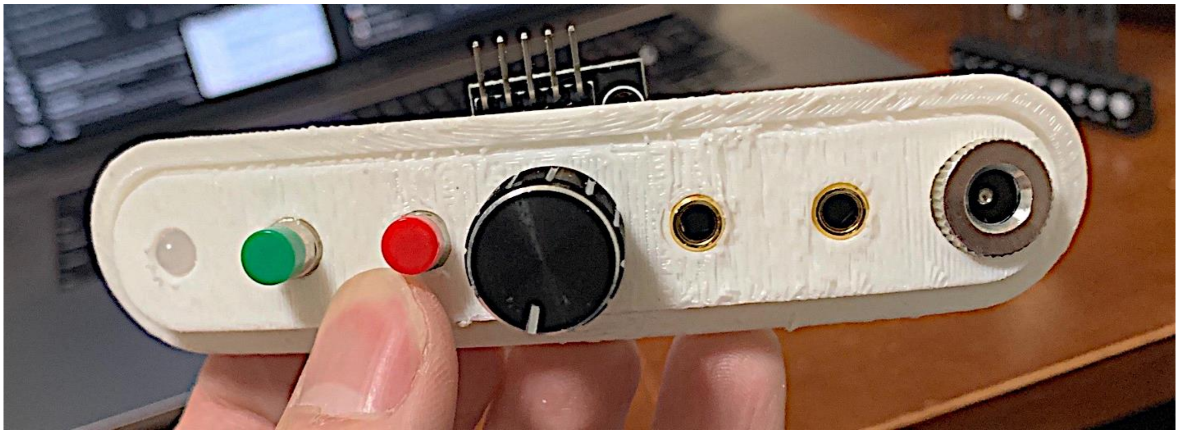

Figure 45: RX300 I/O panel – front

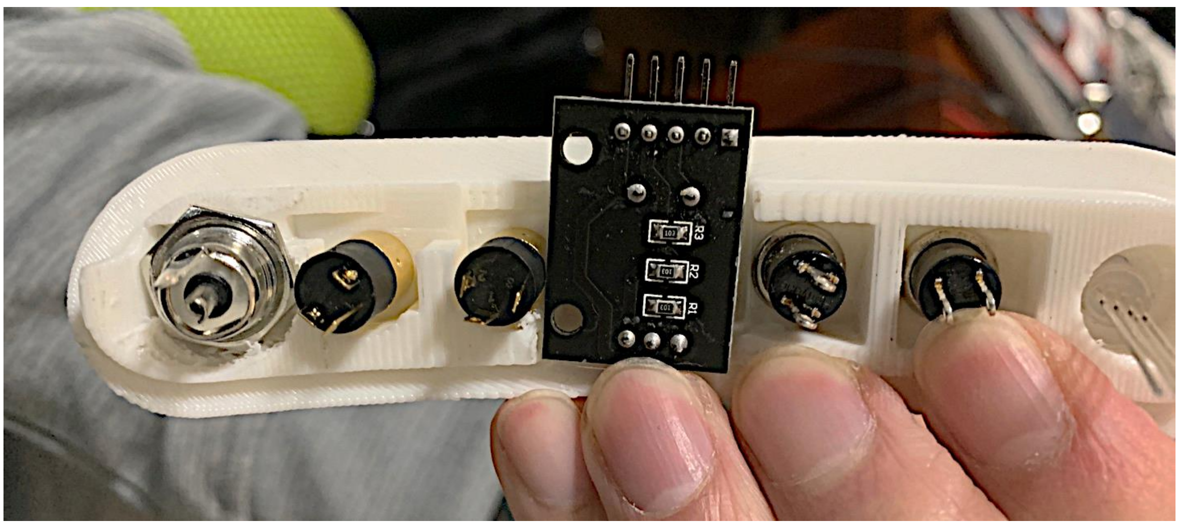

Figure 46: RX300 I/O panel - rear

Panel items from the front, left to right:

- Multicolor (RGB) status LED light
- Green ‘shutdown’ button

- Red ‘calibrate’ button
- Digital encoder with push button for mode switch
- Headphone/line-out 3.5mm jack (3-pole stereo)
- Line-in 3.5mm jack (3-pole stereo)
- DC barrel jack for power input

The individual items were responsible for interacting with different electronic components of the RX300 as indicated by this hardware block diagram:

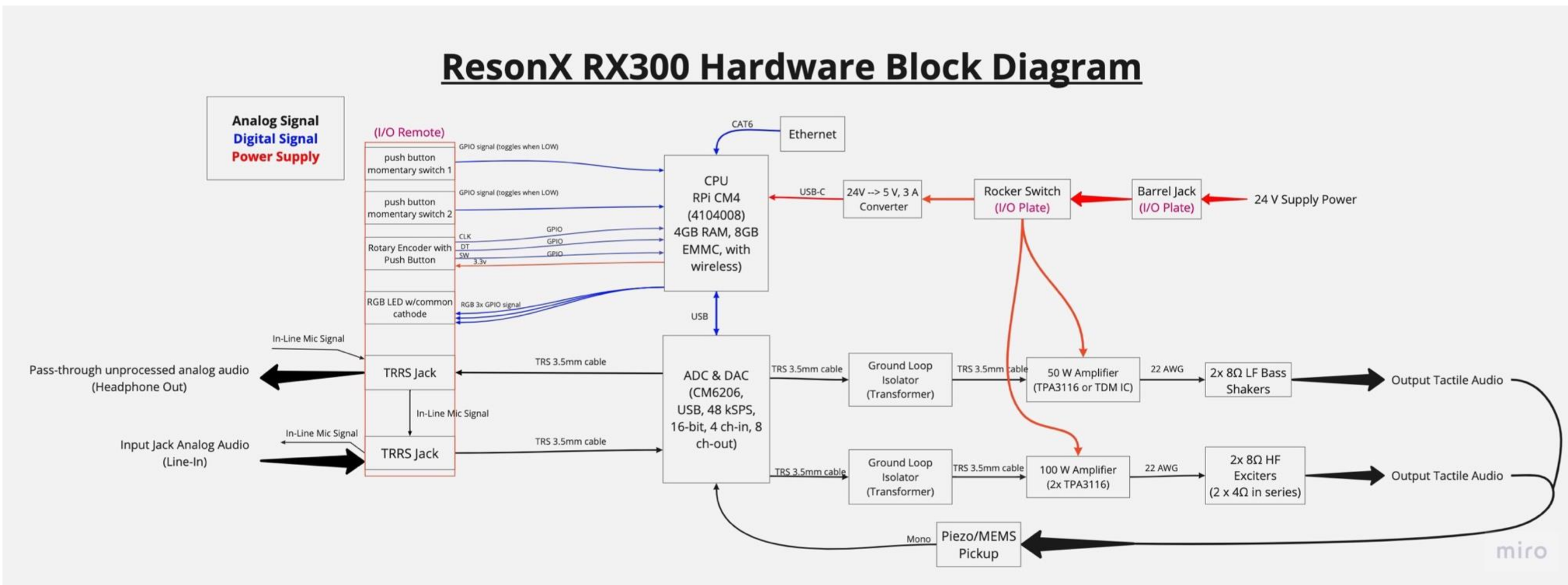

Figure 47: System block diagram of RX300

A software block diagram created by software engineer Winson Bi would show how the auto-calibration process was intended to function, in our custom operating environment.

The diagram in Figure 48 depicts the three main operational states that the device undergoes. The first state is the 'shut-off' state, where the device initiates the process of shutting down when the shutdown button is pressed. The second state is the 'calibration' state, where the device generates correction equalization filters for Pyo to apply if the calibration b

utton is pressed. Lastly, the 'normal' state is the default state when no buttons are pressed, and the audio is streamed with the corrective equalization filters applied:

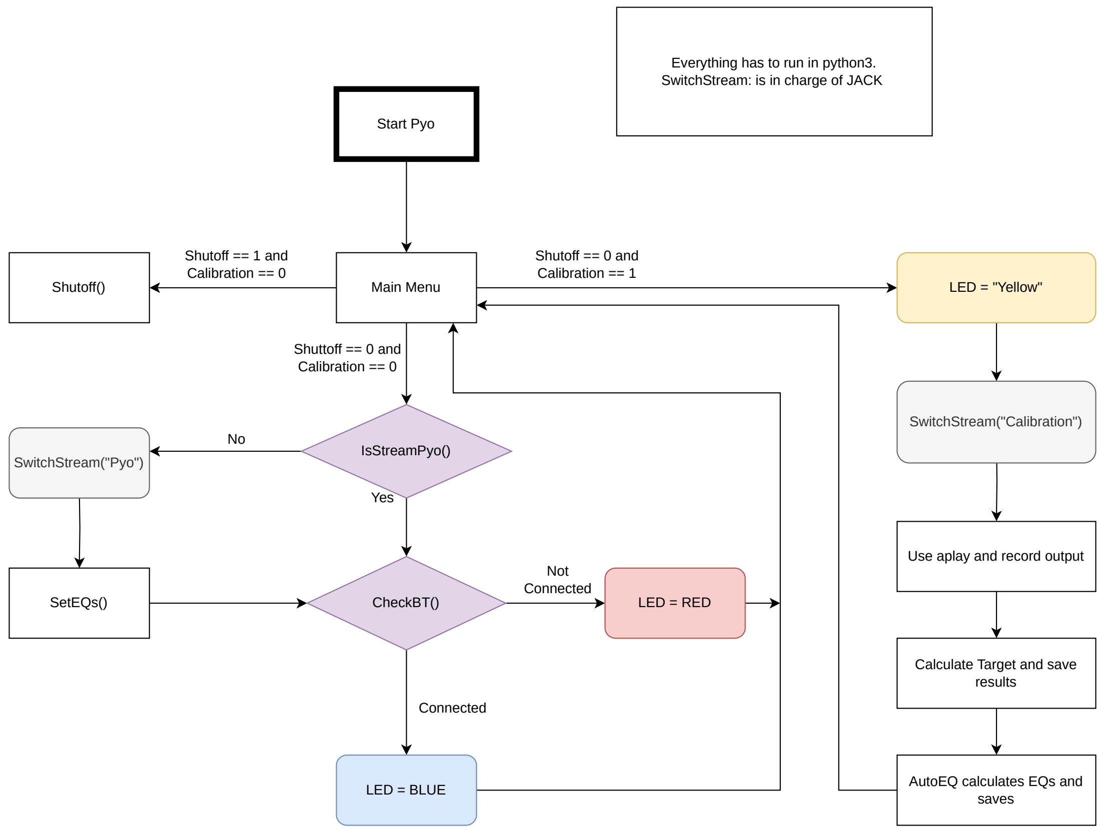

Figure 48: ResonX RX300 software block diagram for the custom operating environment

Together, the electronic hardware and software function as the user interface of the ResonX experience, regardless of enclosure.

RX300

The first prints to come out of the Snapmaker, turned out surprisingly well, with a consistent quality, and reasonable roughness. Vincent assembled and sent over photos of the first ResonX RX300 enclosure:

Figure 49: First RX300 3D print shells

Once Vincent confirmed the fit, we proceeded to print our own set of RX300 enclosures in Los Angeles, using the same .STL files. We had the smaller Snapmaker Original printer available from a previous grant, which we used to simultaneously print the smaller I/O panel. Overall, we were able to successfully print and assemble our own set of ResonX RX300 enclosures with the necessary modifications.

Figure 50: RX300 second print with I/O port

After completing the construction of the resonant plate, our next step was to mount all the transducers onto it. While we used the built-in adhesive on the exciters, we decided to opt for silicone to mount the ABS plastic of the bass shaker to the plastic PLA that we used to construct the enclosure's chassis. This is because we removed the mounting ring for the bass shakers, and silicone is the most sensible adhesive for this purpose.

Our reasoning behind choosing silicone is that it is compliant and pliable even when dried, which allows it to transfer most low-frequency vibrations. Additionally, it protects against plastic-on-plastic noise transmission that stiffer adhesives would have caused due to brittleness.

Furthermore, we took this opportunity to lay out the electronics on the surface plate. It's worth noting the silicone O-rings around the screw threads that insulate the electronics plate from vibrations coming from the resonant plate:

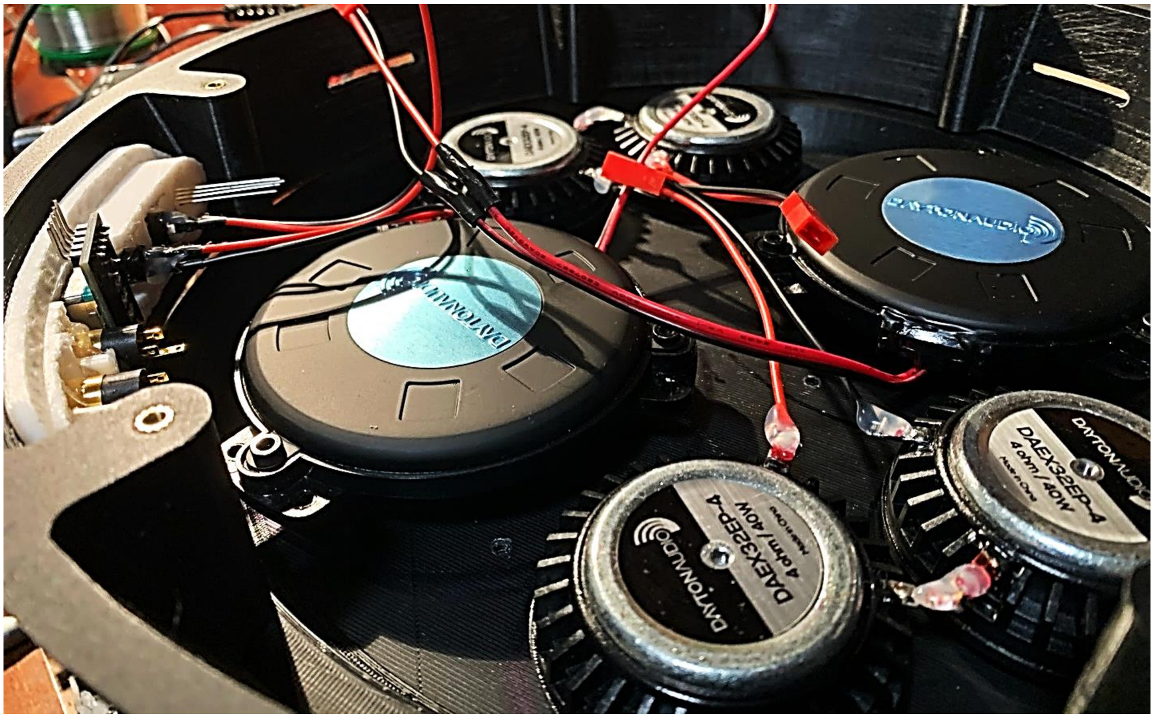

Figure 51: Transducers in RX300 RP, surrounded by the mid wall and I/O panel

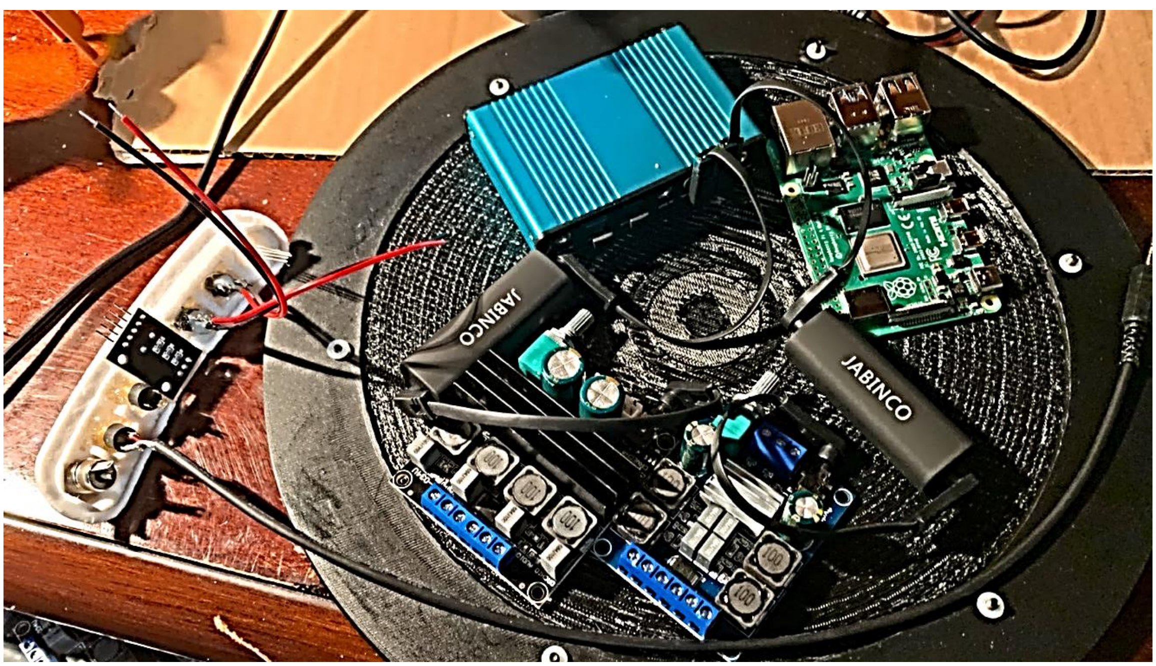

Figure 52: Electronic components sharing space on the RX300 EP

At this stage, we were able to define the three sections of RX300 (plus the I/O Panel):

- **Resonant plate (RP)** where the transducers are affixed, designed to be placed upon a substrate.
- **Electronics plate (EP)** where the components that receive and transform raw power and signal into conditioned powered signal for the transducers on the RP to use.
- **Mid wall** - a thick ring that separates the RP and EP, while holding the separate **I/O panel**

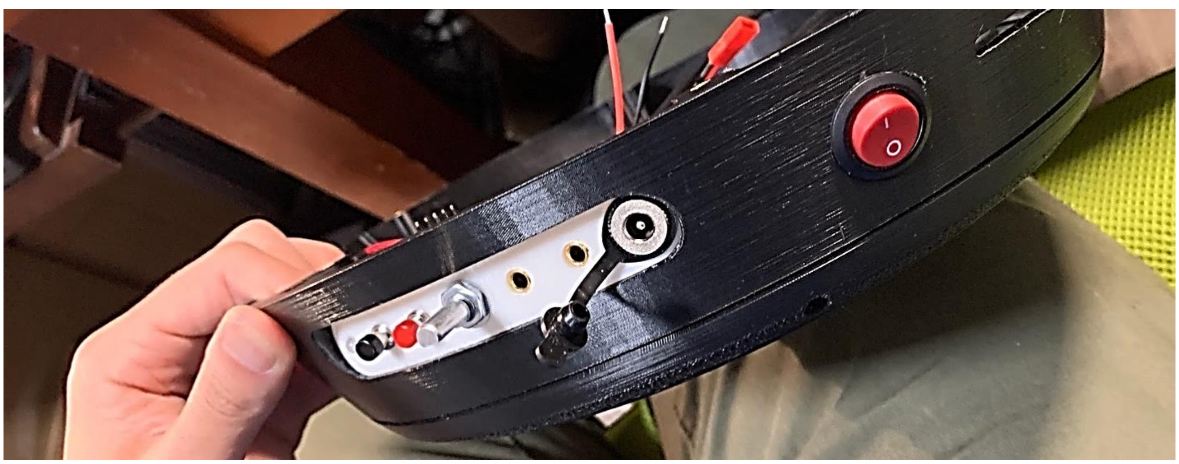

Figure 53: External view of RX300 I/O panel within the mid wall, missing knob on digital encoder

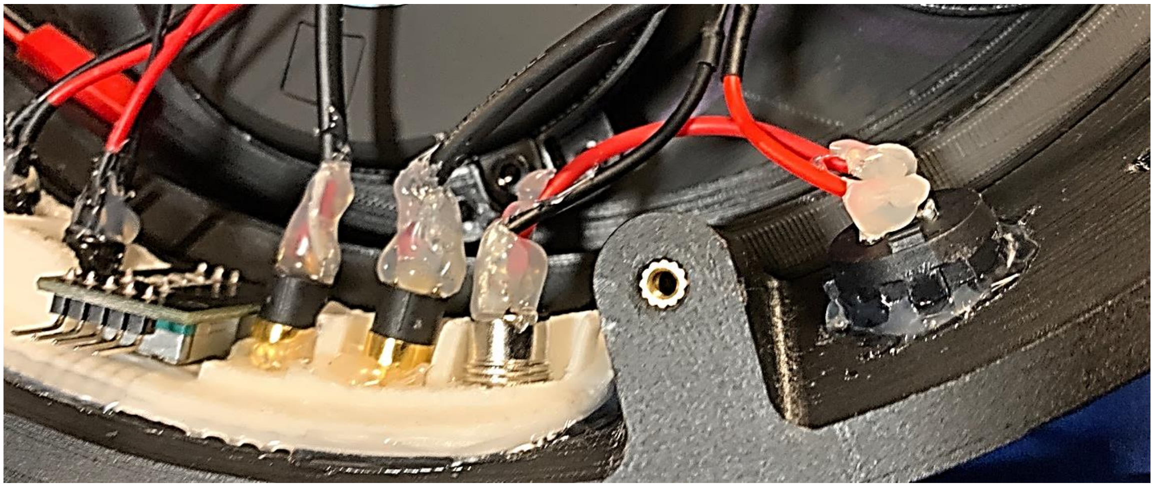

Figure 54: Interior view of fully assembled RX300 I/O panel, missing header pins to digital encoder

Integrating built-in leads and lead-less components can present challenges when connecting them without additional wiring. To address this issue, we opted to use JST wire-to-wire quick disconnect connectors. These connectors allowed seamless swapping of any component that did not already have a removable connector, thereby streamlining the troubleshooting process.

It took roughly nine hours to connect all the components in a single prototype because every cable had to be custom-made to a specific length, depending on where the electronics were placed on the electronics plate (EP). Mounting the components was particularly frustrating since after making custom cables for every component, we found that we needed more compliance to insert the jack at an awkward angle, and then re-mount the component, which made it extraordinarily difficult to measure the distance needed for creating a custom cable. This problem was compounded with several components, such as the amplifier and sound card, where the 3.5mm male connector itself is often as large as the distance needed to connect the plugs.

Figure 55: Ethan Castro building the first RX300 prototype on March 16, 2021

The cable assembly inside the device was positioned in a way that allowed the EP to lay flat, while the RP was propped up at a 90-degree angle for easy connection of the quick-disconnect JST cables before securing the RP onto the mid wall. Silicone O-rings were placed around the screws to reduce vibrations between the RP and the rest of the device, but it was frustrating to see the O-rings fall off the screws just as the device was being closed, getting trapped within the RP and mid wall.

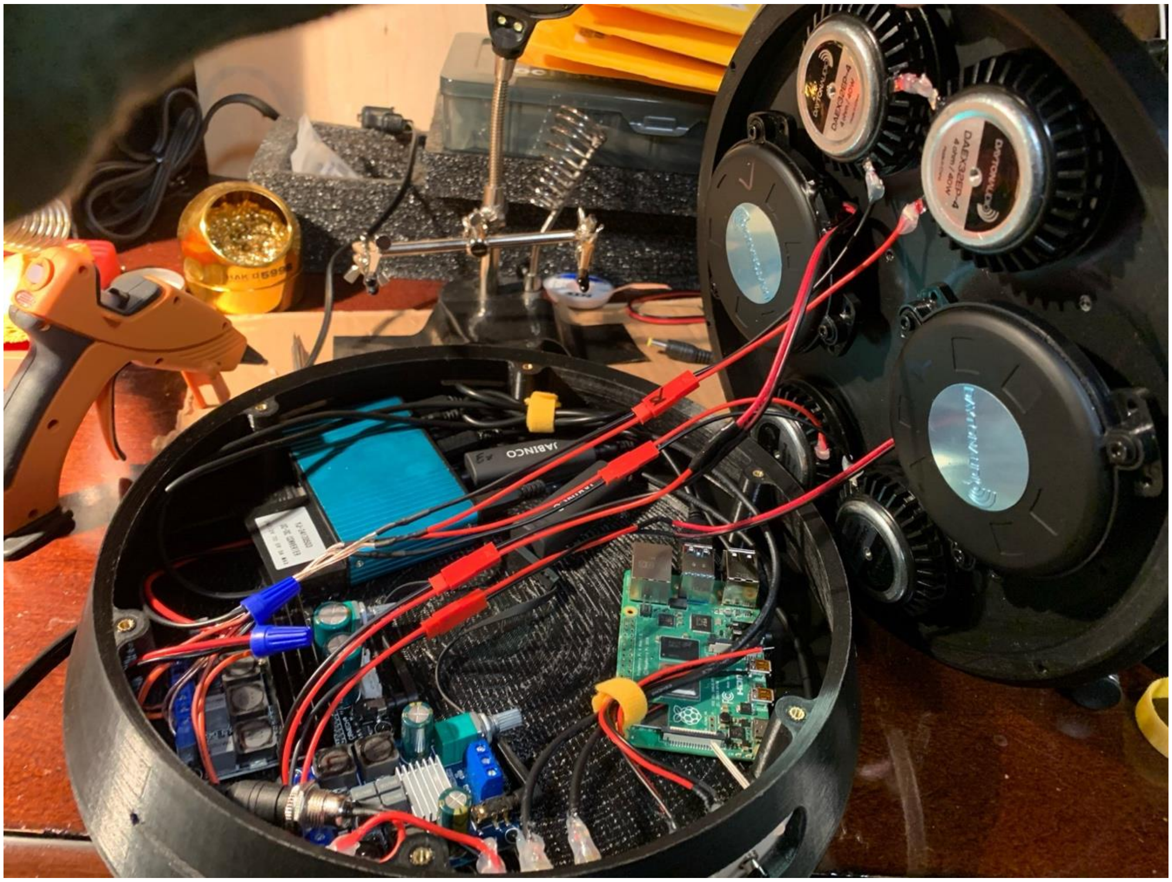

Figure 56: The first RX300 prototype fully assembled.

The following day, we verified that the wiring was correct and proceeded to enclose the device. However, we ended up accidentally breaking the ResonX, since the copper around the GPIO pins was accidentally torn off when attempting to solder directly to the board, which may have also broken the SD card reader in the process.

RX301

On March 24, 2021, we built a new prototype that took 16 hours to complete. This version features a refined I/O panel, and the Raspberry Pi microcomputer was able to retain its pins. Winson finished the software that allowed someone to experience the user journeys that we expected the users to have. In addition, we rearranged the electrical components to make it easier to work on both the RP and EP simultaneously with both sides open flat:

Figure 57: RX301 prototype - March 24, 2021

After presenting the prototype to a few individuals, the device ceased to function properly the next day. Upon closer examination, it was discovered that the hot glue had not properly adhered to the soft-plastic which was wrapped around the ground-loop isolators. To address this issue, we opted to expose all of the components to the circuit board and directly hot glue them to the plastic. This approach ensured a more secure hold and minimized the risk of further detachment.

RX302

During our product development meetings, Vincent and the team collaborated to find a solution for the straps that would fit all chairs, regardless of their specific design. We aimed to simplify the manufacturing method by reducing the number of components required. At this stage, our design included five components that could adjust the height and width of the chair, in addition to the buckles required to strap them together.

During one of the brainstorming sessions, I proposed the idea of having the straps form an 'X' shape. This solution would provide a secure hold in both the vertical and horizontal positions, while also aligning with our 'ResonX' branding. Implementing this design would significantly reduce the complexity of the product. Figure 58, 59, and 60 show deployment of X-straps.

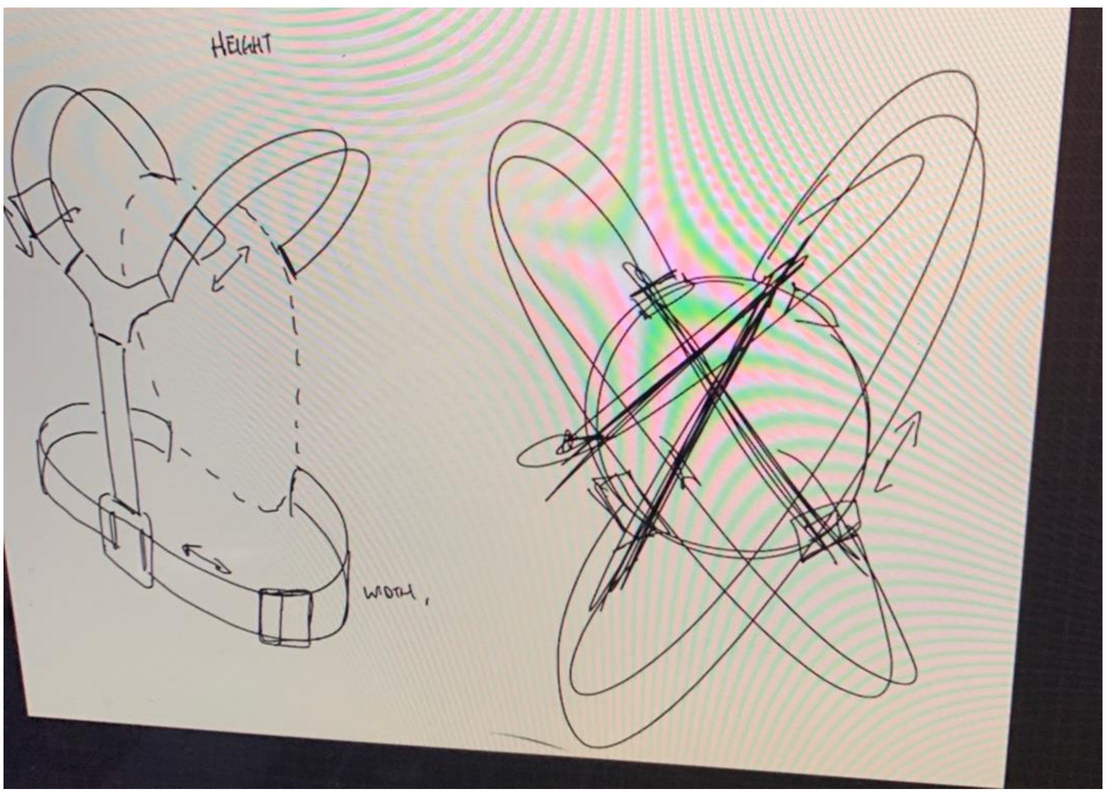

Figure 58: Vincent Zhang's sketch of RX301 with 'X' straps - March 25, 2021

Figure 59: New straps: strong attachment for RX301 with limited interference - April 17, 2021

RX303-305

At this point, we were fairly confident in our device, as it operated with consistency, and was fairly reliable, and the design was approachable by new users. There were three significant issues that we still faced, however: **heat**, **glue**, and **latency**. It would take some experimentation to diagnose specifically where the issues were occurring, and ultimately it would take the feedback from Alpha testers to determine if these issues were even an inhibitor for the end-user.

Figure 60: RX303 on chair back and exploded view of components inside

Glue problem:

Because the components tended to heat up during use, prolonged use caused the hot glue that bonded them together to soften and release. A more robust adhesive was needed that could withstand higher temperatures.

The built-in 3M VHB mounting tape on the exciters could also fail under stress. This was a critical issue as it affected the attachment of the exciters to the RP. A more permanent solution was needed that could ensure a secure attachment of the exciters without causing any interference, similar to the method used for bass shakers.

Three different attachment options for the exciters were proposed to be tested: gel super-glue, epoxy, and silicone, to find the most suitable attachment method that could provide the necessary level of stability and durability for the components' adhesion. All three types of adhesives were attached to the same exciter, on the same 3D print surface, so that an accurate comparison of their performance could be made.

We used mini 3W exciters from Dayton Audio[110] and affixed each one to a spare 3D print part according to manufacturer instructions on package:

Figure 61: Glue test with exciters - epoxy and silicone labels were accidentally swapped - 4/16/2021

During our testing, we discovered that the silicone (the same silicone from adhering the bass shakers) was a suitable adhesive to use with exciters. It did not prevent smaller vibrations of high frequencies from passing. Interestingly, we felt that the gel super glue was easier to control in application, had a shorter dry time, and was slightly less compliant than the silicone. Based on a subjective listening test, it appeared to transfer smaller vibrations more efficiently. Epoxy, on the other hand, was difficult to apply, messy to mix, and gummed up the exciter. It was also the most brittle option.

110. "Dayton Audio DAEX-13-4SM Haptic Feedback Transducer 13mm 3W 4 Ohm," Parts Express, accessed March 26, 2022, https://www.parts-express.com/Dayton-Audio-DAEX-13-4SM-Haptic-Feedback-Transducer-295-258?quantity=1.

Heat problem:

The ResonX device was equipped with a Raspberry Pi and two amplifiers that continuously operated at full volume while the device was on. During testing, one of the researchers reported that his prototype had "melted". We were initially skeptical, but upon inspection, we found that his unit had indeed undergone plastic deformation of the 3D-printed PLA plastic:

Figure 62: Close up of RX 304 deformations in the EP's external face, seen as dark spots and shadows

Upon examination, we found that the deformities were consistently located where the Raspberry Pi and amplifiers were placed among the EP. Using a thermal infrared camera,[111] we observed a significant amount of heat being generated by these components in the exact areas where the deformation was occurring. This confirmed our initial suspicions:

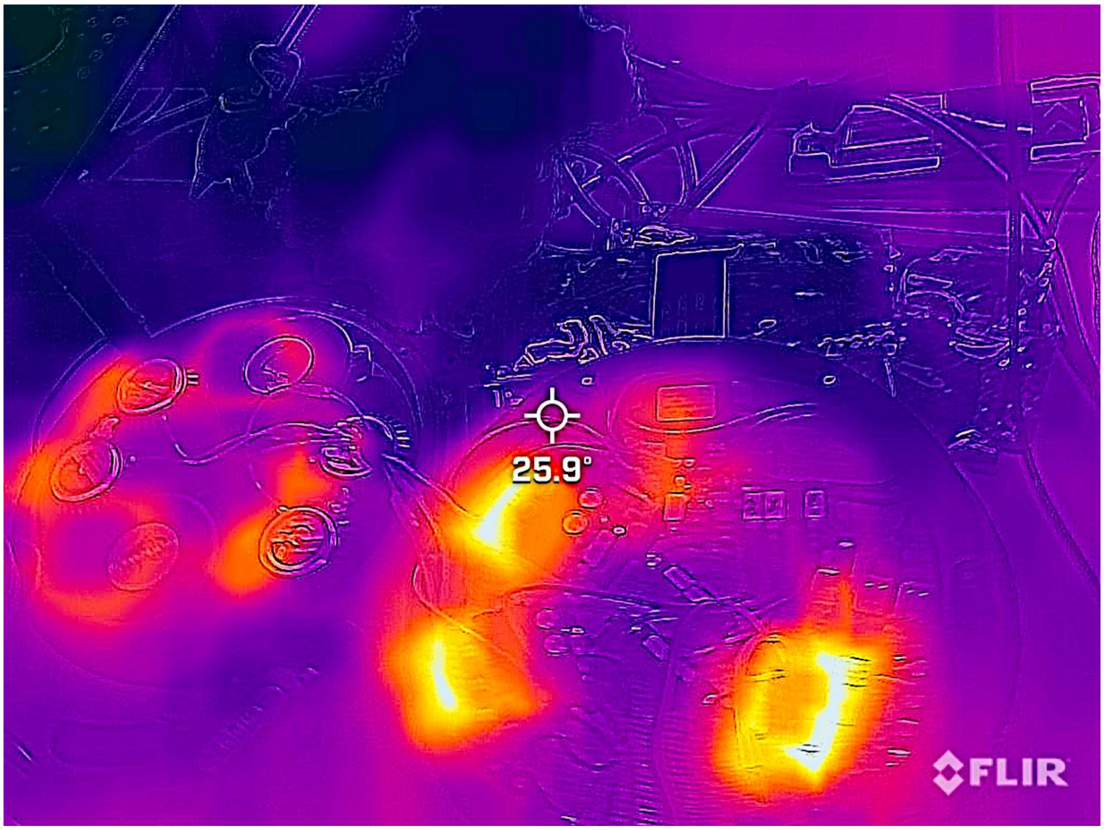

Figure 63: Thermal imaging of hot components inside ResonX 300, causing plastic shell to melt

Latency Problem

The latency issue was initially identified during alpha testing, and later experienced firsthand during the *Aurora* project. The audio signal was injected by the sound card, then

111. "FLIR ONE Gen 3 - Thermal Camera for Smart Phones," Amazon LLC, 2019, accessed May 26, 2023, https://www.amazon.com/FLIR-One-Thermal-Imager-For/dp/B0728C7KND/ref=sr_1_3?crid=CO3GO59TB3EU&keywords=FLIR%2BONE%2Bgen%2B3&qid=1685645551&sprefix=flir%2Bone%2Bgen%2B%2Caps%2C165&sr=8-3&th=1 (Model#: 435-0004-03-NA).

processed by our software, and then sent back out through the sound card before being amplified. This introduced a significant latency of over 100ms, which proved to be a significant obstacle in creating the *Aurora* experience. While 100ms of latency is acceptable for music listening, *Aurora* is designed around the idea of multiple modes of communication happening synchronously where latency around a single mode can destabilize the synchrony. This is why low-latency is very important for simultaneous exposure to events, and can be especially distracting during team-based gaming, which was expressed to the team by one of the company's alpha users. Within the time constraints, we were unable to reliably reduce latency compared to the installation's other modes of communication.

Discussion

It is not generally considered acceptable to refer to a device as "consumer-ready" after just three rounds of design and five prototypes. This approach is not consistent with the standards of a professional design firm or product development agency. For example, in the interest of quickly preparing the device for alpha testing, several critical processes were omitted, such as stress testing, simulation, and iterative design of individual components. Due to the limited resources available as a student startup with restricted funding, many intuitive logical jumps were employed instead of proper evaluation and testing.

Conclusion

This experiment built upon previous prototypes that demonstrated the ability to use vibrotactile and vibroacoustic signals to recreate a significant portion of the human perceivable frequency range (20Hz-20kHz) through a substrate. The material change from layered plywood to a lightweight plastic with ample air within the support structure of the extruded PLA significantly enhanced the transmission of high-frequency vibrations compared to previous designs. A new strap arrangement and form factor redesign from large triangle to a compact circular shape simplified the design and introduced more stability when affixing to the back of a gaming chair.

The most problematic issues arose from glue, latency, and heat. Lack of airflow for the many heat-generating devices caused hot spots within the device that can deform the PLA plastic enclosure material. Enclosing all components inside the device caused the component's built-in adhesives to fail from heat, necessitating a stronger and more compliant adhesive like silicone. Latency was introduced due to the signal chain flowing in and out of modified software packages, removing viability in critical circumstances like live sound reinforcement or studio environments.

The primary areas of improvement for this device include the addition of a remote control, enhancing bass response, condensing all electronics into a single logical device, and reducing the weight, density, and complexity of individual pieces needed to encase the components.

Chapter two conclusion

This chapter examined five distinct experiments to assess the feasibility and limitations of developing a vibration-based sound device capable of producing interpretable signal across the entire acoustic frequency range (20Hz-20kHz).

The team and their collaborators first created a tactile stage bass floor-panel unit and combined with a DML high frequency stereo system to evaluate acoustic parity with traditional loudspeakers. The team found that while the DML and tactile stage provided the entire acoustic frequency response, it was confirmed that higher frequency vibrations were capable of being interpreted as a feeling and moved on to create a chair prototype to immerse a user in the sensation to increase body surface area in contact with the vibrations.

The second experiment involving the chair proof of concept and prototype confirmed this hypothesis and established a performance ceiling with clear acoustic performance from -20Hz to 17kHz and clear wideband vibration frequency response amongst various power levels. In order to obtain additional research funds, the team applied to a university grant program who recommended the team form a startup company to apply for several grants aimed at student startups.

Based on comments from the entrepreneurs in residence (EIR) at the university, the team realized quickly that the technology must be modularized to attach to other types and form factors of chairs. The third experiment demonstrated that the vibrotactile and vibroacoustic performance demonstrated in the second experiment was able to be miniaturized in an all-in-one package. While this package was much more compact and still able to deliver performance, it was only capable at very lower power levels, and could barely overcome the enclosure's resonant properties, limiting the range of substrates the device was able to successfully tune. The miniature prototype was also the first (unsuccessful) instance of our proposed auto-calibration DSP to tune the device to the resonant properties of substrates.

The fourth experiment explored various hardware configurations to find an ideal balance of size to power, and shared the first design capable of enclosing the components so the experience could be non-destructively attached to the back of a gaming chair. The researchers used gaming chairs as a target substrate since the new startup company performed user interviews to identify gamers as a likely early adoption candidate of the technology.

The fifth and final experiment aimed to create an optimized design of the system that addressed size reduction, ease of prototyping, and a sleeker visual language that the company's potential customers would enjoy. While there were some remaining challenges, the team was able to successfully build five working prototypes that were eventually used for the *Aurora* Installation.

The student startup company, EDGE Sound Research reports activity in April 2023 and continues the ResonX core product and embodied sound technology. However, this dissertation is limited in scope to the development of the technology leading up to the *Aurora* installation in June 2021.

Chapter 3: *Aurora* - Multimodal Embodied Installation

Background and Approach

This chapter will detail activities pertaining to the research of technology and product development which led to the *Aurora* installation.

Inception of Idea

Aurora tested the hypothesis that compositions could be more effective and benefit from tactile-audio presentation. The multimodal nature of the technology allows the audience to hear and feel the composition simultaneously, resulting in a stronger effect on the audience. To explore this hypothesis, I needed to develop a proof-of-concept "stage" to fully understand the tactile experience. I hypothesized that the tactile sensation would help reinforce my statement on the status of climate change.

When responding to the self-imposed challenge, I faced a paradox: should I construct a limited system that matches the specifications of the composition as best as possible, or reduce the composition to take into consideration the limitations of the system and existing infrastructure? These paradoxes led to several tradeoffs that compromised my expected results but allowed me to gain a deep understanding of the acoustic limitations of materials and transducers, as well as the limitations of embodied sound on the listener.

Draw The Line - Spring 2014

The inspiration for *Aurora* came from a prior collaboration with Joan Sharma - Professor of Art at California State University, Fresno.[112,113]

Professor Sharma requested assistance on the sound design and acoustic reproduction portion of a collaborative installation piece by herself and Carol Tikijian. called “Draw The Line” that was hosted at Gallery 25 in Fresno from March 6-30, 2014. A video summarizing the event can be found on YouTube.[114] The synopsis for the installation:

> Artists Joan K. Sharma and Carol Tikijian collaborate to focus their concerns for Earth and climate change by creating a multisensory, multimedia installation at Gallery 25. “Draw the Line” employs light, sound and text to offer viewers an opportunity to reflect upon global issues around climate change that threaten the health of our planet.

For Draw the Line, Prof. Sharma approached me while I was working at the Instructional Technology Resource Center, or INTERESC at the Kremen School of Education at Fresno State. My position was responsible for helping instructors, staff, and professors to prepare audiovisual materials for their classes, including physical and virtual technology, creating audiovisual aids, conversions of vintage resources into usable digital

112. Also known as Fresno State.

113. Professor Sharma’s bio on Fresno State website indicates she teaches Interaction of Color, Photography and Two/Three Dimensional Design

114. "Draw The Line Version 7 1 2014," YouTube, 2014, accessed March 26, 2023, https://youtu.be/0U6FFPUUpuc.

formats, and maintaining/upgrading the capabilities of the audiovisual studio and green room for continual usage and futureproofing.

Professor Sharma needed help crafting a 5.1 mixed loop of certain water droplet sounds and frequencies she wanted present throughout the entire duration of the installation. Also she wanted it to be easily performable through her DVD player with 5.1 amplifier that she purchased, since we thought we could just loop the ‘chapter’ that contained the file for the duration of the performance. Initially I thought multichannel performance would be simple enough since my digital audio workstation (DAW) could easily work in multichannel, but the extra steps of converting the project to an Dolby AC-3 file, and authoring to a DVD was an extra level of difficulty that I did not anticipate. Eventually I figured out how to use Adobe Audition to place the water droplet sound bytes across the channels, and side chain long echoes of the droplets to make the impression that the environment full of glacier-emulating structures was ‘melting’ around the visitor.

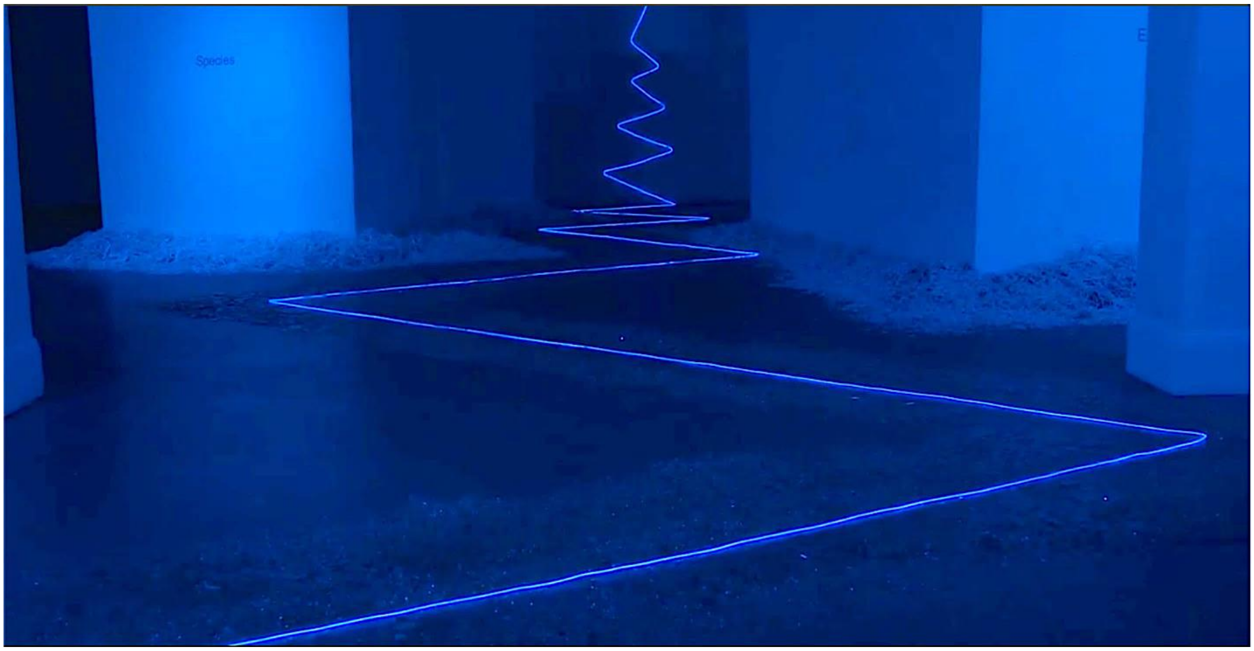

Figure 64: Screenshot of "Draw The Line" recap video on YouTube

I remember visiting the installation after installing and confirming the audio setup, and being completely immersed in the glacier structure that Sharma and Tikijian had created. There were audible droplets all around the room—more than what I remembered programming. A jagged LED strip created a glacier crack in the center of the room. There were decals on the wall spelling out terms referencing climate change, and in reading them, I felt cold. Altogether, the installation made me believe, in the middle of Spring, that I felt colder than I actually was, which forced me to reflect on the impacts of human behavior on climate change, while surrounded by an actively melting glacier—the most stunning sensation I've ever felt.

Any singular mode of immersion would not have allowed me to feel the sensation that all modes together provided.

Ever since the installation, I have been moved to recreate that feeling for others, and since the gravity around global warming had increased dramatically since “Draw the Line”, *Aurora* was the perfect opportunity to continue the conversation around climate change, while exploring how embodied sound could help get the point across. Professor Sharma and I began working on the concept in 2016 during my Master’s program at CSU Northridge, but my effort into the commercial music industry prevented us from moving significantly on it until my acceptance to UC Riverside in 2017.

Big Ideas Innovation Competition - Fall 2017

For the UC Berkeley 'Big Ideas Innovation Competition',[115] I proposed two systems in a pre-proposal: one is a mobile unit that provides discrete surround sound on-the-go, and the other is an embodied sound room that would, for all intents and purposes, be a precursor to what would become the *Aurora* experience. The Big Ideas Competition was originally developed to challenge students to identify and tackle real-world social and environmental problems. The competition was launched at UC Berkeley in 2006 and offered up to $300,000 per year in prizes to interdisciplinary teams of graduate and undergraduate students. Applicants received invaluable support as they developed their ideas, including information sessions, writing and budgeting workshops, graduate student advising,

115. Now Rudd Family Foundation: "Big Ideas," Blum Center, UC Berkeley, accessed March 26, 2023, https://bigideascontest.org.

networking opportunities and an 8-week mentorship period where students worked with industry and civil society professionals.[116]

For the 2017-2018 competition, my ‘Big Idea’ was to use tactile transducers and exciters, to physically vibrate differing materials in order to bring physical touch to music. Interacting with physical vibrations allows listeners to connect to—and learn about—the physical aspects of sound. By learning about and connecting to the physical properties of sound, I aimed to help those with hearing loss become sensitive to these properties in everyday life, unlocking the power to hear through touch.

There were two form factors for this technology: an interactive sound room, where listeners can feel interactive materials, and an immersive mobile unit, where the listener is wearing vibrating technology which transmit low frequency vibrations and high-frequency micro vibrations to the body, resulting in intelligible sound. Both settings may be converted into a hybrid setup, featuring traditional speaker components, in order to facilitate immersion experience of the environment.

Embodied Sound Room

The high-fidelity demonstration room used several high and middle frequency tactile transducers, with multiple low frequency tactile transducers to achieve a high-fidelity tactile experience. When these transducers are affixed to a structure, the structure will provide the embodied experience that students and listeners can touch and learn about

116. "THE BIG IDEAS COMPETITION," Development Impact Lab, accessed March 23, 2023, https://dil.berkeley.edu/students/big-ideas/.

sound vibrations in speech and music. If selected, we planned to process the signal with a custom crossover and digital signal processing unit, to provide a more realistic sound impression.

This tactile system can be augmented with a traditional speaker array in order to balance out difficult frequencies, and to demonstrate pure tactile experience against traditional speaker (plus subwoofer) setup for a hybrid vibroacoustic + vibrotactile experience.

Portable Embodied System

The mobile demonstration system was designed to be worn as the user moves about, consisting of a bone-conduction headset—worn just over the front of the ears—in addition to a wearable tactile transducer—worn on the chest/back. Like the demonstration room, I planned the mobile system to be processed via customized DSP with crossover in order to achieve a tactile, tonal balance that would rival traditional headphones, but with an extended bass response. I proposed to collaborate with a team who was involved with an augmented reality (AR) project to provide this high quality, semi-immersive tactile experience to their project:

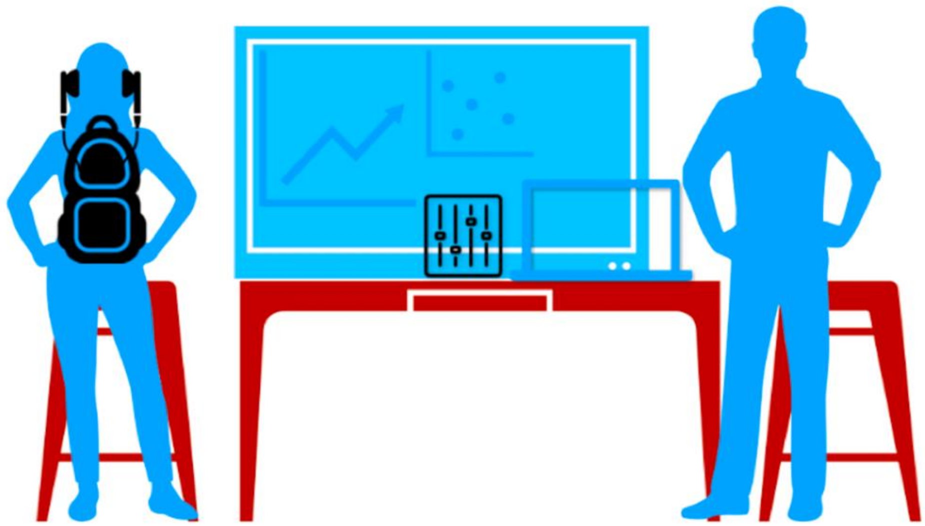

Figure 65: Drawing showing a user experiencing the portable embodied system at a booth.

As a hybrid solution: this proposed mobile tactile-audio system could be augmented with a pair of traditional in-ear drivers to provide a fully-immersive reality, suitable for true virtual reality (VR), as well as the highest fidelity tactile listening experience - hard of hearing or otherwise.

The ultimate challenge was to integrate multichannel media (multiple discrete channels of audio) with one of the hybrid demonstrations to investigate if we could get users to effectively perceive four discrete channels of audio in a media example. I created a quadraphonic demonstration track of the song “The Perfect Kiss” by the 80s English alternative dance and rock band New Order, which has a very clear synth stab at the beginning that outlines left and right channels discretely. I cut the stab of each channel and repeated it for every channel in the quadraphonic system in order to give a very clear presentation of the surround channels on any system with four discrete speakers. I experimented with a few channel-specific effects and vocal productions, and eventually a full-fledged, albeit short remix to also explore mixing in quadraphonic.

Ultimately, the project was not selected to move forward in the competition, but this was the first instance of demonstrating a possible multichannel sound system - leveraging bone conduction headphones or tactile exciters. I did not know this at the time, but learning about exciters and bone-conduction systems would stick with me until Spring/Summer 2018 when I would continue to investigate other sorts of vibrotactile and vibroacoustic systems, which would inevitably lead to the key invention of a multimodal vibrotactile + vibroacoustic embodied sound device, necessary for creating the *Aurora* experience.

Big Ideas Innovation Competition - Fall 2018

After playing sound through the DML panels, I felt their surface with my fingertips and suspected that there might be more tactile information present in the panels than previously expected. I hypothesized how we could scale up the *Aurora* collaboration with Professor Joan Sharma from Fresno State. This would be an extension of our collaboration on her "Draw The Line" installation from several years prior. In another proposal to UC Berkeley's Big Ideas competition, I suggested the first instance of a balanced full-frequency multimodal vibrotactile/vibroacoustic system, which would provide a visceral experience that the audience would feel sound vibrations throughout the piece. In another proposal to

UC Berkeley's Big Ideas competition, I suggested the first instance of a balanced full-frequency multimodal vibrotactile/vibroacoustic system: [117]

> I have composed a ~20-minute demonstration piece that utilizes multiple channels of audio, and heavily emphasizes sub-bass frequencies only felt by tactile transducers…
>
> We have designed a demonstration stage using several…exciters, with multiple…bass shakers to achieve our high-fidelity tactile experience. When these transducers are affixed to the stage where the audience will sit, the stage will provide a visceral experience that the audience will feel sound vibrations throughout the piece. We also plan to process the signal with our custom crossover and digital signal processing unit, to give a more realistic sound impression.
>
> Aside from our custom pieces and special audio components to this event, we will be featuring a triple-projector setup projected floor-ceiling, collaborating with artists to create custom video elements that take advantage of such a large canvas that compliments the audio pieces.

In my previous proposal for UC Berkeley's "Big Ideas Innovation Competition" in 2017, I suggested using tactile transducers and exciters to physically vibrate different materials to bring a physical touch to music.

In the 2018 submission, I proposed a revised version of the mobile tactile unit. This time, with a clearer vision and an additional mobile version featuring a wearable tactile transducer:

117. Full report in Appendix A

> We plan to further the technology by designing a mobile demonstration rig that can be worn as the user moves about. Our mobile rig will consist of a bone-conduction headset, worn just over the front of the ears, in addition to a wearable tactile transducer, worn on the chest/back. Like the tactile stage, this mobile rig will be processed in order to achieve a tactile, tonal balance, rival to traditional high-fidelity headphones, but with an extended bass response and greater immersivity. We have identified a team who is involved with augmented and virtual reality (AR/VR) game development; we can collaborate to provide a high quality, semi-immersive tactile experience to their project.[118]

These proposed systems mark the first mentions in my research of seeking a tonally balanced series of tactile transducers to achieve a high-fidelity, full-frequency, multimodal vibrotactile/vibroacoustic array. While I did not receive the awards to execute the experiments, the thought experiments while designing the systems were the prototypes to what would eventually become the physical design of the *Aurora* installation.

118. Full report in Appendix A

Aurora Composition

Overview

From the outset, my goal for this composition was to create a highly immersive experience that utilized the full range of tactile frequencies available within existing technology. Collaboration with Prof. Sharma reinforced the need to take the audience on a journey, and I endeavored to reflect this in the music. I sent in-progress samples of "Prelude" and the vision of *Aurora* to librettist, sister, and longtime collaborator Gabrielle Dêsirêe Lee. She returned a brilliant poem and libretto, with literal word shaping to emphasize certain elements.

Aurora

mama
I'm cold
do you have a blanket?
grow me some cotton

do you have shelter?
birth me some comfort

Mother's green and blue fade far away

as i *f* *l* *o* *a* *t*

Figure 66: Excerpt of libretto by Gabrielle Lee showing word shaping that was inspiration for motivic elements of Aurora.

Throughout the composition process, my focus remained on leveraging the direct coupling between the audience and sound source to create impactful moments.

Prelude

The installation fades into “Prelude” via a soft setting of clouds fading in from black moving against a blue sky. A series of beeps rhythmically spell out ‘nature’ in morse code. Lyrical phrases fly across the screen as they are sung:

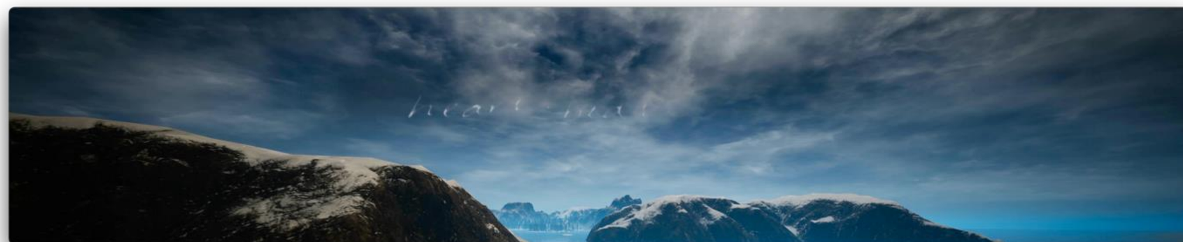

Figure 67: Screenshot of “Prelude”, showing text “heart•beat” floating amongst mountains and clouds.

The words are a physical writing out of the entire libretto on a piece of linen paper, and then captured with a Blackmagic Pocket Cinema Camera by my good friend and successor Alex Johnson at INTERESC.

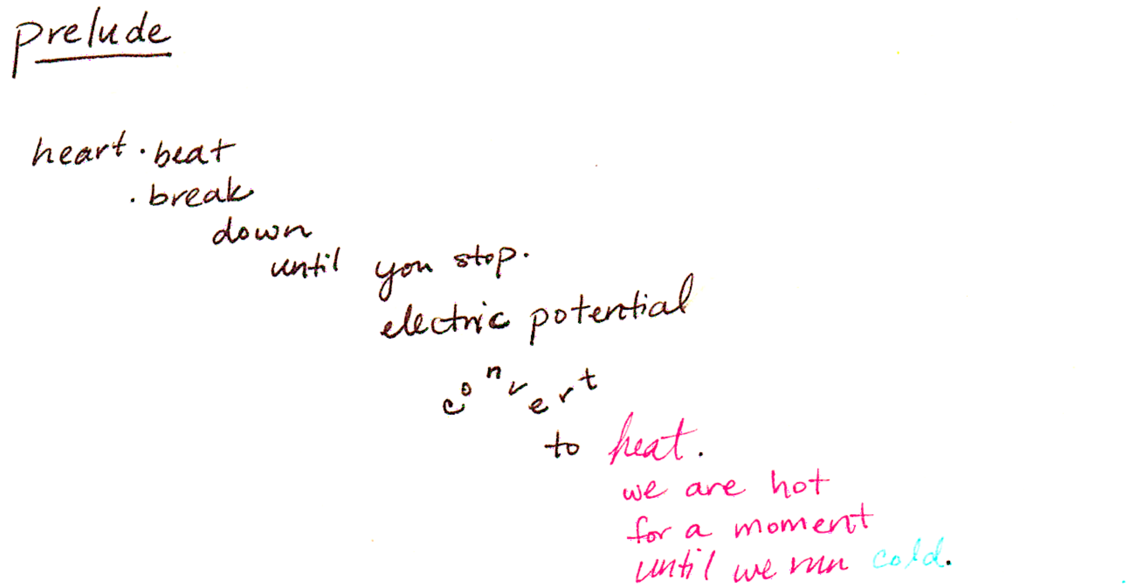

Figure 68: Aurora - Written Layout

The lyrical visuals engage for the entire duration of the event, as well as captured media from Professor Sharma, of which several pieces are superimposed over the virtual landscape for the entirety of the piece.

"Prelude" opens with the words "heartbeat…" vocally performed in an ascending stepwise three-note figure that repeats and is echoed in the background.

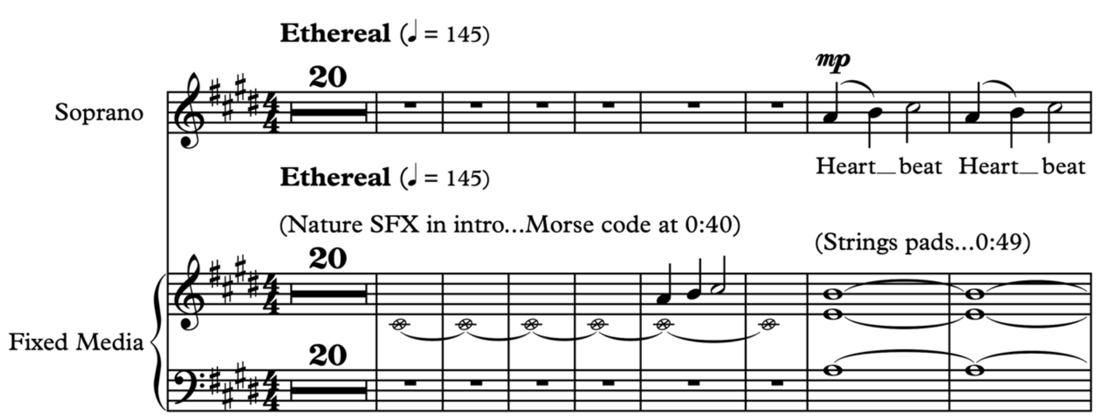

Figure 69: Opening of "Prelude" showing stepwise ascending motion of initial vocal figure

“…breakdown, until you stop” descends and finishes outlining the arc of the line. Next, I reverse the arc, ascending and completing the greater arc at a higher pitch than the first entrance.

Figure 70: Descending and ascending figures at the end of the vocal arc

“electric potential, convert to heat. we are hot for a moment…” is portrayed as a monotone computer-voice passed through a vocoder. The sung voice then descends from the arc “…until we run cold” while “cold” transitions into the next stanza, and is the first instance of a tactile frequency with a bass-focused impact, teasing the sub-bass binaural beats that introduce a ‘rolling’ sensation. The scene shifts from day to night.

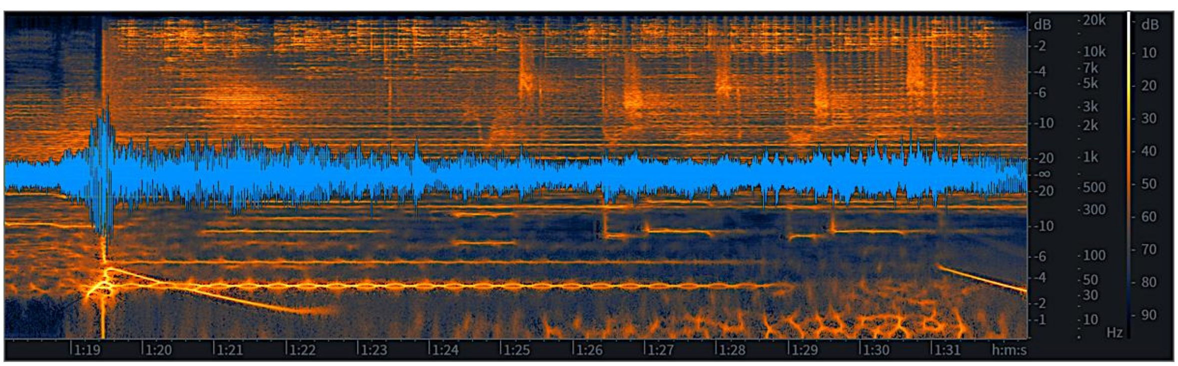

Figure 71: Screenshot of “Prelude” - showing initial bass impact and sub-bass binaural beats.

I replaced "does she rest?" in this stanza as a summation of the omitted lines "then we stop running at all. we rest". A stronger bass impact, re-introducing the tactile-only binaural beats underlying Heisenberg's uncertainty principle.[119]

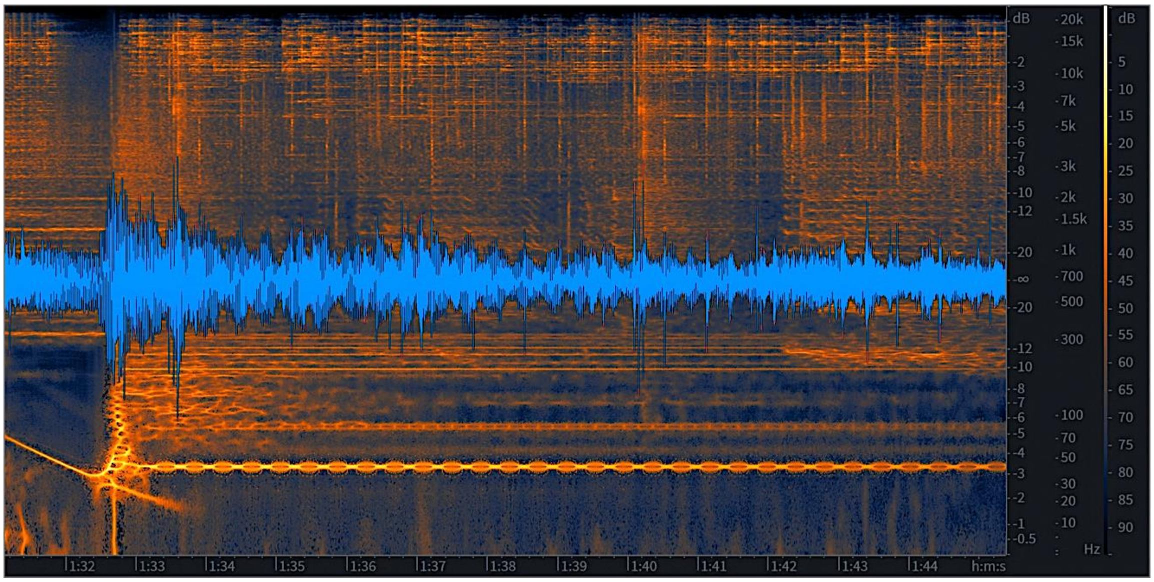

Figure 72: Second stronger bass impact with visibly interacting sub-bass binaural beats at around 45Hz

I wanted to embody the core tenets of the principle, and the corresponding confusion it creates, so I put the presentation of the equation both forward, backwards, reversed, echoed, reverberated, with different effects and octaves presented on either left or right channel, allowing the audience to hear the equation several times, but immediately obscuring the presented words with strong modulated effects. Also represented in visual moving forwards and backwards, with colors and other effects obscuring the audience's perspective. Whether or not this fully emulated the principle is up to the observer.

119 Originally about not being able to know a particle's speed and position perfectly, the thought can be extended to anything that exhibits wave-like properties. Since *Aurora* is based on oscillations. Expressed it reads: "delta epsilon delta tau is greater than or equal to h over two".

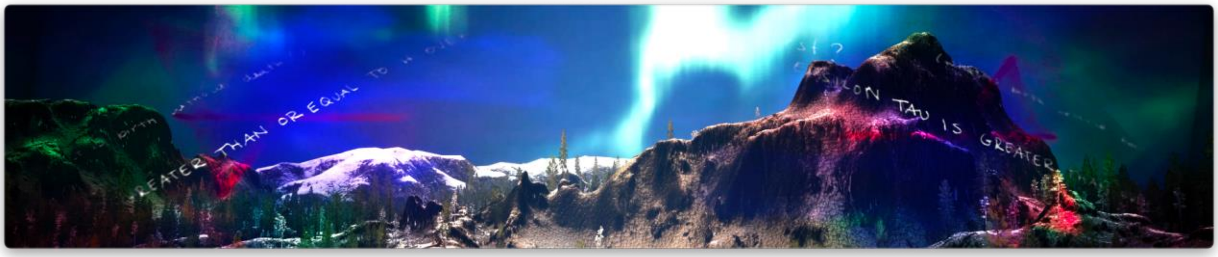

Figure 73: Heisenberg's uncertainty principle moving both forwards and backwards on both sides of the screen.

The line "Interrupt solar wind, enter night" stands as its own arc. Initially, I had composed a very clichéd fanfare-style motif, followed by an unnecessary run for the first half of the line. However, I replaced it with a steady monotone motif separated by a minor third. The melody may not appear to evoke an interruption, but it serves the intended effect of interrupting the driving instrumental arpeggio with the melody line, while also transitioning the visual into a sky-only view in the soft ambient background.

Figure 74: Original ascending melody. This was replaced by a more monotone figure.

Figure 75: "Prelude" 2:03 - "interrupt solar wind" is in focus against an aurora borealis in the background

"Curtain your parade of light…into Mother's sky" continues the sky-only section. I wanted to try to bring the audience into this sense of floating, since I knew I needed to surprise the audience in the upcoming stanza, with the intense climax of the piece.

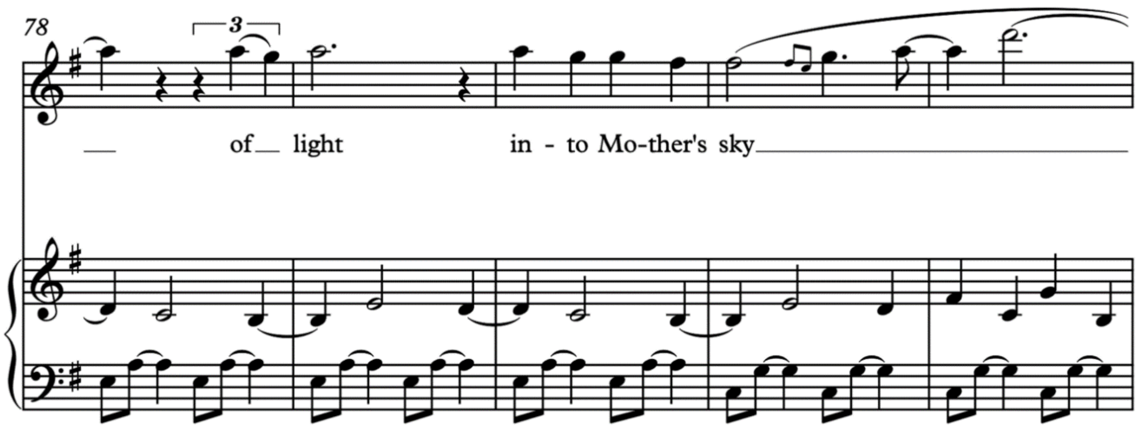

Figure 76: "Prelude" 2:21 - "Sky" of "Mother's Sky", receives focused attention, musically and visually.

"raise us in the altitude of your atmosphere" is the perfect line to bring the audience high into the sky, on top of the highest mountain peak in the virtual environment. I removed most of the overlayed images and begin to narrow the field of view with a vignette to draw the audience's perspective to the center of the visual.

I present "and see our colors glow…we categorize ourselves" as a continuation of the soft ethereal process of raising the audience in the sky, but also to present the climax in a recognizable fashion, so that the audience has a cue to recall.

Figure 77: "Prelude" 2:45 - centered text focuses attention the center, the sides begin to obscure via vignette

I repeat the final stanza from "raise us in…" but with a stark instrumental change—I remove the arpeggio and replace it with deep synthetic strings and a metallic jingle of keys against the morse code of 'nature' that began the piece. The camera peers out towards a foggy picture of snow-capped mountaintops.

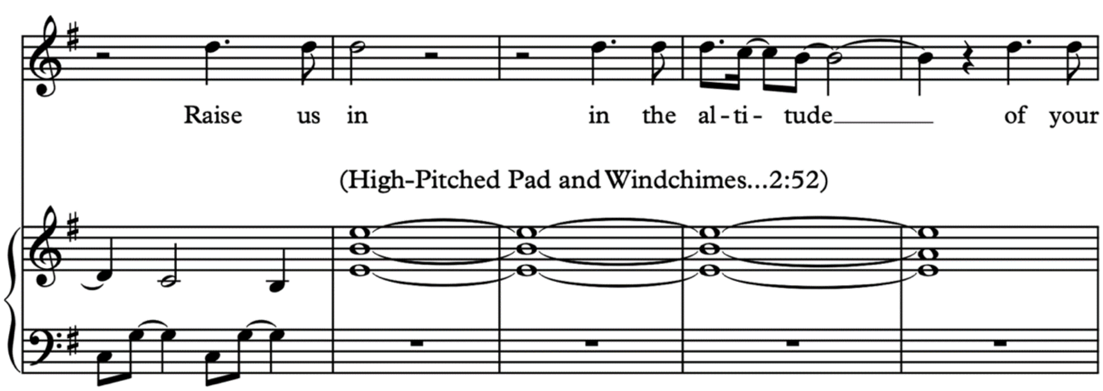

Figure 78: Second repetition, against synthetic strings and metallic chimes

A timpani-like swell and reverse kick drum with subtle flash bring the piece to a momentary halt to outline the repeated phrase "and see our colors glow."

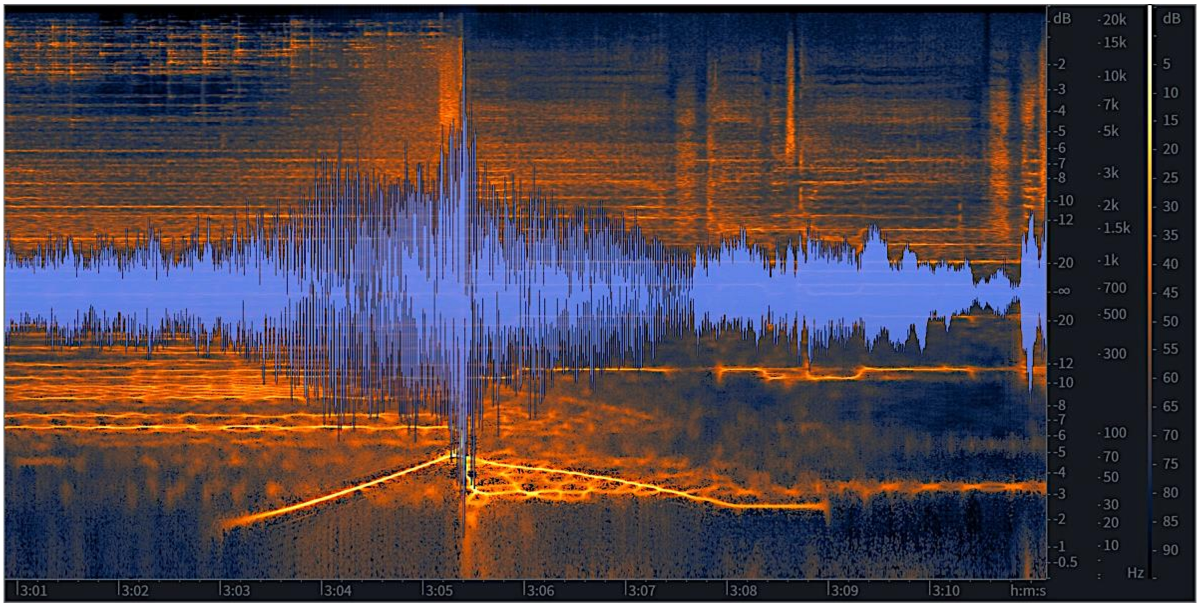

Figure 79: Timpani Swell, reverse kick drum, and deep bass descent into "and see our colors glow".

Then with a quick pitch upwards, the camera does a small leap towards the sky and glitches before a rapid descent on the word "categorize", with the camera falling down the mountain, through the trees, before finding a resting position facing the direction the camera entered, with a single tree on top of a small rock ledge.

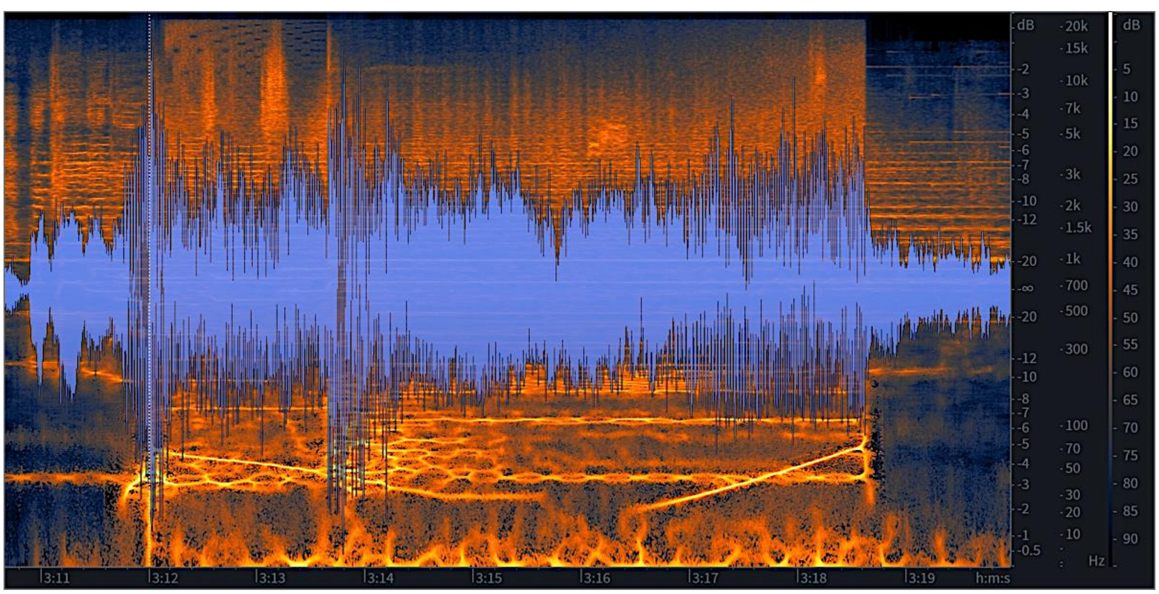

Figure 80: "Prelude", "categorize" first impact, "ourselves" second impact.

Figure 81: "Prelude" 3:12 - Camera glitch at "categorize", fall begins.

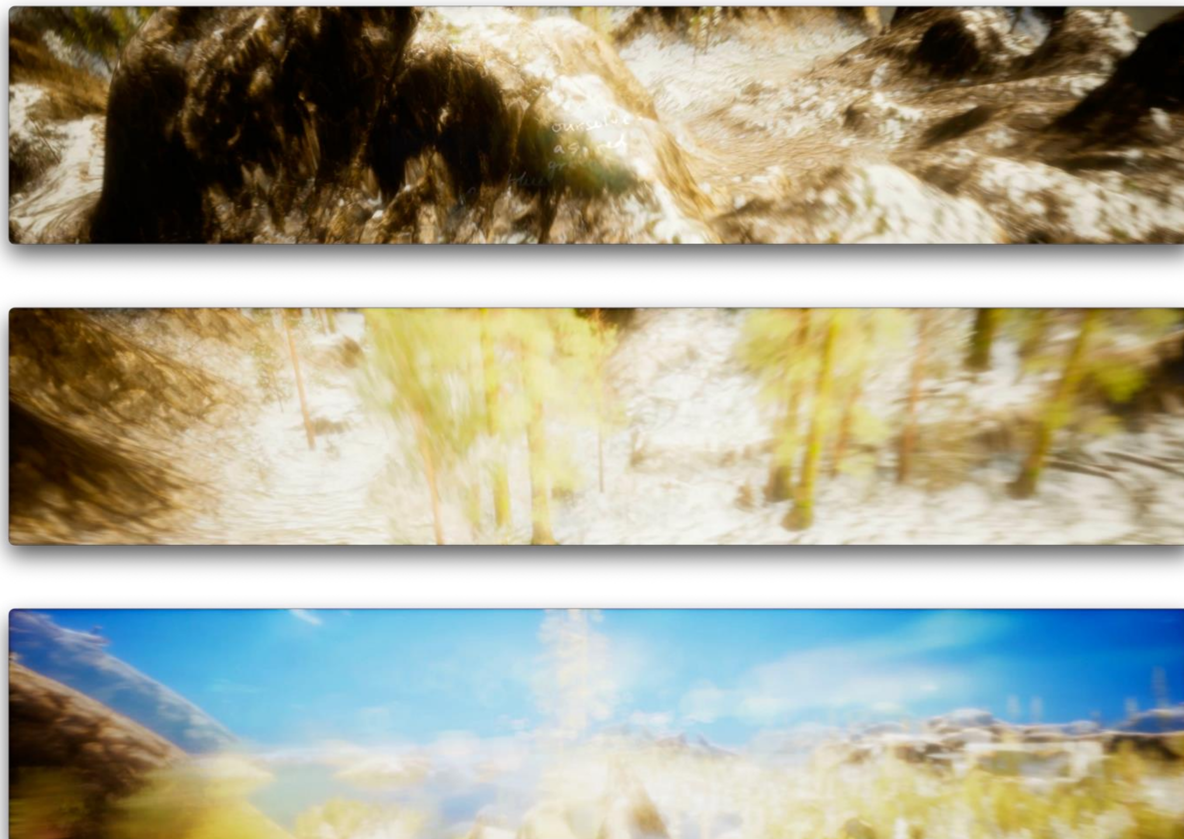

Figure 82: "Prelude" 3:16 - camera ascends rapidly to a clear sky.

The colors "as red, green, blue, yellow, pink, infrared, ultraviolet" appear in word form, in the color of the word they represent at various points across the screen gently floating in a singular horizontal direction. I wanted to have the audience look for the colors at different angles of the wraparound screen, so I place each alternating color closer and closer towards the extreme sides of the screen, to lead them towards the end. “when all we are is light” closes out the phrase.

Figure 83: “Prelude” 3:22, colors in their represented color appear on the screen.

“Dissipating comfortably…into nothingness” repeats, emulating the phrase and filters out higher frequencies, while echoing side to side in the left and right channels. The tactile binaural beats become the prominent feature, also fading out, while the instrumental, vocal, and visual all disappear via reducing resolution until they eventually…dissipate…into nothingness.

Figure 84: “Prelude” 4:15, as the bitcrusher effect mimics the shape of the waves, the screen pixelates and distorts along the same lines, continuing the multimodal behavior of every idea.

Furiosa

“Furiosa” was intended to display the potential of tactility in composition. The piece featured a range of elements, including super-staccato notes, long drones, deep vocals, warping bass, and even hard drums. I owe a great deal of thanks to Dr. Dana Kaufman for her persistent challenges, which forced me to find highly creative solutions to incorporate my "beats" into the movement. This resulted in some remarkable glitch-style sound design and odd-meter, yet still catchy grooves.

From the beginning, “Furiosa” was designed to challenge the audience. The gentle fade transition from “Prelude” to nothingness is concluded by a far-away thunderclap.

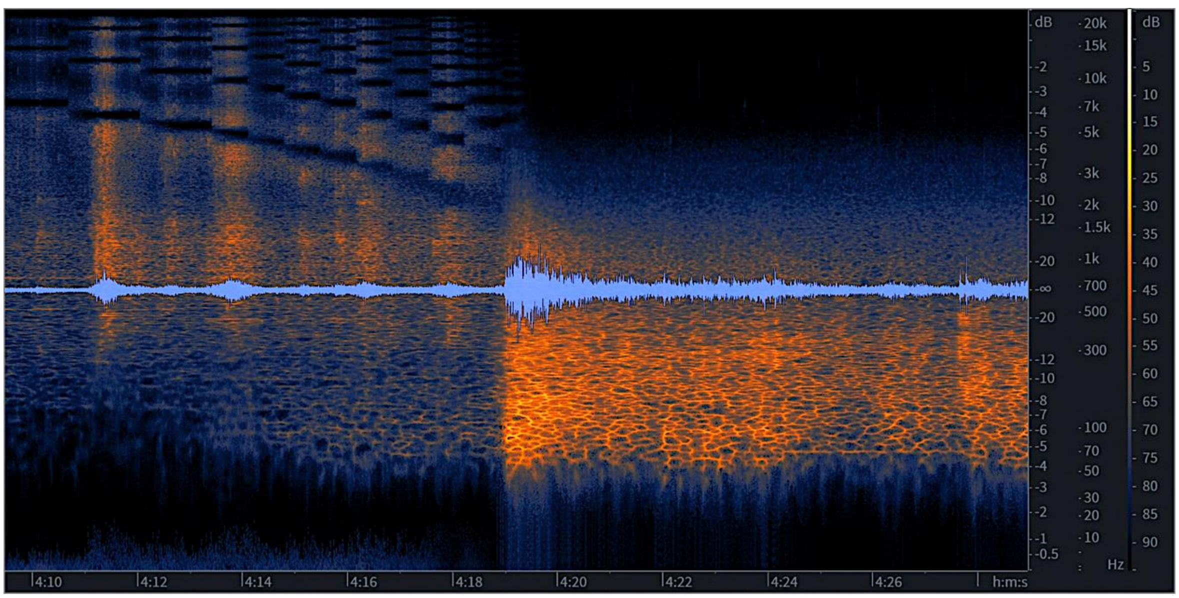

Figure 85: Spectrogram showing spectral transition from bitcrushed “Prelude” to “Furiosa” via thunderclap.

A reverse chime instantly negates any organic feel from the “Prelude”, and the extended black keeps the audience in a suspended state until the reverse chime glitches with a rapid gating effect, perfectly in sync with the visuals. The audience is suspended in black once again, suddenly interrupted by an even faster gated presentation of the chime. This stereo stutter-effect, along with the visual glitch, is a constant theme in this movement.

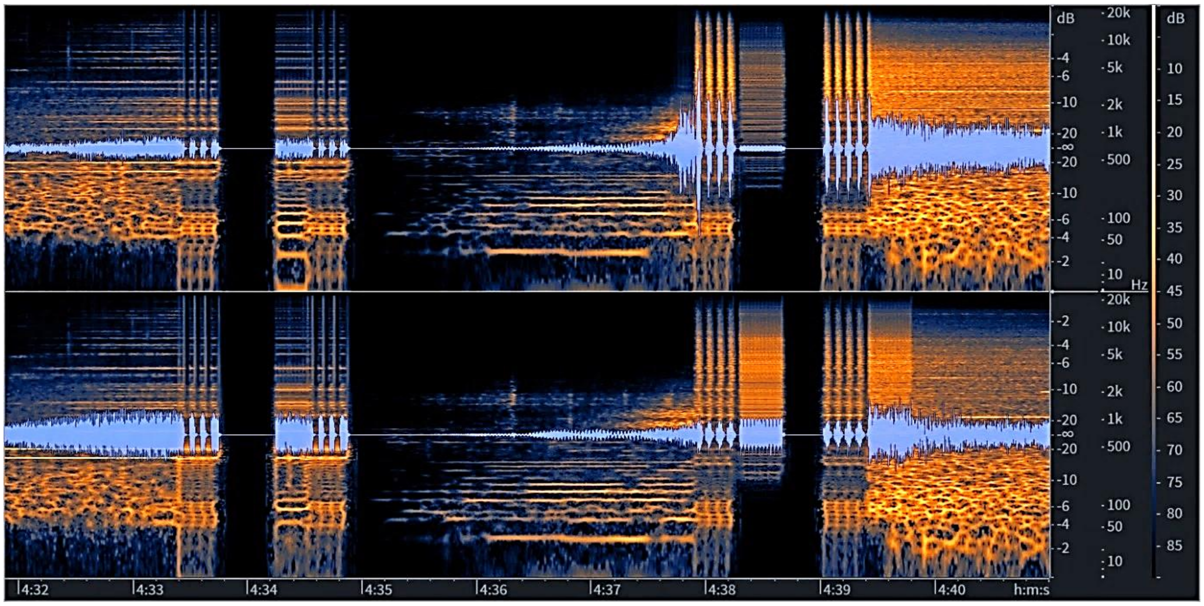

Figure 86: Spectrogram showing glitch figure moving between left and right channels.

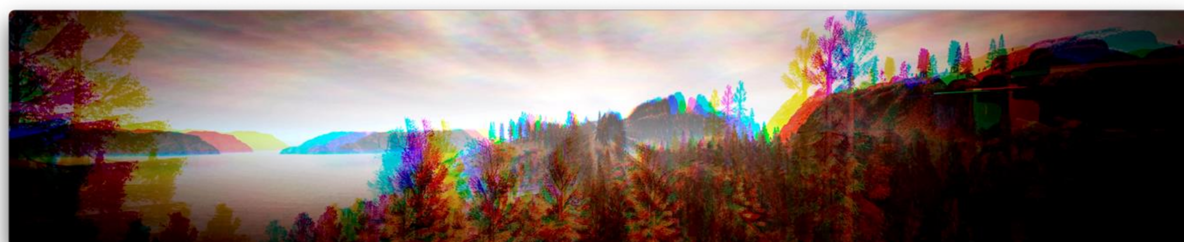

Figure 87: "Furiosa" 4:34 - screenshot showing glitched video in conjunction with audible glitch figure.

A presentation of the discordant transitional theme is presented in a high-pitched bell, before combining with the reversed chime, inverted impact, and filtered synth to bring the audience into the main motivic idea of "Furiosa".

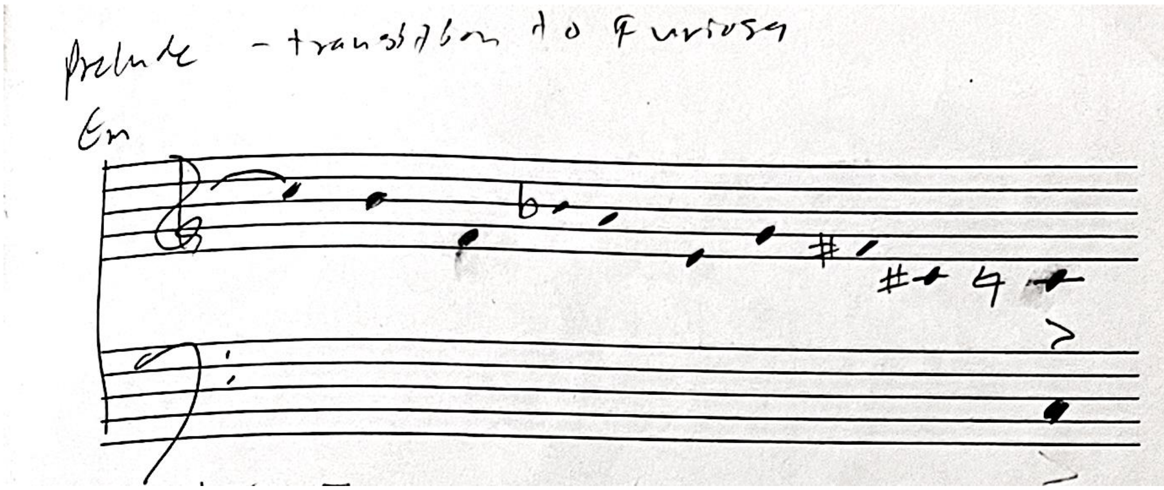

Figure 88: "Prelude" transition, from E minor, to C double harmonic minor of "Furiosa"

The main 16th note pulsating staccato rhythm is a very strong statement and is both constant and discordant. Starting with a mid-frequency focus, as to not trigger a strong tactile sense, I wanted to create a sense of unease, and nervousness—physically and symbolically to the uncertainty over the future of our relationship with Earth.

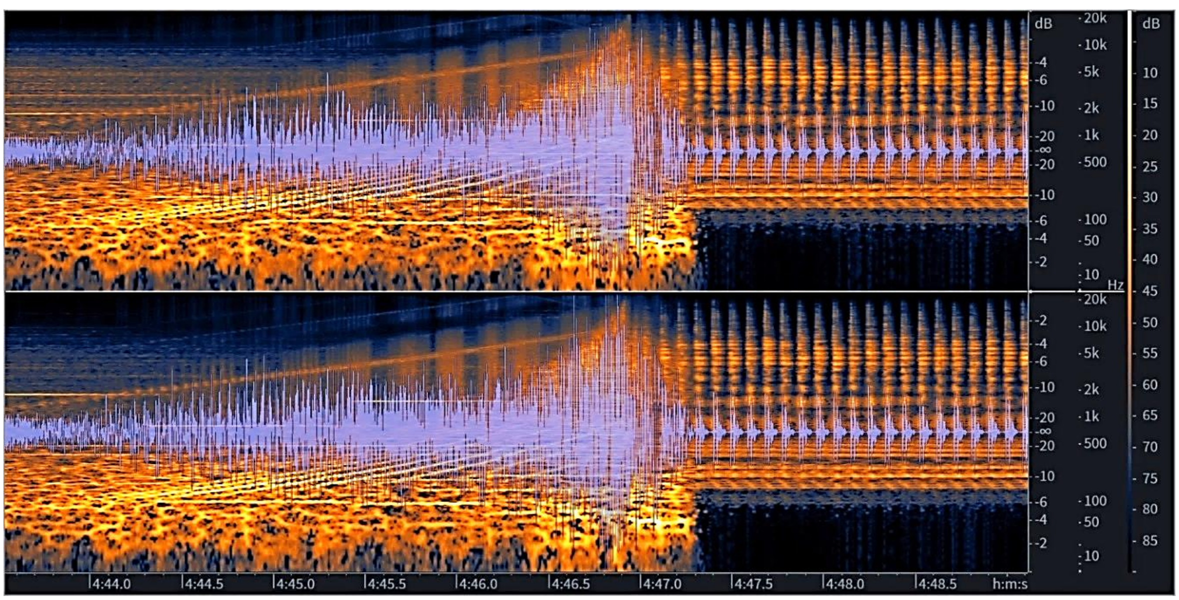

Figure 89: Spectrogram showing the transition to the mid-frequencies-focused 16th note ostinato figure.

I leveraged the opportunity of having so much footage at my disposal from Prof. Sharma to intersperse between the footage of the *Aurora* environment, especially in between strong gated elements. A series of narrow smoke plumes subliminally imprints the suggestion of smoke, fog in the background field of view, and dropping the camera close to the ground, with shrubbery and foliage obscuring parts of the camera which served to disorient the audience. After the subliminal smoke images, a thunderclap introduces the 1/16th staccato motive in the bass frequency range, which then is reproduced more intently by the tactile transducers.

Figure 90: "Furiosa" 4:52 - smoke plume video from Prof. Sharma, processed to contrast against black background.

Then I riff on the 1/16th staccato idea by bending the pitch up, filtering the sound, and adding glitch effects like distorted screaming, and then varying the pulses so they're not constant 1/16th notes of the same layers.

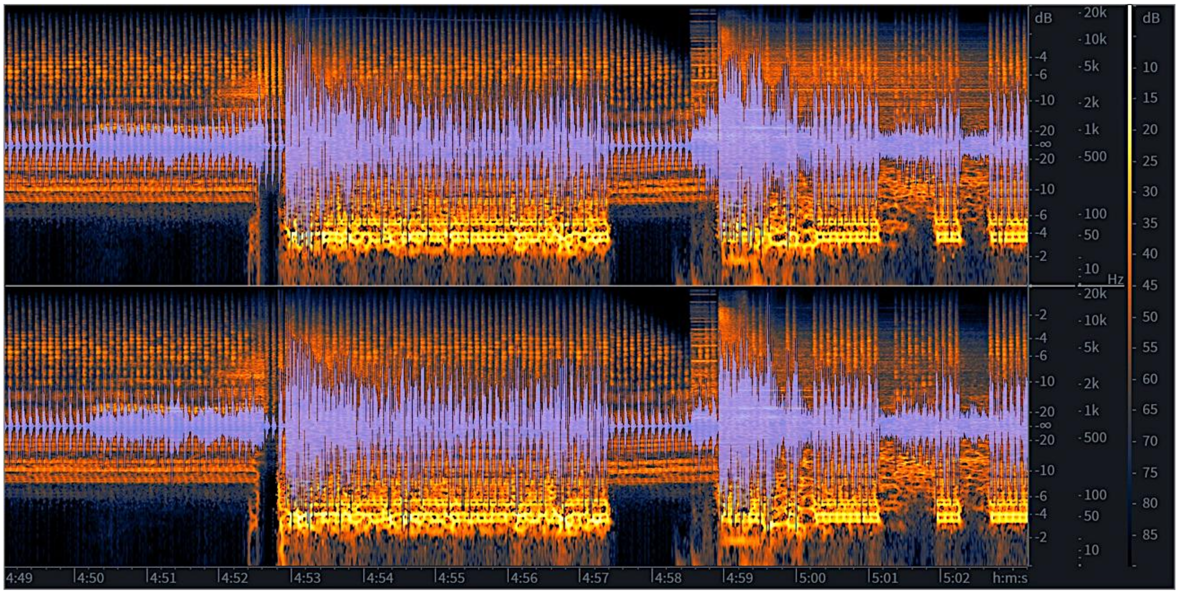

Figure 91: Zoomed out spectrogram showing the stereo and spectral play of the 16th note ostinato.

Visually, the camera is swerving through foliage that is being tormented by a strong wind, programmed into the *Aurora* environment—the thick fog limits field of view. A quick overlay of Joan's smoke pattern strobes in the center of the screen to mark the end of a phrase. The camera then gently lifts before crashing down again on the downbeat, introducing another layer of synth-heavy music. This layer articulates certain 1/16th pulses, while chroma displacement adds to the punctuative stack. Reversed piano, and the first tonal elements of the song are punctuated by the words "the ozone…. our own lungs" and "suffocate…choke" strobe on screen. Another reversed piano leads into a sharp gunshot as the screen goes dark, plunging the audience into sudden darkness.

Figure 92: "Furiosa" 5:04 - smoke plume composited on top of rendered environment.

Figure 93: "Furiosa" 5:07 - fire video manipulated as a 360º video encircles the whole frame before quick cuts.

A strong impact sounds, and the repeated ascending minor 2nd phrase "breathing crying shaking stomping" is presented in a strong but intelligible filtered effect along with the piano syncopated rhythm.

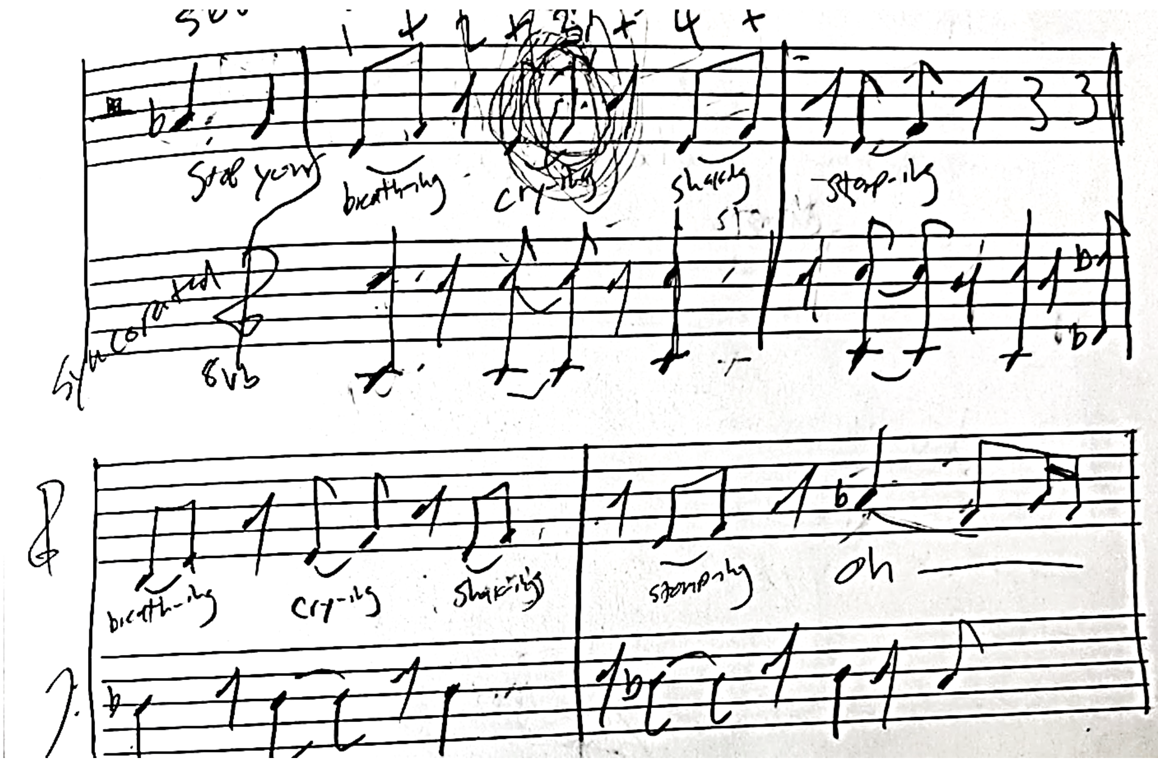

Figure 94: Original sketch of the "breathing crying shaking stomping" motif.

Sounds of fire and rain cross left and right, as the written "breathing crying shaking stomping" travels across the screen, Joan's fire recording with a kaleidoscope effect morphing the flames at the edges of the screen. The activity accelerates, as the vocals feedback the echo, pitch and formant shift, leading the vocals to disappear into chaotic screams. The impact swells and suddenly vanishes like earlier, but in total darkness and total silence.

Figure 95: "Furiosa" 5:14 - "breathing crying shaking stomping" text with fire fading in around the side extremities.

Figure 96: "Furiosa" 5:21 - Fire kaleidoscope effect becomes more pronounced as intensity swells.

A quick swell to distorted impact introduces a heavily glitched instrumental percussive feature accompanied by shots of a forest center covered in smog and haze. The drums are glitched, pitched, distorted, and hard panned amongst the left and right channels.

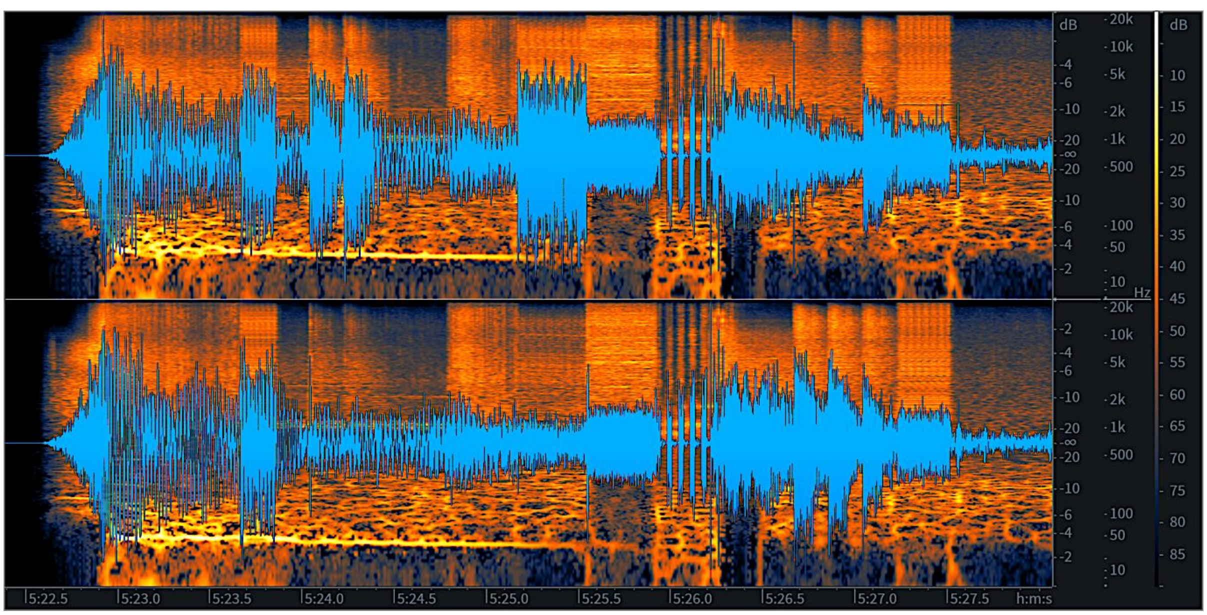

Figure 97: Waveform showing the left and right movement of the glitched percussion.

Every impact is represented on screen with an overlay of Joan's colorful oil footage, creating a bleak, sickening portrayal of the forest trees. The artificial colors over the bleak environment cause a strobing dissociative effect. I purposefully eliminated color from the base footage to give the color overlays more impact.

Figure 98: "Furiosa" 5:25 - no color during percussion feature

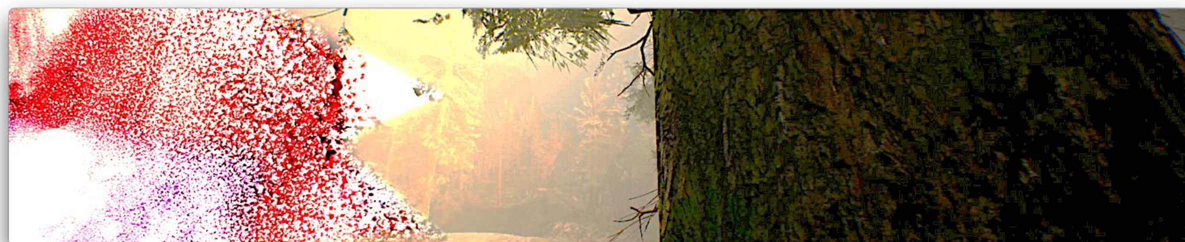

Figure 99: "Furiosa" 5:25 - the glitched drums are synchronized with contrasting color overlays in between frames.

The processed drums tell an arc of their own - beginning their feature section sparse and discretely panned left and right, but quickly incorporating more elements and deeper/faster processing. I wanted to give a sense of progressive chaos, emulating the rate of acquired knowledge of human impact on climate. Finally, the source of the drums - the original beat pattern - emerges as proof of the section's foundation. The audience is presented with an unprocessed drum chop upon which the section is based, which leads into a strong thunderclap. This presents the audience with a sneak peek of the movement's final motif: "she bleeds beneath us."

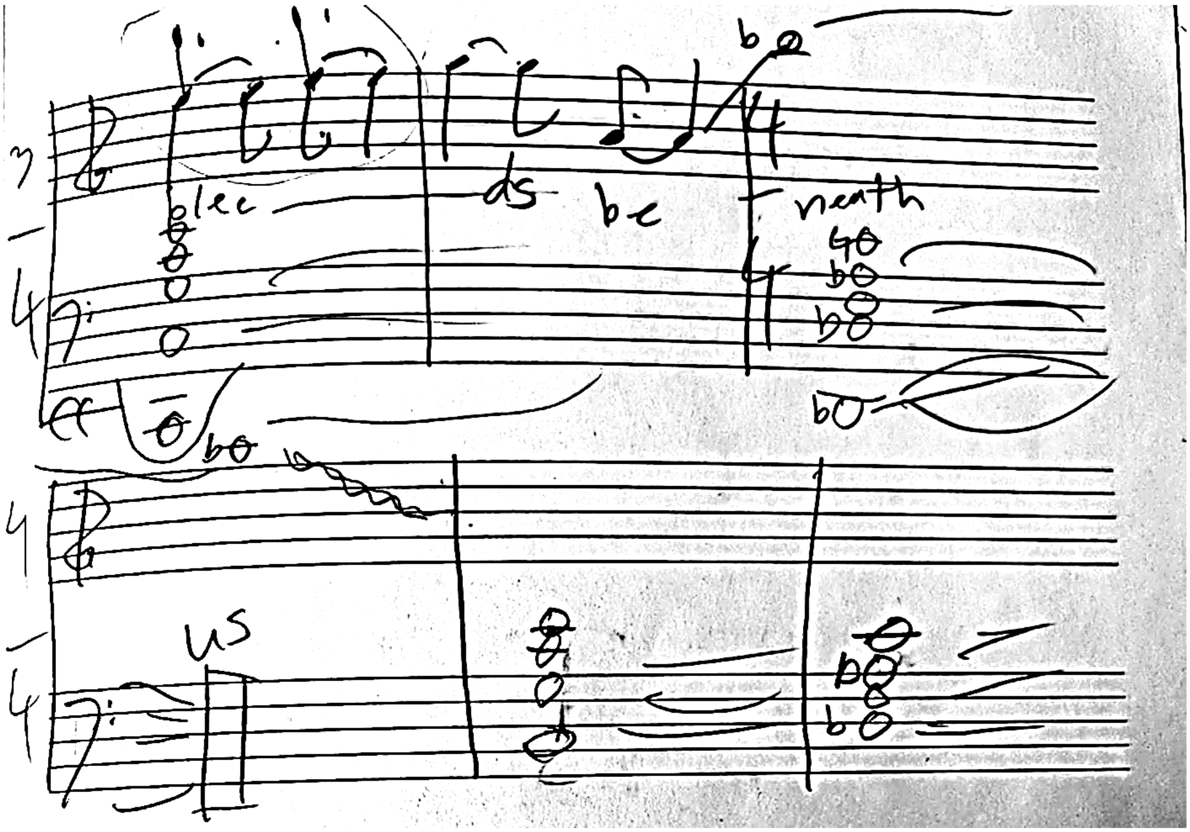

Figure 100: Original Sketch of the final motif "she bleeds beneath us" that is teased at the end of the percussion feature.

Joan's fire footage fades and filled the screen, the kaleidoscope effect from earlier exponentially increase the facets which the fire reflects, creating a warped frame-filled abstraction of the fire, reducing the fidelity to color areas and pixels.

Figure 101: "Furiosa" 5:39 - Mirrored flame fills the frame once more.

Figure 102: "Furiosa" 5:40 - Geometric patterns begin to take shape as the harmonic intensity increases.

Figure 103: "Furiosa" 5:40 - Geometric patterns begin to take shape as the harmonic intensity increases.

Figure 104: "Furiosa" 5:41 - Tightening angle of reflection creates tighter symmetrical patterns.

All elements immediately fade away except for the camera, instead of moving rapidly and intensely, gently zooms towards a tree in the middle of the lake, a strong vignette blocks out all sides, leaving only the very center in focus with light.

Figure 105: "Furiosa" 5:49 - strong vignette shows a large and small tree on an island in the oasis.

A soft abstraction of the transitional theme plays out slowly, playing with just a few notes of the theme, a gentle orchestration of bell and high strings accompanies the abstracted theme. The camera zooms beside the tree, to bring a new seedling into view, shaking in the wind, almost scared behind the strong trunk of its maternal protector. A gentle swell of dissonance before the camera yet again, suddenly drops to black.

'Stop' and 'your' words gently appear on the screen before an ominous deep synth underlines the full transitional theme presented in a Kenong.[120] The 'breathing crying shaking stomping' motif feeding back into the echo, reversing and accelerating the echo and all the while increasing in pitch. The transitional theme completes and is punctuated by outlining of the double harmonic major scale feeding back to the root note.

The root note leads to the downbeat, introducing a rolling/rubbed bass sensation which filters a deep bass synthesizer so that the sensation would roll between the Buttkicker Advance and the higher bass Dayton Audio bass shakers placed on different sides of the

120. Tuned gong Instrument of Gamelan ensemble - an array of different size enclosed pots with large 'nipples' that are struck with a wrapped wooded stick, not unlike a vibraphone of sorts.

floor module - in complete darkness. A demonic whisper[121] portraying humanity as the Judeo-Christian concept of the angel of death (in relation to the Earth), travels from side to side of the installation—the bass frequencies traveling through the audience's body, again in complete darkness. The outline punctuation of the scale transitions the demonic presences into the next section.

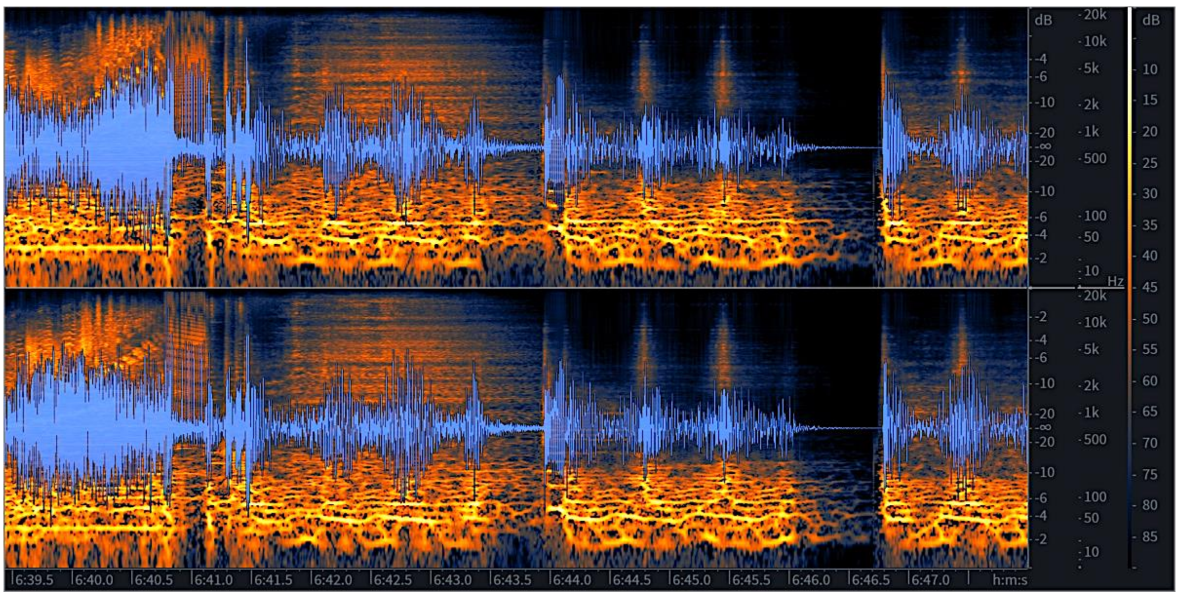

Figure 106: Spectrogram showing rolling bass effect.

A flash of glitch-chroma distorted film tears punctuates the second instrumental breakdown of the movement. We focus on wind-blasted trees, in a strong sepia haze, with Joan's fire footage inverted and portrayed as black flames on each side of the frame, appearing to emanate from certain objects in frame. Heavy drumbeats punctuate a cello groove, created with a MIDI arpeggiator, to deliver the distinctive grove. The drums are

121. I recorded myself whispering one of the final lines of the movement 'how long must we wait for death…' and pitched down a few octaves. I re-processed the word 'death' for the first breath, and then faltered out of saying the whole line for the second.

created by splicing together a groove to accentuate the beat, and the syncopation that drives this section.

Figure 107: "Furiosa" 6:53 - Sepia haze as the environment burns, and black flames continuing the Judeo-Christian allegory of humanity destroying Mother Earth

After four repetitions of the percussion and cello groove, each with a different micro-transitional processed effect, the 'breathing crying shaking stomping' theme returns as a down-pitched variant to pay homage to the fire overtones alongside the earlier stuttering 1/16th gated synthesizer from the beginning of the movement, however this time the gating punctuating and interactive with the "breathing crying shaking stomping" motif's rhythm. As the "breathing crying shaking stomping" theme travels from side-side on the listener, Prof. Sharma's fire footage has been transformed into a widescreen fury of strobing fire fractals that overlay onto the ashy Aurora environment. Every micro-transitional between four-bar phrases, the fractals become smaller and more hectic.

Figure 108: "Furiosa" 7:03 - Fire fractals visually combining the 1/16th note ostinato, "breathing crying shaking stomping", and percussion feature motifs.

Figure 109: "Furiosa" 7:07 - second repetition fire fractals become denser.

Figure 110: "Furiosa" 7:08 - third repetition fire fractals become even more dense.

Figure 111: "Furiosa" 7:12 - final repetition fire fractals become more intense.

"Insistence" breaks the activity, and introduces the heaviest, deepest bass in the piece so far, with a sub-bass sustained frequency of 33Hz, putting some heavy focus on the Buttkicker transducers.

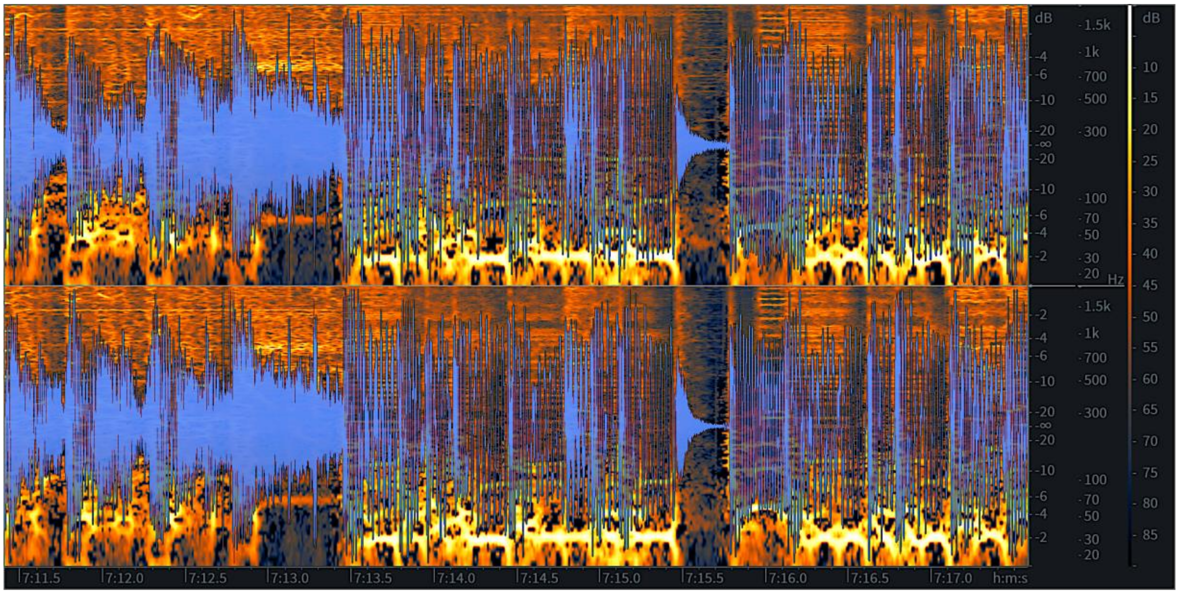

Figure 112: Spectrogram showing 33Hz strong sub-bass at 7:13 that really shakes the Aurora experience.

The camera leverages a slow pan across the scene, pulling out slowly from the dark, windy active storm, the beat heavy in a long eight-beat pattern. The pattern repeats but is interrupted by a pattern outlining the lyric that requires a bar of 12/8: “that this is just you”, which closes out the 5-bar phrase. The lyrics are punctuated with quick camera moves that grow increasingly off-kilter, providing unease to the audience. The phrase repeats, with different camera movements, and a different melodic phrasing of the lyrics.

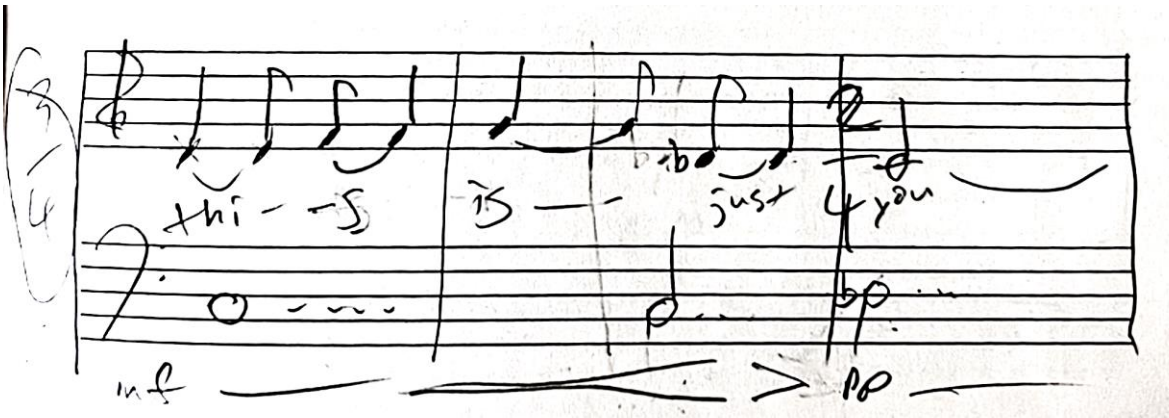

Figure 113: Original sketch showing "that this is just you" motif as two bars of 3/4 instead of a single bar of 12/8

Suddenly the screen darkens, all instrumentals have disappeared, and a vignette covers most of the screen except for the center of the screen, the lyric "she bleeds beneath us" appear on the screen alongside the vocal element in concert with the Kenong[122] instrument of the same, and on the syllable "-neath us" the vignette seems to explode away, the camera flies upwards to reveal the environment in a smoky haze, with a warm, sepia-like hue overcast the scene.

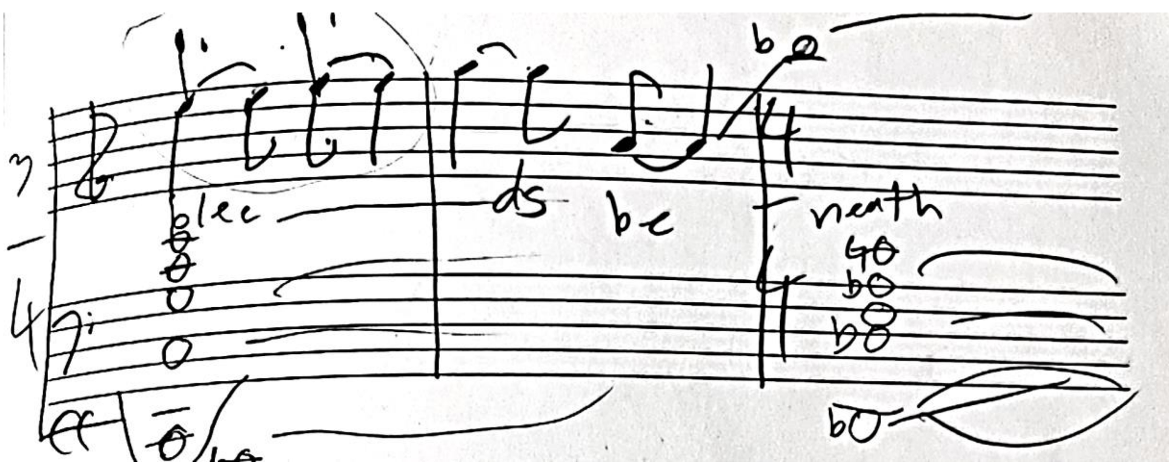

Figure 114: Original sketch showing syncopated "she bleeds beneath us" motif.

122. Kenong is the larger of the pitched gongs within a gamelan ensemble

Figure 115: "Furiosa" 7:31 - "she bleeds beneath us" on screen, strong black vignette

Figure 116: "Furiosa" 7:32 - impact and visual explosion on "-neath us"

An alternating CM - DbM progression cycles, with the voice chanting "under our plastic roads" and 'as we eat our plastic foods' punctuating the cyclical repetitions. 'We pluck her roots and burn them' introduces the burning theme with the last two words in the line. Meanwhile, Joan's fire footage grows and grows from the side of the screen, as the haze of the environment obscures the forest and foliage. A screeching synthesizer wails in octaves lamenting the mass genocide of natural kingdoms of beings.

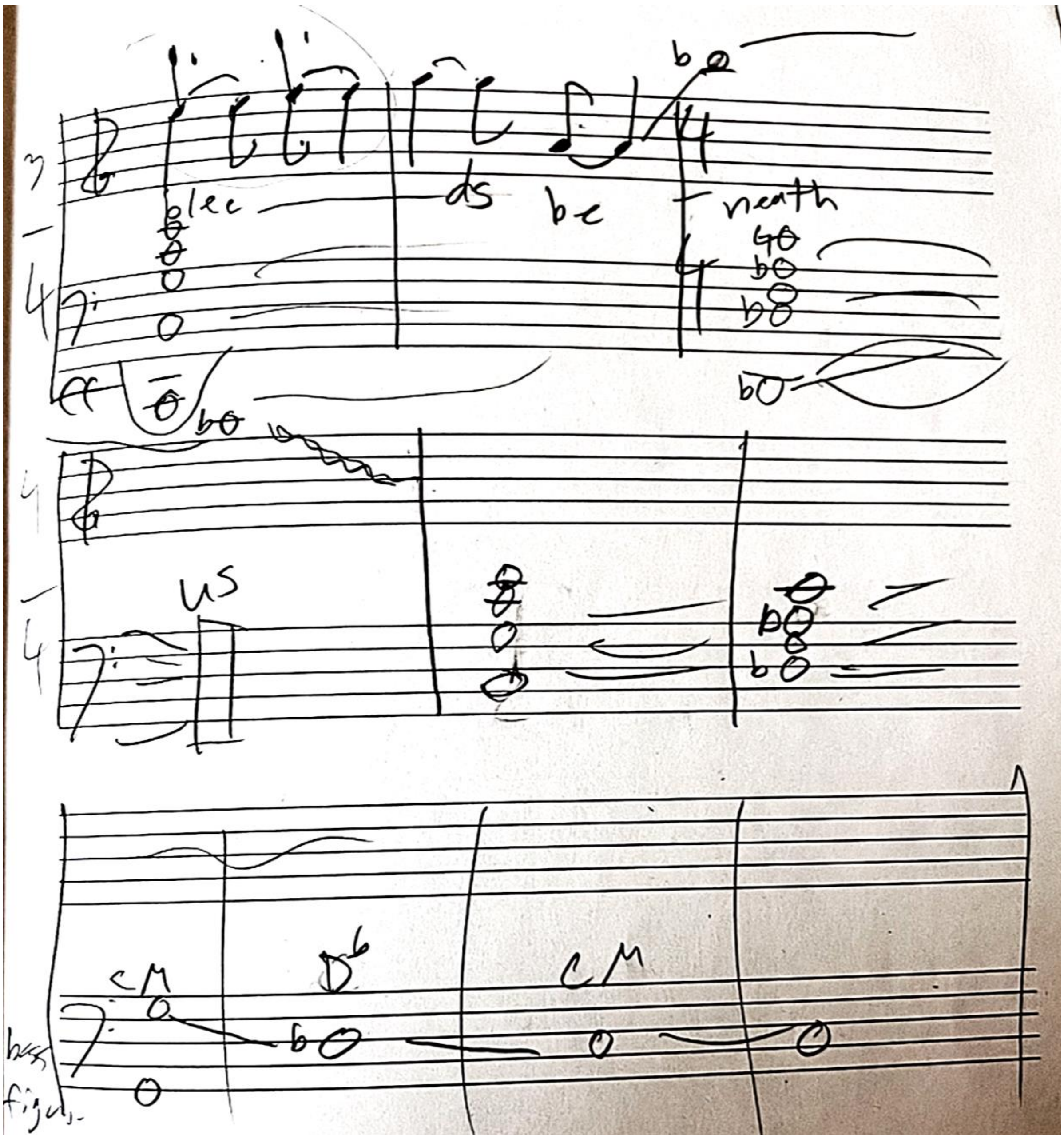

Figure 117: Original Sketch of the end of "Furiosa" alternating between CM and DbM chords.

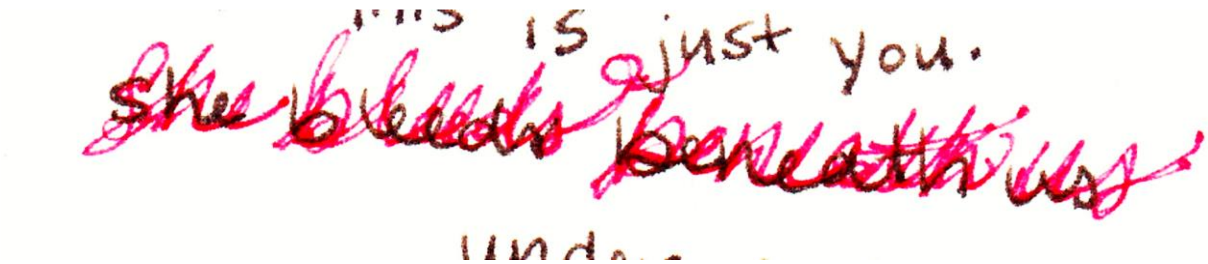

Figure 118: Aurora Written Layout - "Furiosa", showing bleeding letters of the text

Figure 119: "Furiosa" 7:46 - text and lyric "under our plastic roads" against fire seemingly burning the edge of the frame, and thus, the Aurora stage (when projected on the walls)

Figure 120: "Furiosa" 8:11 - "burn them" remains on the screen, matching the vocal melisma.

How long must we wait for death…'til we survive?" introduces the final, echoing melodic content of this movement, a vignette concurs with the fading out chords. Fading out to total darkness.

Figure 121: "Furiosa" - 8:23 - The flames grow stronger but also more distorted as the frame (and stage) is mostly burned away.

Finale (Aurora)

A single repeating half note bell begins this movement, outlining the new ♩=145 tempo and the key of G minor, like an ethereal clock counting the seconds past the point of relevance. A small glimmer of light gently fades in the center of the screen. A delicate bell outlines a harmony, before a voice seems to appear out of the glimmer of light, the light responding in concert with the voice singing "mama…I'm cold". The delicate voice continues to plead to an unresponsive participant:

"*do you have a blanket? grow me some cotton"*

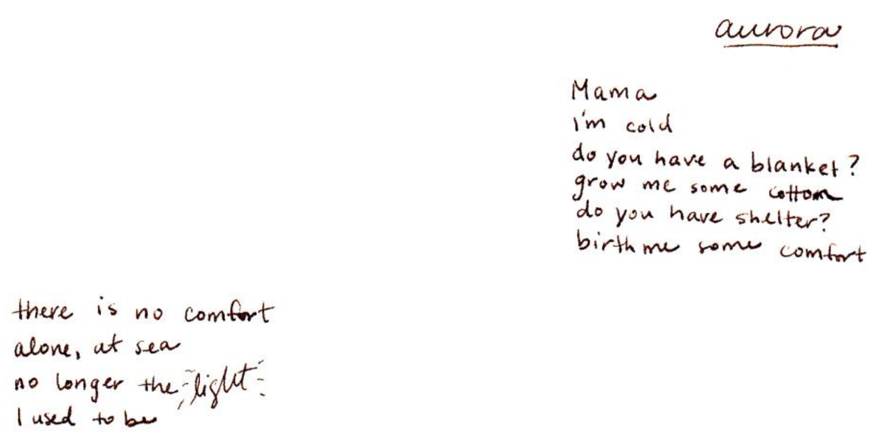

Figure 122: Aurora - Written Layout; aurora showing the delicate small text pushed to the corner of the page.

The stark ticking of the ethereal bell continues unmoved, albeit the space between grows as the tempo begins to slow. The delicate bell continues to assist the voice as it struggles to outline notes of the G minor scale until the voice finally breaks down into un-pitched whisper *"do you have shelter?"* Finally subduing any attempt at melodic effort: *"birth me some comfort"* is presented almost at a whisper. The ethereal clock winds down, the glimmer in the center of the screen appears to grow as the bells' harmony ticks ever onward as the tempo feels the effects of entropy slowing to ♩=114. Shapes begin to form as the glimmer expands across the screen, revealing more geometry.

Figure 123: "Finale" 9:37 - The gentle light brightens in response to the voice, now begins to reveal more shapes.

A wooden resonant instrument marks a distinct transition, while the visuals reveal that the glimmer was merely a leaf moving in the bleak ash-covered aftermath that has befallen the environment. A descant voice fades in from the bleakness, stating the apparent "there is no comfort…alone, at sea". A morbid counter melody (G, A, Bb) rises in a bass instrument, and the voice follows "no longer the light… I used to be". The camera pans around the shrub responsible for the glimmering of light.

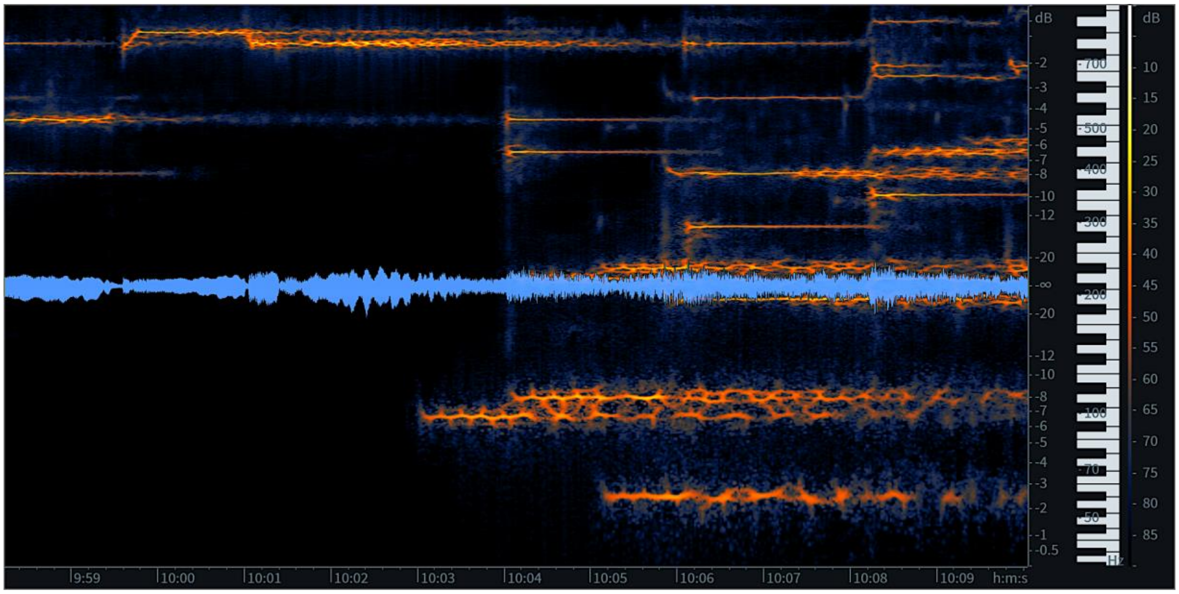

Figure 124: Spectrogram showing the descant voice line singing "alone at sea" (top left orange line with the slide going into the note) and bass countermelody (bottom middle orange lines showing the ascending line, displaced by an octave by the third note).

Figure 125: "Finale" 9:47 - the gentle light reveals to be ash-filtered rays shining through a hidden shrub.

"mother's green and blue fade far away" sets the camera pan outside of the cove:

Figure 126: "Finale" 10:31 - camera pans to look out of cove where shrub was hiding

"as i float" launches the camera over the whole environment in a hopeful chordal foray. Visually, the camera shows a white, ash-befallen consequence of the fire from "Furiosa". The text "float" literally floats above the environment, with the vocal melody following suit accompanied by soaring synthesizers and a stronger presentation of the steady piano pulse.[123]


Mother's green and blue fade far away

as i *f l o a t*

Figure 127: Aurora - Written Section showing "float" typed out within a document

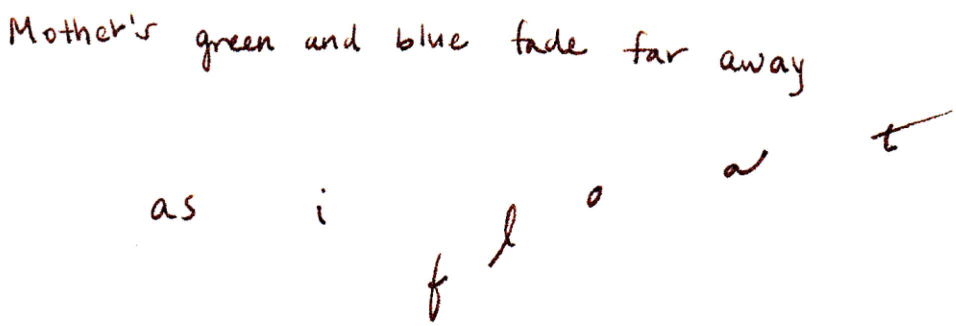

Figure 128: Aurora - Written Layout showing hand-written "float" spacing on paper.

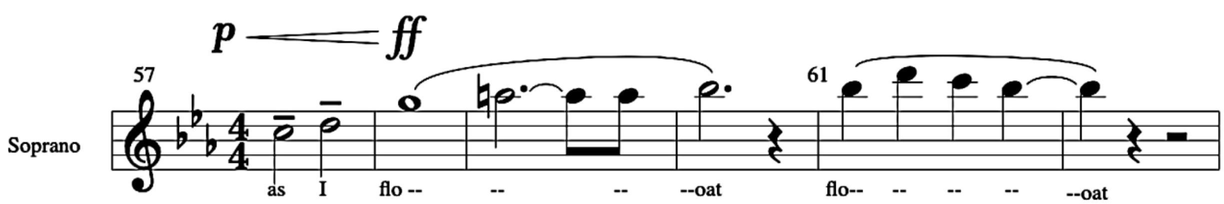

Figure 129: Score interpreting "float" spacing from text

123. This is a clear example of the effort to present an idea in as many modes as possible. The word 'float' has an implied meaning of weightlessness to it, coupled with the soaring melody, soaring synthesizers, the soaring camera work– it really gives the feeling of floating or at least gliding down gently to the next section of the piece.

Figure 130: "Finale" 10:39 - camera floats over the (should be) ash-covered oasis

The stepwise motion descends into a whole tone-figure, as the camera explores the new ash-covered environment, with an ethereal child-like harmonic wandering hanging in the space. At this point, I wanted to leave the conclusion undetermined - the audience could decide to feel hopeful or bleak about the outcome. We could rebuild as a society; we could correct our manmade contributions towards climate change and renew our relationship with Earth. Or we could ignore the unfathomable damage and necessary efforts that lay in front of us and await our impending demise. I chose to write an ending around the latter.[124]

A sudden uptick in dissonance brings us to the final climax of the piece. The final three minutes of *Aurora* were inspired by a piece I made at CSU Fresno under advisement of Dr. Kenneth Froelich, where he challenged me to create music that wandered from my traditionally electronic pop-oriented style. That piece, *Entropy*, featured a solo cello, that

124. As a quick note - I tend to generally fall into a positive-thinking category, so much so that, according to those close to me, I may have a "toxic positivity" condition where I want the positive outcome so badly, that I will sacrifice myself and others' comfort to deliver my intended outcome and deny space for any naysayers or realists who try to temper my expectations. At the time, it was the fourth year of the Trump presidency, and the country was divided into polar opposites, with tribalism and misinformation as the main deciding factor of many efforts. It was very difficult to see past towards a future that would return to 'normal' without reconciling the sins of the past, especially with both sides refusing to concede on the ground they made with their base by vilifying the other. With so much effort focused on the day-to-day operations and avoiding economic recession from the pandemic, long-term issues such as climate change were pushed to the wayside, and away from dinner-table conversations. It was tough to remain optimistic.

was accompanied by a prepared electronic tape that was based off exploring the idea of time within a space, and so I made drums out of a clock ticking sample, and featured an ostinato of an ominous gong-like instrument over long deep bass notes that created pressure in the concert hall alongside the heavy dubstep-like drums. That piece explored the breakdown of time into chaos, and I wanted to bring that feeling into the climactic finale of *Aurora*, as an emulation of the breakdown of climate-based social structures.

The final section begins with a new progression based around f minor, with each chord sustaining for four measures at the at 145bpm rate. First raising the 3rd, to create a subtle vocal descant over a marimba-like sound presenting the ostinato, outlining the harmonic structure for the climactic breakdown.

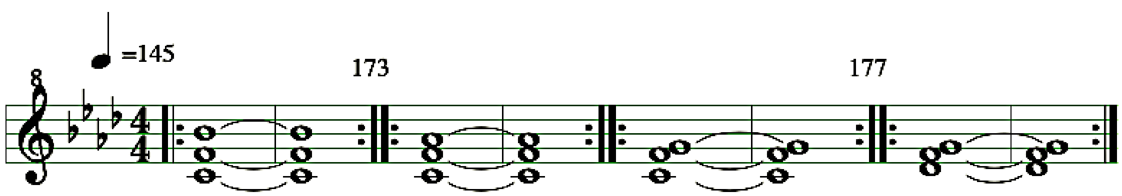

Figure 131: harmonic progression of the final section

The camera fades into the central area of the *Aurora* environment island, called the Oasis. The oasis features a lake, with a single tree and seedling in the middle - featured earlier in “Furiosa”. An ethereal blue flame burns persistantly in the middle of the screen, while the text follows the vocal melody, ascending in skips: “the way it floats….your candle on the water….the light flickers….the halo…” words are omitted, as a function of entropy - order begins to degrade, and whole words begin to drop completely.

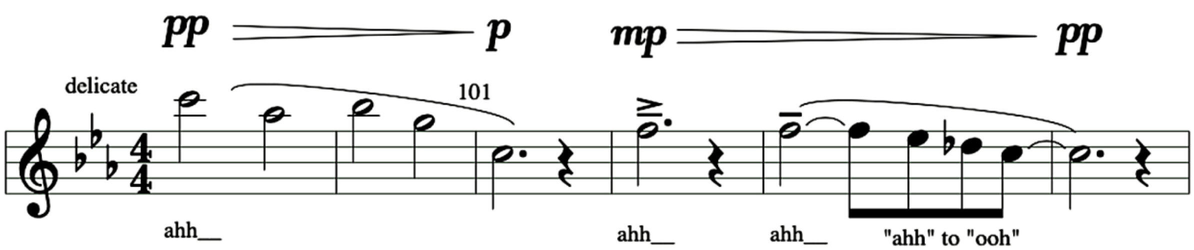

Figure 132: Vocal descant descending line

Figure 133: "Finale" 12:04 - Blue flame in the middle of snowy (ash) covered.

"It burns, it burns….sets fire across the river" then followed by a reprise of the chilling descant "ah" closing the phrase. The camera pans upwards briefly, showing a cloudy sky, the wind beginning to pick up, blowing across the water. Thunder punctuates "Unstoppable….shock-faced lovers", the word choice becoming more chaotic and varied, the piano pounding like a hammer on the lower octaves outlining the harmonic structure. A clock tick begins to make its way from the sub-bass frequencies, I record a lower octave to match the vocalist's higher octave to provide more emphasis on 'in the middle of the night'. The clock tick becomes faster and more audible, she repeats "it burns, it burns" but instead spells out the result I have chosen to adopt for our world: "their teeth, become ash".

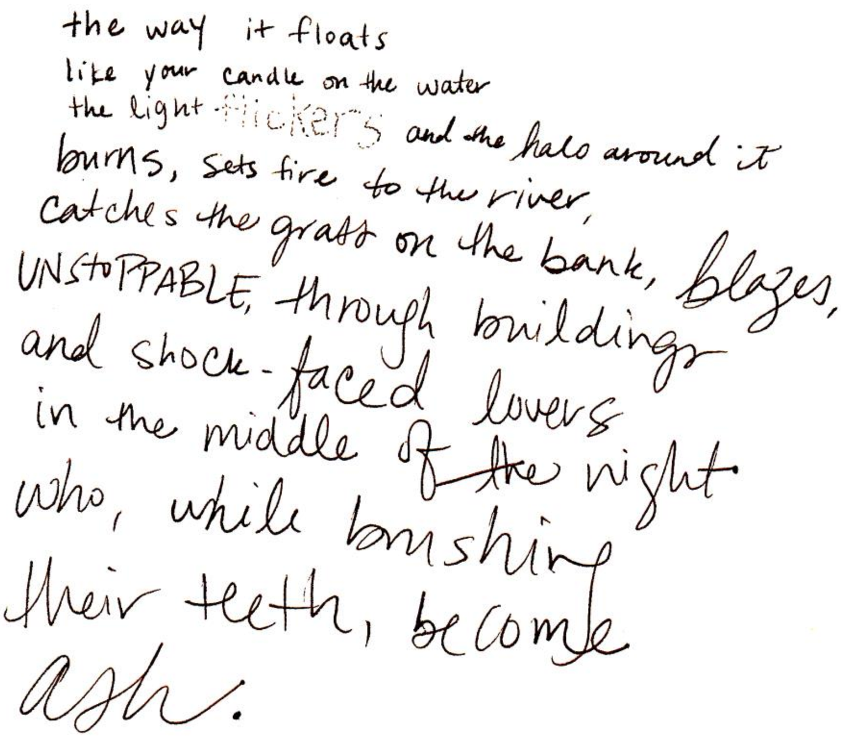

Figure 134: Aurora - Written Layout showing the increasing desperation within the calligraphy.

Figure 135: "Finale" 12:46 - the color tone changes, from stark blues and whites to warmer colors and sepias.

The second repetition of 'become ash' introduces the clock tick as a heavy impact. 'Ash' joins synthetic instruments as the environment becomes torrential and wind begins to sway trees. The clock tick impacts outline a syncopated rhythm against the descant as the blue flame struggles to stay aflame. A vignette begins to extinguish the light in the frame, the little blue flame holding out as long as possible, while the world seems to fall in on itself. The clock-drums beat away any resistance, signaling the absolute end.

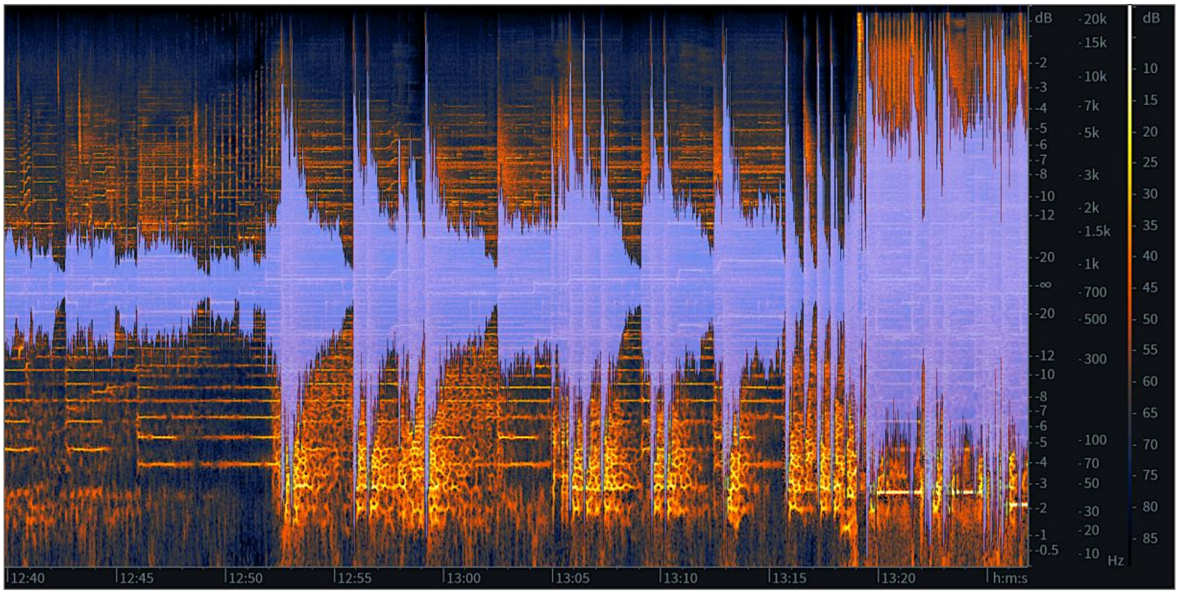

Figure 136: Spectrogram showing clock-based drums filtering in at 12:45 and cutting through just after 12:50.

Figure 137: "Finale" 13:16 - the wind intensity grows, vignette chokes the frame, forcing attention to the center of the screen

A sudden harsh glitch, which is the extreme pitch distortion of the clock-based drums, surprises on the downbeat, and explodes into a combination of synths, bass, drums, and presentation of the ostinato as a feature. The camera shoots upwards over the island, and the aurora erupts across the sky, with the RGB chroma colors distorting the visual while wind tears at the branches, and clouds race across the sky. The ground shakes as the clock drums slam against the audience, and the constant sub-bass notes rattle their teeth. A synth feature against the ostinato grieves for once was, and what could have been. The two harsh drum glitches that introduced the climax, also punctuate the ending, before the drums are granularly sampled into the final syncopated drum figure, with the swirling camera angles gated by each drum hit, chaotically strobing in consonance with each other.

Figure 138: "Finale" 13:18 - glitch before the final climax of the piece

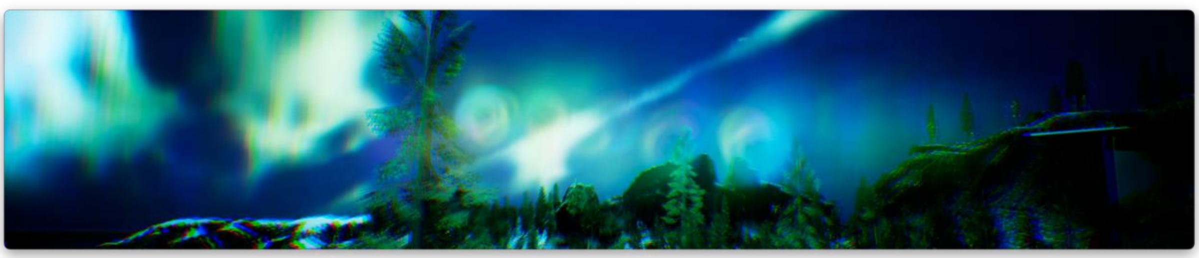

Figure 139: "Finale" 13:22 - Aurora Borealis, with post-processing to brighten the night sky.

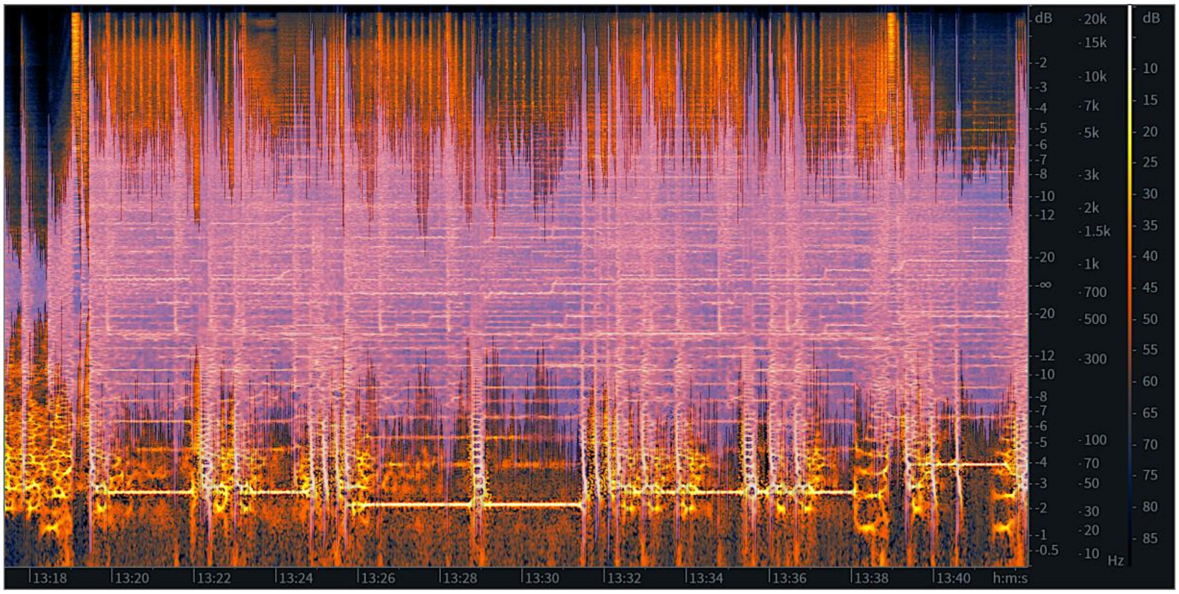

Figure 140: Spectrogram showing dense harmonic presence of final climax

The final climax features major elements from each previous movement. Sub-bass presence from “Prelude” performs the progression of this section, 1/16th note ostinato from “Furiosa” returns but in high frequencies from the clock drums, and Fusiosa synth the vocal descant line from earlier in the section.

A final impact leaves just the sub-bass and ascending arpeggios bells outlining the harmonic progression as the final ostinato. The syncopated arpeggiated synth bell from the first movement returns, bouncing around the chords of the same progression almost with a sprite-like playfulness against the dark mood. The camera moves away from the island along the still water as a synthetic descending “breath” instrument performs an abstracted descant “sigh” counter motif to the ostinato which contradicts the final lyric: “inhale”.

Figure 141: "Finale" 13:59 - final text appears on screen, the action only realized by a synthesized impression of a voice, outlining my expectations for humanity's survival

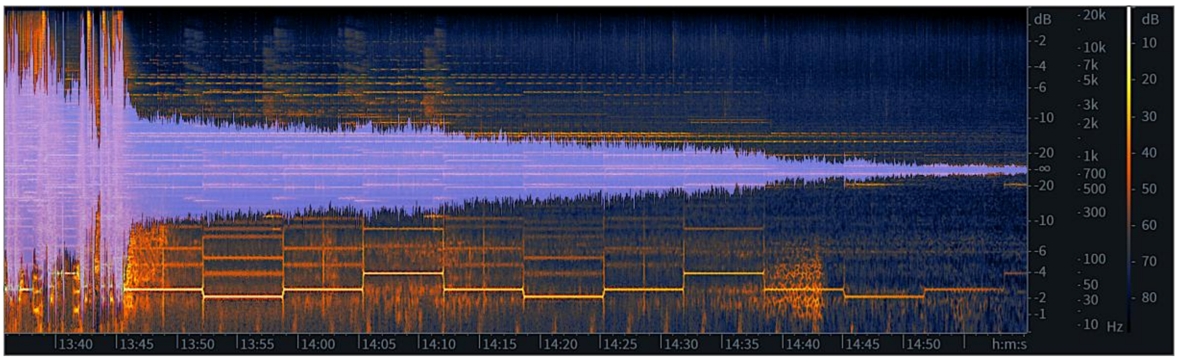

Figure 142: Spectrogram showing sustained bass notes and ascending bell arpeggio filtering out over the end of the piece

The "sigh" marks the end of the "breath" figure as the bass, and ascending arpeggio outlining the progression are all that remain as the camera leaves the island and returns to the sky, where the journey began. Either we have influenced everything, and our outcome has been created by ourselves, or our actions mean nothing and the Earth will protect itself as it always has for millennia. Either way, our outcome is certain.

Creating Aurora

Sound Design

As is evident by some of the descriptive nature of the program notes, *Aurora*'s sound design was created in such a way to embody the performance from the audience's perspective. I wanted the audience to feel as much as possible, which meant emphasizing transient information of each element, and often doubling elements with a sub harmonic generator, or pitching an octave down, or simply using octaves in general, the resulting harmonic characteristics which create their own sensation of embodied complexity.

I used Logic Pro X as my digital audio workstation (DAW) to compose the piece, using built-in synthesizers such as Alchemy, ES2, Sculpture, Retro Synth, but also Xfer Records's Serum synthesizer. The rest of the instruments are mostly built from processing sampled instruments, recorded and processed vocals, or—in the case of "Prelude"—two individual-generated sine-waves that were pitched a minor second apart to generate the binaural beats, but instead were panned left and right, and are essentially binaural beats that happen to create a left—>right rolling sensation when both signals (stimulated by different transducers) are present in the same substrate.

Processing vocals and instruments used a variety of creative tools, but the most significant 3rd party plugins were created by iZotope, SoundToys, Xfer records, Antares, and Waves. Otherwise the built-in plug-ins from Logic were sufficient for the majority of processing needs.

Mixing was by far the most difficult task. Too much harmonic information would muddy the presentation, since exciting a surface already creates harmonic distortion. Additionally, the end-result vibroacoustic setup was not available until about a week before we started showings, making the task even more challenging. I used SUBPAC's M2X to help produce and mix the bass and sub-bass information, but I needed higher frequency tactile information as well. EDGE Sound Research's ResonX system helped me gain critical information about the vibrotactile information, concurrently with acoustic information, allowing me to understand—at a critical level—how the vibrotactile and acoustic presentation of *Aurora* would be perceived at a large scale.

Mastering was done in Logic Pro X with iZotope's Ozone 8 Advanced, Xfer Record's Serum FX, and some Waves plug-ins. Each movement was mastered independently, with each movement needing a bit of mastering automation, and slightly different parameters, since they were all made in different sessions.

Visual Design and Resulting Cinematography

Professor Joan Sharma took the initial lead and spent over two years experimenting and finding clips that interested her and that she thought would interest me. Her descriptions of concepts from a relatively abstract viewpoint set my mind wandering towards all sorts of possibilities. We aimed to create the environment and replace the textures with her captured content and footage, so that the *Aurora*-created environment would seem reality-inspired, without having to try to emulate real textures—a real difficulty without huge render farms.

Unfortunately, due to unforeseen delays in preparing the ResonX technology for large-scale use, dedicated development time for the audio and visual aspects of the project had to be pushed back. Consequently, I was unable to fully integrate Joan's existing footage, and I ran out of time before gaining complete control over the Unreal Engine session.[125] As a result, I was not able to adjust the parameters as precisely as envisioned.

I had never used Unreal Engine 4 before this project, only Final Cut Pro X and other motion graphics such as Apple’s Motion software. This was the first time I had to deliver production-ready motion graphics, and a high-quality capture of footage from Unreal Engine. The *Aurora* island environment was a single level created in Unreal Engine 4 with landscape design by Max Louis Creative, made from a base of MAWI forest and generative foliage, and using stock CineCamera and other stock plug-ins.

I programmed the camera parameters, as well as all environmental parameters of the *Aurora* to be able to record footage within the game engine. I then captured and exported from the built-in cutscene tool within Unreal Engine 4, then transferred to MacOS where I converted the large .avi files to even larger ProRes files with Apple’s Compressor software. I imported the footage into Final Cut Pro X, and used plugins from Pixel Film Studios and built-in effects to edit the footage to the music with alternate looks. I also integrated Joan's footage, along with Alex Johnson's close-up footage of the written layout, as a layer of creative captions for what was functionally a very finely produced lyric video.

125. Unreal Engine is a free-to-use software created by Epic Games for video game development.

Once all the prepared footage was done, it was projected onto the walls with Epson-sponsored laser projectors, and mapped out with MadMapper software with help from RabCup - a projection mapping company out of Los Angeles. Once RabCup set the system up, composer and audio programmer Dr. Christiaan Clark and I had to figure out how to setup the Go Button MIDI controller to control both MadMapper and Christiaan's custom Max Patch, and to also have them interface with each other, and automatically route the whole system to restart again after a showing, so the experience engineer on call would only have to press the green 'go' button to re-launch the installation theatrical presentation.

Aurora Event at Riverside Studios, June 11-24, 2021

The event took place Friday June 11th, and the installation remained in place until June 24th. We began to develop the installation since May 25th when my friend Scott Yocum brought the completed wall panels to Riverside Studios. May 27th we began making the floor panels, and testing whether or not my plan was even going to work - would the panels transmit vibration the way I anticipated? Would having multiple bass shakers on the same floor panel cancel each other out? Would it be a pleasant experience? Would one completely overpower the other? While we had some ideas from the smaller prototypes and experiments, we were unsure if the same principles would apply to the larger form-factor.

The walls were setup with four ResonX devices spread across every two sections of wall, and each of the two floor segments were composed of two Dayton Audio BST-1 or BST-2 bass shakers and a single Buttkicker Advance. I used the Dayton Audio DSP-

408 to tune each of the channels independently. The front two ResonXs were tuned to focus on middle frequencies and attenuated slightly overall. The side two ResonXs were focused on high frequencies and provided most of the volume. The the Dayton Audio BST-1 and BST-2 bass shakers focused on higher bass register, and the two Buttkicker Advances were dedicated for lower bass and sub-bass frequencies. I used the Dayton Audio OmniMic v2 to tune the room with Room EQ Wizard (REW), but mostly relied on my ability to detect vibroacoustic information via my body, and I relied on the “golden ears" of Santiago Tavarez for any acoustic mismatches.[126]

On Wednesday, June 8th, Christiaan and I both figured out how to make the Max Patch work, as I was finishing the Unreal Programming, as at this point - we were still trying to figure out how to use a plug-in within Unreal to have it talk to MadMapper, so it would render the environment live for each showing. It wasn’t until late Wednesday June 8th/Early Thursday June 9th when Christiaan and I gave up trying to get Unreal and MadMapper to communicate to each other, and just export the footage from Unreal and re-do all of the visual editing within a day and a half of the installation opening day.

The first time I saw the whole audiovisual experience was alongside the first group of attendees who arrived right on time. Fortunately, the pre-installation experience we had setup in our rooms, that took the audience on a zig-zag journey first to visit Vincent Zhang’s water sculpture he made to explain the technology through a visual medium, tour through our workshop, the holding room, before their turn in the theatrical presentation

126. Someone with a “golden ear” is considered to have a set of ears that can hear small discrepancies in sound and can be relied on in critical situations. Like someone with 20/10 vision.

space, bought me some time to finish exporting, and transfer the file to the show computer. Luckily, poor quality or not, the experience came out fairly decent for the very first showing.

Saturday morning I fixed some elements, and re-exported the show file in much higher quality, and from Saturday June 12 and on, the audiences had a much higher quality audiovisual experience.

From June 11-24, we showed the installation to over 140 individuals. June 25th we tore the installation down, June 26th we shipped the projectors back to Epson, and cleaned up the loading dock to return to Riverside Studios.

Evaluation of expected results:

In the prospectus, I proposed a series of goals that I aimed to achieve with this dissertation. This section will evaluate if the effort to achieve the stated goal was a **Success**, **Partial Success**, or a **Failure**. Since the nature of the project changed from conception to execution, some goals became unnecessary, and this section will acknowledge the updated aim accordingly.

15 minute multimodal composition experience with multiple immersive modes

Success. This actually ended up fairly close. The intention was to split up each of the three movements into five-minute segments, each with their own arc, starting and ending soft to allow for easy transition. The final duration of the piece, when combined together was 15 minutes and 25 seconds, although the very beginning and very end are so soft, that some low bit-depth systems may perform the early/late gradient of fades as silence.

I decided on three movements because of the natural occurrence of three within natural settings and the relationship the natural world has with the piece. The modern usage of "rule of three" or the "rule of thirds" stems from visual composition, where the human eye is naturally drawn to content that resides on the same plane as lines that intersect each other, horizontally and vertically to create a grid of nine equal squares. First described in John Thomas Smith's *Remarks on Rural Scenery*, the nine squares' borders outline a grid whose lines intersect in four distinct places, each a third of the distance away from the outer edges of the same plane. This may be more familiar to some as a tic-tac-toe grid:

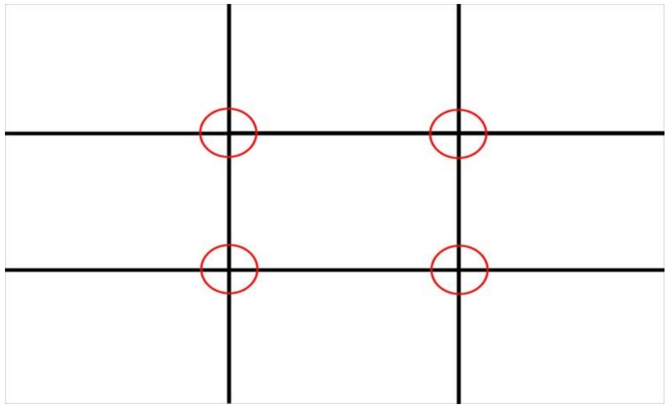

Figure 143: "Rule of Thirds" grid

The "Rule of Thirds" grid can be thought of, in *Aurora*, as humanity's need to organize and identify patterns. Three is the smallest number of elements needed to perceive a pattern, so this concept has been found within visual arts and design, persuasive communication in both written and oral rhetoric, religion, and much more.

In *Aurora*, the "Rule of Thirds" is in direct contrast with the "golden ratio", or the "golden mean".[127] The golden ratio (phi φ) is expressed as the function $(x + 1)/x = x/1$; letting the length of the shorter segment of a line be one unit and the length of the longer segment be x units. The ratio is also known as the Fibonacci number sequence (1, 1, 2, 3, 5, 8, 13…) where each number after the 2nd is the sum of the previous two. When expressed, the ratio between successive terms of the sequence very closely calculate to the golden ration. This "law of nature"[128] is seen in nature as the spirals of sunflower heads and petals, the structural design of snail shells, and much more.

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127. Stephan C. Carlson, "golden ratio," in *Encyclopedia Britannica*, ed. The Editors of Encyclopaedia Britannica (Encyclopedia Britannica, March 31, 2023 2006). https://www.britannica.com/science/golden-ratio.

128. Christopher D Green, "All That Glitters: A Review of Psychological Research on the Aesthetics of the Golden Section," *Perception* 24, no. 8 (1995), https://doi.org/10.1068/p240937.

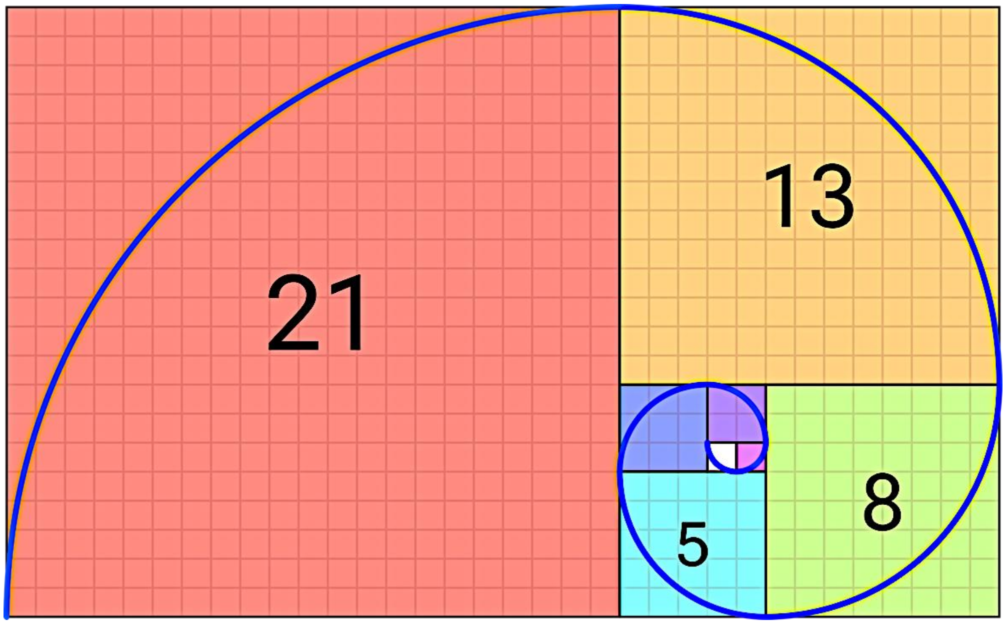

Figure 144: Fibonacci Spiral over tiled squares[129]

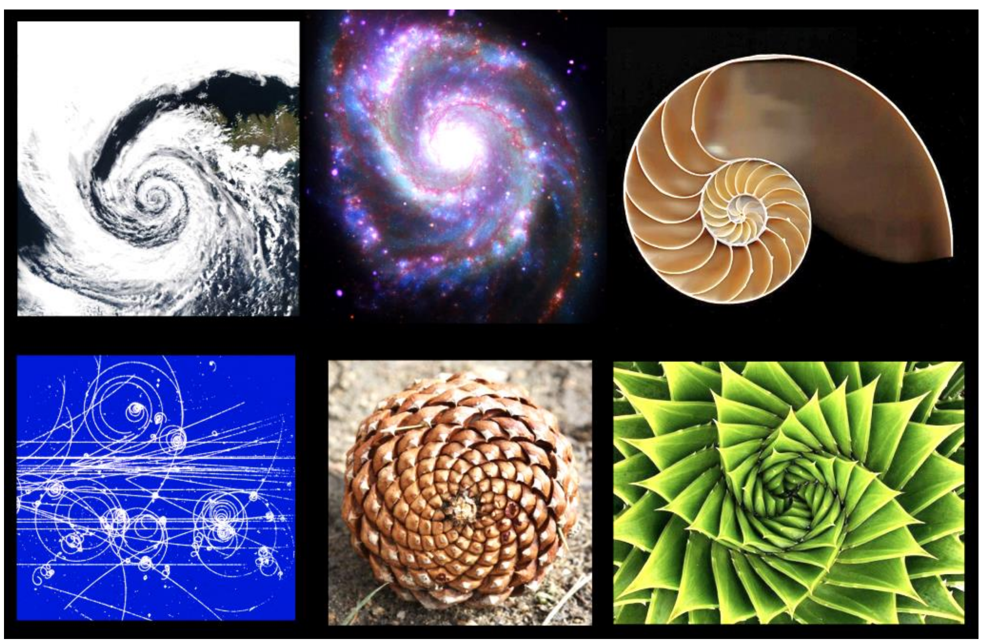

Figure 145: Geometric spirals in nature[130]

129. Randaum, *Fibonacci Spiral*, 2022. Fibonacci Spiral over tiled squares, 512 × 317 pixels, file size: 11 KB. Wikimedia Commons.

130. "What is the Golden Spiral?," Seeing Math in Nature, Tumamoc Sketchbook, updated May 29, 2021, 2021, accessed March 26, 2023, https://tumamocsketchbook.com/2021/05/what-is-the-golden-spiral-to-understand-it-we-need-to-draw-it.html.

While the outlining apparent form of Aurora exists within three movements, and both “Prelude” and “Finale” movements can be sectioned out in three distinct sections at a high level, “Furiosa” focuses on dyadic relationships, and an absence of the golden ration. “Furiosa” exhibits more A/B form, if this then that relationships, hot/cold extremes, dyadic harmonic structure, etc. This was meant to represent human intervention and human dyadic approach to humanity which often is exhibited with false dichotomies such as good vs evil, total salvation vs damnation, optimistic vs pessimistic approaches to the environment.

Within the two outer movements, “Prelude” and “Finale”, each contain many aspects tied to the golden ratio (or at least an approximation). These aspects are more related to the speed and rate of automations, audible convergence of harmonics present, and both form’s climax happening in roughly $(x + 1)/x = x/1$ in relation to the longer section of each movement’s total time.

Immersive modes use more than a singular sense, and with the intention to perform *Aurora* with consonant audible, tactile, and visual elements, *Aurora* experiences frequent concordant multimodal events. For example, near the beginning of “Furiosa”, the quick 16th staccato notes in between drum hits are emulated with frame strobing in the visual, as well as generated tactile-range staccato notes, to give a sharp sound, visual, and tactile feeling of incessant tapping—an aggressive sonic aggregate. Also in “Finale”, complete black is used as an emphasis point before climactic moments, and in between drastic environment movements within the virtual environment.

Custom-built enclosure for at least five persons (10 ideally)

Partial Success. With significant assistance from Scott Yocum, Carson Welty, Brandon Babu, and Jack Adams, we were able to build a lifted stage, with walls surrounding 3/4 sides of the stage with projection mapping seamlessly surrounding up to 16 observers. Initially, I wanted a mini-planetarium style enclosure, where I could project around the audience, with the structure itself being the source of audio reinforcement.

Figure 146: Renderings of early installation idea by Catherine Chooljian

This idea turned out not feasible due to cost and size—engineering a safe structure was going to cost more money than I budgeted for the effort. Even with a drafting engineer sponsoring the drafting of the enclosure, it was quickly apparent that anything beyond simple straight-edged geometric shapes was going to be cost-prohibitive, and not at all comfortable in the Riverside Studios dock that was available to us.

We ended up drafting a lifted stage within the area that could also fit three walls, where the top surface of the projector stands would fit right over that would host the high-end digital projectors provided by Epson America Inc. thanks to RabCup's connection to Remi Del Mar on Epson's Digital Experiences team.

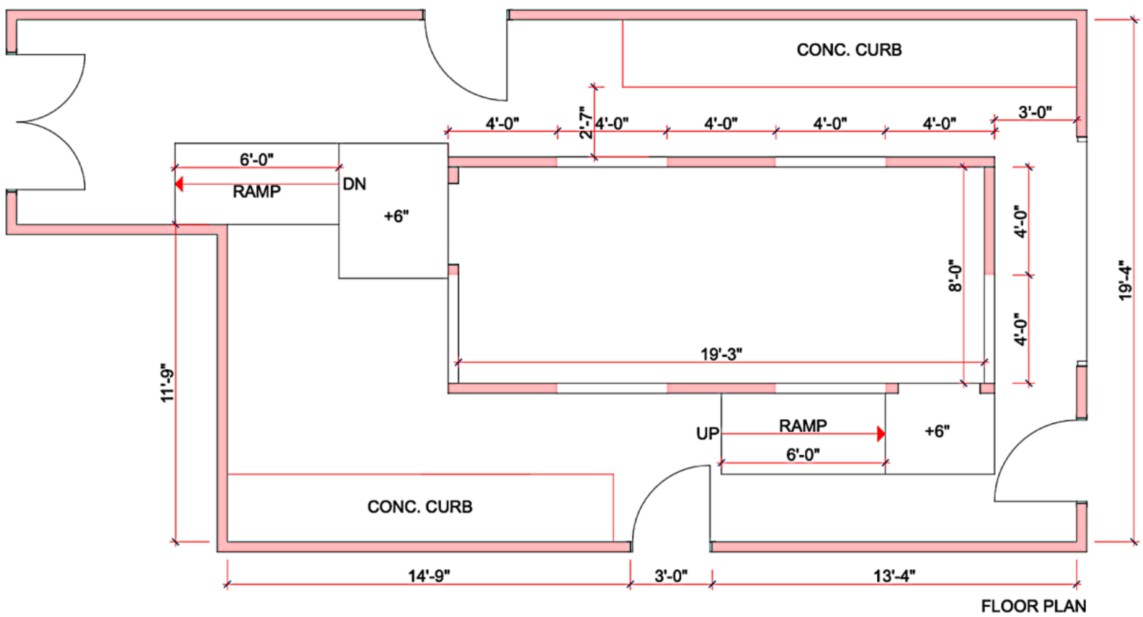

Figure 147: Drafting of Aurora installation within the walls of Riverside Studios.

My good friend Scott Yocum was able to help me interpret the draft plans into an actual structure, where due to lumber shortages from the (still) ongoing pandemic, we were limited to 10’ lumber pieces, instead of the 8’ we originally planned for. This turned out to be a blessing in disguise, as most platform truss have 5’ or 10’ as a standard length/height.

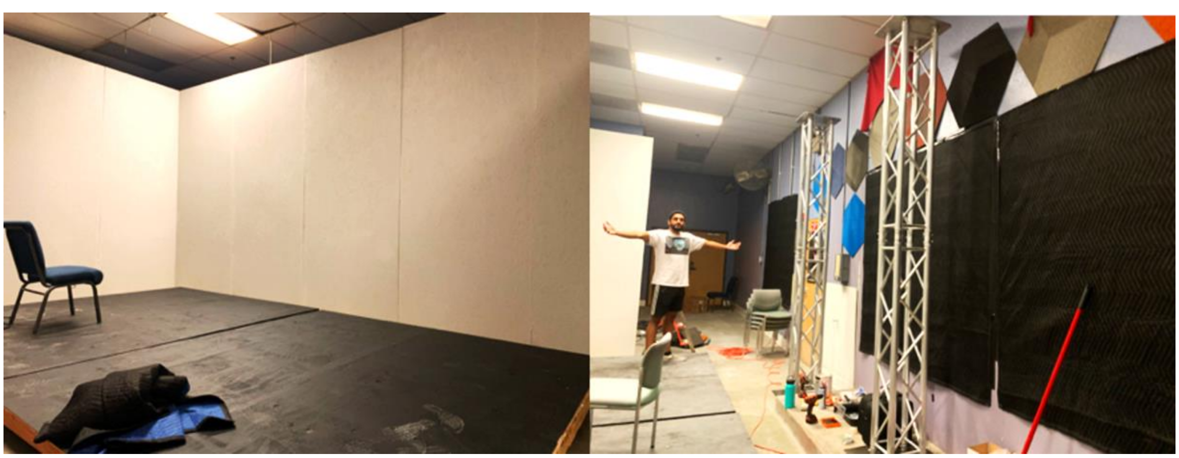

Figure 148: The completed Aurora stage (left), projector stands (right).

Modular design for quick setup/teardown and transport between venues

Partial success. A continuation of the previous point, our nine wall modules, and four floor module design is technically able to be disassembled and transported. However, once assembled with final support hardware, each module became heavy, unwieldy, and awkward to carry over any significant distance without assistance. The floor modules, being 4' x 10' each, fit very nicely in pairs, as each 4' x 10' module functioned as a single mono speaker/woofer, and paired well with another module in a L/R configuration. Two stereo pairs (8' each) suspended 6" off the ground served as the base of the installation, with each 4' x 10' wall module configured in 2 x 5 x 2, with the series of 5 panels facing parallel to the long (16') side of the floor system.

In the end, the system was not easily modular for manual transport. However, we were able to dismantle the system in a single day, and the modules could be packed into a pickup truck. Although we did not attempt it, I am confident that the electronic components could fit in the backseat of a standard pickup truck with rear bench seats.

A variety of immersive sound devices: DML technology, balanced mode radiator (BMR) technology, bass-shakers

Success. We ultimately did not need to add BMR technology to the system as the ResonX technology was sufficient enough to create the necessary frequency range needed for performance of the piece.[131] Originally I believe that we would have needed BMR or other speaker drivers as center channels to act as directional reproduction, or for higher

131. BMR technology is originally defined and discussed in Chapter 1.

frequencies. I ultimately decided against it after the EDGE Sound Research Team convinced me that it would be more impressive if we could claim that there are absolutely no speakers within the entire system, as any traditional speaker may have become a scapegoat and wrongly attributed to the entire system performance.

Therefore, I designed the system to have a ResonX 300 adhered on each of the extreme sides (L and R) as well as on each side of the center wall panel. I configured and tuned the 'front' L/R to be slightly softer and equalized to de-emphasize any sharp resonant frequencies so close to the audience. I attached four of the 50W (@ 4Ω) Dayton Audio bass shaker on each floor panel, with both panel sets wired in parallel with the other. Each stereo module pair shared a ButtKicker Advance to assist with Sub frequencies. The smaller bass shakers were paired with my QSC GX5 model amplifier, which can deliver up to 700W/channel at 4Ω. I purchased a higher-powered GX7 model to help drive the pair of ButtKicker Advance systems, which can handle a max wattage of 400W each, which was somehow still difficult for the 1000W/channel at 4Ω amplifier to drive.

Immersive sound format: 5.1, 7.1, or Dolby Atmos + Tactile Sensation (4D)

Failure. This section did not pan out the way I hoped. Initially I started composing in 5.1 because I thought I could create a perfect transition surface of the enclosure between the channels, creating a seamless embodied surround experience. However, I could not figure out how to present in multichannel effectively enough within the time allotment, especially when the enclosure was reduced from 360º to the front and sides (possibly just over 180º, See Fig. 149)

Figure 149: 'Hallway' design render by Catherine Chooljian (left) actual Aurora event (right)

At the time of the prospectus, I was learning about software creator tools like Dolby Atmos software renderer which would have made the whole process of re-mixing the stereo "Prelude", to match the 5.1 mix of "Furiosa" possible. However, to transfer all of the elements to object-based elements would have taken too much experimentation time to create an effective presentation.

Immersive video format–screen wrap around audience (at least 160º)

Success. Fortunately, I was connected with the projection-mapping company, RabCup. AJ Freysteinson and Jen Moore from RabCup (brilliant, and deserving of their own feature-length paper addressing their contribution to the visual and interaction art mediums) connected me to Remi Del Mar at Epson America, Inc. to sponsor projectors for the project as part of their educational outreach. The high-powered 5000 Lumen+ laser projectors from Epson were all synchronized with a WX9100 graphics card connected via Thunderbolt 3 to a small Intel NUC computer (10th gen Intel processor) with weak internal graphics processing power. Each projector was connected to a dedicated port on the graphics card, with the external display ID (EDID) forced to always deliver output to the same physical ports every time the computer was turned on, instead of auto-assigning the ports.

The resulting projection was warped with a software called MadMapper, covered the 36’ x 10’ screen real estate, and was quite immersive. On this custom display, we projected the visual portion of *Aurora* in incredible detail, even at 1080p resolution from each projector:

Figure 150: Software Madmapper being used to warp projector output to Aurora stage

Motion Actuators (if budget allows or sponsor can be secured) on flooring

Failure. Unfortunately, due to a lack of funding, larger motion actuators were not included in the installation.[132] Although it would have been a great addition to

132. Such as the PA-14P-2-35 from Progressive Automations, "High Speed Linear Actuator."

provide longer throws of motion at slower oscillations to simulate larger movements and direction, it would have required additional programming to make them useful due to their slow throw speed. Despite this setback, the rest of the audio and visual aspects of the project were successful.

Synchronized abstract video, lighting and theatrical FX: fog, heating/cooling

Failure. I was interested in adding these feature as additional modal pathways of certain key elements of the experience. *Aurora* featured synchronized discrete visuals to audio and tactile modes, but having more modes communicate the same idea to the audience contributes to the dissertation's central tenant that every sense activated greatly increases immersion. For example, during parts that were intended to make the audience feel cold, I would have liked to introduce dry ice and run a cooling element on demand to reduce the temperature of the installation environment. Ambient lighting's color temperature can serve to simulate the sun's position at different times of the day, influencing the audience's perception of time, and sun energy.

Prior to *Aurora*, I had some experience with digital multiplex (DMX) programming for theatrical lighting from my days as a DJ and live performance technician. However, adding this feature would have required additional programming beyond my already extensive task list for the visual and audible components, not including building out the technology itself. From the limited research I conducted, I learned that a possible way to synchronize heating and cooling would have required the use of relays and microcontroller programming via pulse-width modulation (PWM) for precise control messaging, which was beyond my current expertise.

Sensor-interactive generative background effect on loop during standby

Success. I am happy to report that my good friend, Dr. Christiaan Clark, came to my aid when I needed it most! He designed an excellent Max patch that was able to generate random pitches from a set. The patch receives trigger input from piezo crystals that are embedded on the bottom side of each 4'x10' stage module. By filtering the input signal, the patch can pick up significant taps made by people walking across the stage. These triggers then perform steps of a pentatonic scale at different octave ranges.

I created an ambient chord cycle in Logic Pro X to serve as the background music for the cycling arpeggio that would be triggered as the audience walked onto the stage to take their seats. Each floor module occupied a different octave range, with the module closest to the entrance of the experience (right-most side) playing fundamental tones in the mid-high frequencies, the next module to the left playing fundamental tones in the mid frequencies, the next module playing bass, and the final module playing sub-bass - mimicking the natural layout of a piano for a player.

Built-in adaptive and reflective ambient lighting

Partial success. Reflective and ambient—yes. Adaptive—not so much. We were able to adhesively attach a LED light strip underneath the border of the floor modules once they were all assembled together so they provided a very gentle under-glow to help audience members watch their step as they stepped onto the raised stage.

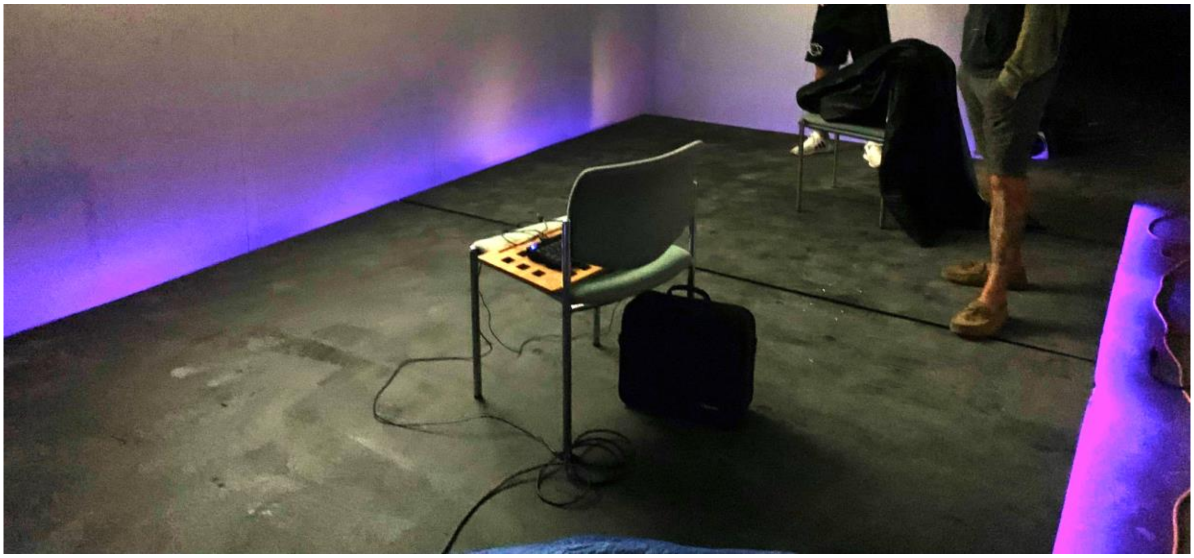

Figure 151: LED light strips help illuminate the underside of Aurora stage.

Server Rack for equipment, automated for easy setup/operation by non-trained staff

Partial success. Although it would have been ideal to have a compact rack for all the amps, equipment, and other gear, we used a simple folding table to hold the operational equipment, such as the computer, external graphics processing unit (eGPU) enclosure, sound card, amplifier rack, and extraneous cabling. We could easily have trained staff to handle the installation.

Dedicated "GO" and "STOP" buttons to control experience

Success. I was able to use my GO button, which I originally acquired for a Disney show I was contracted for back in 2016. The GO Button is a dedicated MIDI controller that can duplicate button presses out of two USB outputs for synchronized playback, stop, pause, next/prior scene, fast forward, reverse, etc. on two computers, simultaneously. It is very easy to configure within both Max and Madmapper software, both of which can take standard MIDI signals and route them as events to trigger other functions.

During the performance, we left the GO button by the side of the stage so that the audience had an emergency STOP button (the red button was programmed for emergency stop) in case the experience became too intense or if an audience member began having seizures due to the intense flashing and tactile stuttering of the piece.

Uplighting and pleasant exterior design elements

Failure. No other lighting was needed once the projectors were up and running. The under-glow from the lights embedded underneath the stage and the reflected light from the projectors was sufficient for ambient lighting. Since the function of the installation was the top priority, we didn't have much time to focus on the exterior design elements. As a result, the structure remained with a raw, wooden exterior.

Acoustically Balanced Frequency Response

While this was not necessarily a stated measurement of success from the prospectus, I feel that this is quite an important evaluation in this effort.

Once the transducers were placed beneath the floor modules, I proceeded to arrange a chair on the stage and set up the OmniMic and Intel NUC computer to conduct some frequency sweeps with Room EQ Wizard (REW). This was done to gain an initial understanding of what we would need to do to tune the room. To my surprise, the system reported a relatively even response across bass and midranges, with a slight emphasis on the 1kHz range and a significant drop-off beginning at the 6kHz range. The bass frequencies were consistent with my physical detection, with resonances at 40Hz, 60Hz, and 80Hz.

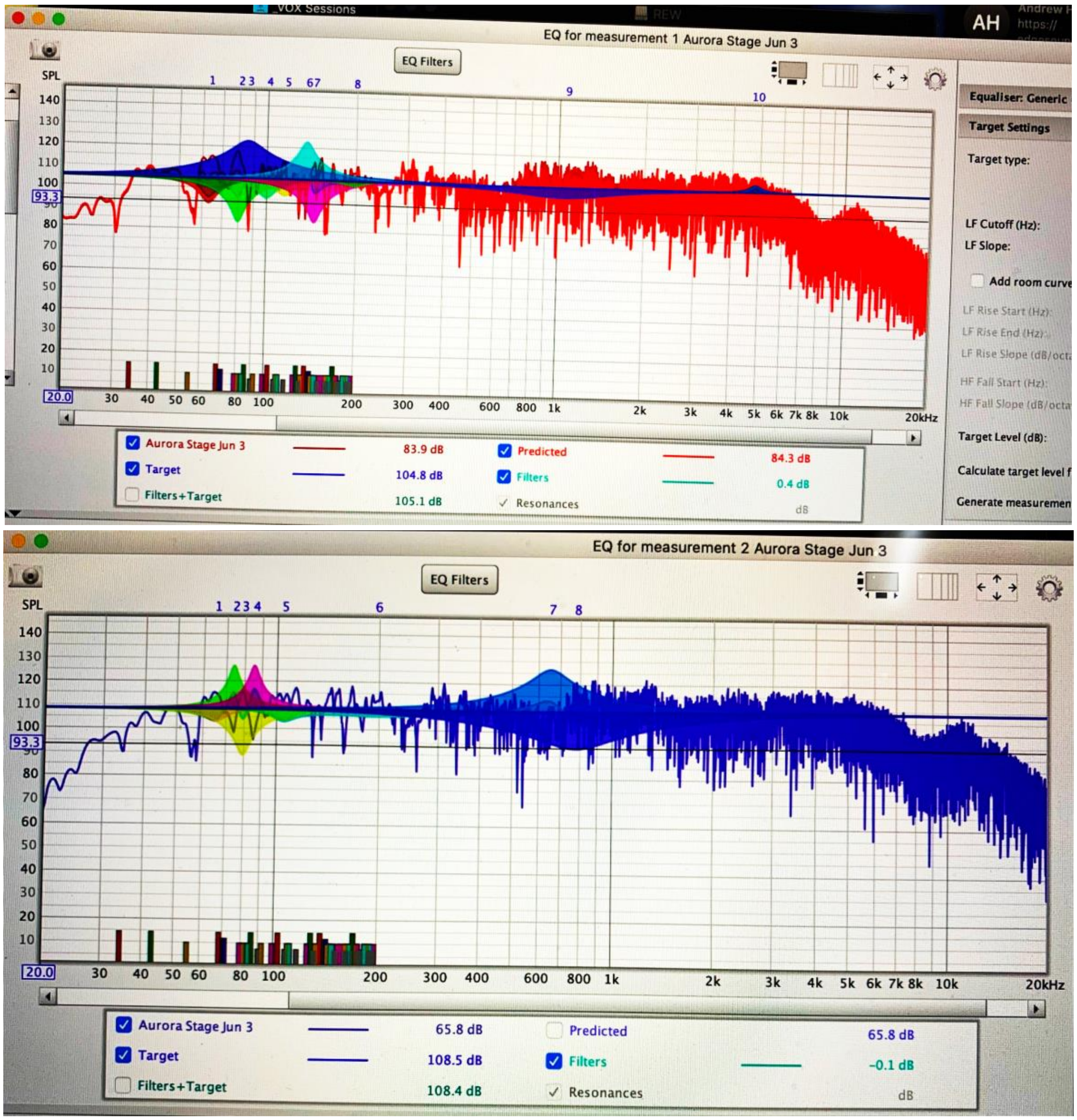

Figure 152: Frequency responses and filter suggestions from REW analysis of Aurora

I conducted two separate sweeps at different volume levels (see fig. 152). The upper image was recorded at an average level of 83.9dB, while the lower image was recorded at an average level of 65.8dB. There was hardly any noticeable difference in frequency response, except for a slight decrease in the bass acoustic response. This is consistent with the way sound is experienced in the body, as the bass transducers were detectable even at lower volumes, but with a drastic reduction in the amount of acoustic pressure since less air is being forced into the microphone.

Aurora Credits and Acknowledgements

The concept was created by myself and Professor Joan Sharma. My sister, Gabrielle Lee—a talented author in her own right—joined the conversation when I asked her to write a libretto that surmised the results from back and forth from Joan and myself.

I then wrote and produced the fixed acoustic portion, and recorded/created most sounds, except for vocal performances from Mackenzie Elliot ("Prelude"), Ashley Silva ("Furiosa"), and Jessica Bradley ("Finale").

Professor Sharma created and produced several clips of oil on water, fire, smoke, color interactions, and more. With help from Max Louis Creative, I created the virtual world of Aurora within Unreal Engine 4, and compiled on-screen text, the visual clips from Joan, and effected the source footage with creatively-timed edits within Final Cut Pro X.

AJ Freysteinson and Jen Moore from RabCup helped plan out the execution of projector mapping and coordinated with Epson to arrange sponsorship of projectors. Catherine Chooljian helped brainstorm the original designs of the enclosure, eventually handing off to Giovanni Quintero to draft so that Scott Yocum could build at Riverside Studios.

Eric Fox of Fox FX sponsored props and set design for the hallway scenes leading up to the installation. EDGE Studios created several visual clips for the waiting room, including two x 30min apocalyptic mixes of EARS/EDGE songs, as well as a series of skits that would continue the world building transition from reality to the fictional world of Aurora.

EDGE Sound Research, composed of Winson Bi, Julian Bell, Brandon Babu, and at the time, Carson Welty pushed the development of the tactile technology alongside company goals, just in time to feature at the premiere.

Constantine Pappas flew all the way from the East coast to Riverside, CA to help with whatever I needed, including hosting the entire opening weekend (and subsequent disc golf therapy). Valtteri Salomaki helped orchestrate the entire event, including lining up the press opportunity with Epson, and helping solve any and every issue that arose, while making the online scheduling system to coordinate the 150+ people that showed up for the two weeks that the installation was scheduled to be installed—all while relentlessly fundraising for development funds and fundraising for EDGE Sound Research.

And of course, my beautiful and talented wife Ixel for keeping me sane and fed throughout the entire process. I could not have done this without them.

Chapter three conclusion

With *Aurora*, I sought to share the fear and despair I felt learning about some of the severe projections about the climate crisis that I began to understand coming out of college at Fresno State, and my collaboration with Prof. Joan Sharma in “Draw The Line”. From that installation, I learned how surrounding the audience with multiple modes of simultaneous communication can greatly increase effectiveness.

When planning out *Aurora*, I aimed for the piece to be accessible in two fundamental ways - for all hearing capabilities, and to appeal to a wider audience, namely those who are likely not to be exposed to this kind of message. When I arrived to UC Riverside for my doctoral studies, I knew it was possible to incorporate physical sensation to *Aurora* from my personal relationship with sound due to my hearing loss, addressing the first aim. My background in audio engineering and producing popular commercial music for artists in Los Angeles gave me a sense of what a successful commercial piece should sound like, addressing the second aim.

The level of intensity and comprehensiveness required for the installation’s vibrotactile and vibroacoustic technology was not originally expected. As indicated by the activities detailed in chapter two, there are many factors to consider and remain mindful of, as I approached the design and build of *Aurora*. Through the turmoil, the entire team learned a tremendous amount in regards to vibration management, but also in terms of creative possibility. Since *Aurora*, the team has had the opportunity to work with various creative firms who are all impressed and inspired with what the student team accomplished at the installation. EDGE Sound Research has been invited to join other creative expressions and complex installations that are under non-disclosure agreement and are outside of the scope of this dissertation.

Composition review

The musical composition of Aurora greatly challenged me, starting off with the sparse minimalism of “Prelude”, where my practical goal was to compose a piece that had few rhythmic crutches that I typically rely upon. The result was an unexpectedly effective featured vocal melody that was first performed by soprano Kirsten Ashley Wiest at Dr. Dana Kaufman’s micro-opera course in Fall 2018. Emotionally, “Prelude” is the most exposed I have felt as a composer for quite some time. I usually rely on heavy drums and bass to create a solid foundation, as I am confident in how those instruments will sound thanks to their typical frequency response. However, since I had the critical moments of the movement to exist in higher frequencies, I had to rely on my peers' comments to determine the effectiveness of the performance upon translation.

“Furiosa” was more in my comfort range. However, I wanted to incorporate commercial drumbeats in this movement, to provide a hip-hop moment as something that would resonate with a commercial pop-music audience. Dr. Kaufman pushed back, challenging me to remove as much prediction from the beat-heavy section as much as possible. After several months of back-and-forth arguments during individual studies, we ended up with one of the most striking and effective moments of anything I have ever composed: the glitched and heavily processed percussion feature which never fails to capture a listener’s attention in every performance since. This teasing of percussion makes the full introduction of the drumbeats in the 2nd percussion feature section much more effective, and the contrast between the stuttered bass throughout the entirety of the piece makes the sustained sub-bass feature after the percussion feature even more effective.

"Finale" was the most difficult for me, since both compositional itches were satisfied: the challenging drum-absent movement of "Prelude", and the familiar entirely drum and percussive focused "Furiosa" movement. "Finale" had to simultaneously tie the two movements together, tie the entirety of the piece together, and deliver the entire work's final climax. Perhaps due to the magnitude of the task, the heavy involvement in the startup company, the development of the many other modes of the composition that were falling behind at the same time, or one of many other reasons, I felt that this final movement yielded the weakest impact, musically and visually.

Musically, the amount of thought required to compile this tall order of expectations in a single movement was too much for an already overworked composer who always had his attention elsewhere. Visually, I certainly ran out of time, and it is most noticeable during the final movement's climax.

Due to the miscommunication between myself, RabCup, and the engineer who helped me create the initial landscape for Unreal Engine, I found myself quickly thrown into hyper-intense skill building of Unreal Engine's cutscene tools to obtain some semblance of the animation that I had in my head for the visual aspects of the entire piece, resulting in a virtual oasis that was unfinished and unrefined, unoptimized captures of the cinematography, and a finale that leaves a bit to be desired. Thankfully, my background in music video editing ensured that the premiered version of the piece had enough visual effects and overlays from the beautiful content provided by Prof. Joan Sharma to smooth over any discrepancies or dropped frames.

The previous section of this chapter, evaluation of expected results, evaluates the aims detailed in the prospectus with a rubric of "Success, Partial Success, or Failure". While the section shares exemplary success and breakthroughs as well as areas of improvement for specific aims, it does not cover my sentiment of the overall outcome.

Desired Improvements

Overall, I am pleased with the outcome, especially given the time, budget, knowledge, logistic and skill restraints. Of course, I hope to revamp several parts of the piece to bring up to the standards I envisioned.

Musically, I am pleased with what I have composed. I am not the greatest composer for acoustic performance, and I will never claim to be. The composition features very simple but creative harmonic and melodic content, with heavily syncopated and rhythmic features that are emblematic of my compositional voice.

However, I would like to re-process my voice in "Prelude", and potentially have another female voice to sing in place of my own, but also to replace the demo vocals that Jessica Bradley quickly provided one evening for the final movement. There are certain elements that do not have the impact that I would prefer, such as the "th-is is just you" section of "Furiosa", and most of the "Finale" climax seems slow to me when I listen back. Perhaps I need to both speed up the whole section, and add some rhythmic element to interplay with the ostinato so that activity seems more intense.

Visually, I certainly plan to rebuild the Unreal Engine map with Unreal Engine 5 as the previous build was made in Unreal Engine 4 (on a low-end mobile CPU) which could explain the difficulty in capturing the programmed cutscenes. Unreal Engine 5 has certain new features that address my exact pain points regarding lighting, fog refraction, physics modeling, and realistic landscape sculpting and complex polygon rendering to help make trees and rocks appear more realistic.

Physically, ResonX technology has continued development since *Aurora* premiered in 2021, and the most recent iteration of the technology is much stronger and more capable of creating full-range high-fidelity tactile frequency response, and the units are much simpler to combine to create complex audio systems. The stage build can be improved greatly - instead of roofing wood, we could use thinner plywood or even a combination of flooring and thin plywood to create an even spread of vibrations across the entirety of the floor. The team has gained a significant understanding of how vibrations transfer since *Aurora*, so sealing gaps and creating a support structure vibration-isolated from the audience's vibrating surface will be much easier.

I would also like to add the atmospheric effects like fog, dry ice, and temperature controls. I have been since experimenting with thermoelectric modules that convert electrical signals into a temperature delta with the ambient temperature. Since these are solid state, they are silent, easily wired, electronically triggered and responsive - perfect for my theatrical use case.

Future works

I am planning an extended play (EP) release of Aurora after I graduate.[133] The release will only happen once the musical changes and a streaming-specific mix and master pass is made. The student musicians who helped me with this project are planning a to create a Remix album, where the artists will collaborate on remixes of individual movements. Once these are out, I will then begin to apply the visual changes mentioned throughout this chapter. I intend to be using the newest Unreal Engine, finish edits of the video, use the newest projection mapping software, and include the atmospheric effects.

I anticipate that the company will take a larger role in a future premiere, using the built environment as a testing platform for the latest vibrotactile technology, but also sharing the stage with other composers and musicians to test out multiple types of technology and fan engagement of their music.

Effect on development of embodied sound technology

The impact of *Aurora* on the development of embodied sound technology cannot be understated. The piece required a level of physical, performant, and adaptive device specification that did not yet exist, pushing the company to create several solutions that have since been used in other large pro-audio scale installations and infrastructure. Additionally, exposure to Unreal Engine has led to collaborations with creatives that have

133. Extended play (EP) has slightly changed meaning since the original extended play records from the days of vinyl. EP still means a release that is longer than a single, but shorter than a full-length album. In practice, this usually means around 3-4 singles or individual songs and between 15-30 minutes of total duration. Different major and independent record labels have their own requirements and restrictions.

resulted in new ventures exploring the relationship between sound and visuals. The ambition and innovation required to achieve a generationally-defining experience in *Aurora* will undoubtedly continue to inspire future installations and premieres.

Chapter 4: Conclusion and Next Steps

Overview

This dissertation explores the relationship between physical sound and my personal experience with it. While others have previously observed the physical properties of sound, my background in composition, audio engineering, live music performance, as well as my growing interest in electrical engineering and digital signal processing, has allowed me to create a unique roadmap for developing future embodied audio devices.

I do not claim to be an expert in any of the industries or fields mentioned within this document. Instead, I can only speak to my expertise in vibrotactile response and my imagination of what it could mean for others.

This dissertation describes the premiere of *Aurora*, an interactive, multimodal, embodied installation that showcased the potential of embodied sound technology as a method of interpreting sound. This composition became the driving force behind the founding of EDGE Sound Research, a student-startup that created the first devices based on embodied audio, called 'ResonX'.

To achieve a successful presentation of *Aurora*, I needed to expand my knowledge beyond that of music composition and audio engineering. This encompassed electrical and software engineering, business strategy, fundraising, grant writing for businesses, navigating bureaucratic structures, the patent process, video game engines, projection mapping software and techniques, computer-aided design (CAD) tools, maker tools such as 3D printing, laser cutting, drafting and building, printed circuit board (PCB) design and drilling, as well as design for manufacturing (DFM), among others.

In addition to the considerable learning curve, I had the opportunity to witness my research activities undergo a transition to 100% online due to the COVID-19 pandemic. During this time, most of my collaborators also shifted to virtual formats while we worked on the hardware portion of the technology. Launching a startup that relied on a hardware product people were supposed to touch and interact with during a pandemic that required social distancing and avoiding high-touch items was an extraordinary challenge.

However, I seized this opportunity to bolster my skills and explore every available avenue. As a result, I emerged from lockdown confident in my ability to hold my own among professionals in the field and eager to continue my journey at the helm of a research and development department of a promising startup company.

Chapter one presents evidence supporting the idea that sound can be impactful when it is felt as much as heard. It explores the mechanics of perceiving sound via the body through several senses and highlights past and ongoing studies that critically examine using compensation methods such as tactile feedback as a solution for intelligibility for those with hearing loss. While the studies are not exhaustive or completely supportive of my claim, their results, along with stories from people like deaf percussionist Evelyn Glennie, suggest that there is an opportunity for impactful improvement in this area.

Chapter one also reviews various sound transmission technologies. The case is made for using tactile transducers as the key prototyping technology due to their frequency bandwidth, cost, and compatibility with existing infrastructure. Additionally, the chapter introduces the first mention of the proposed 'ideal' sound system that suggests pairing modern loudspeaker technology such as balanced mode radiator (BMR) technology with a wide bandwidth vibrotactile system. Chapter one proposes composing *Aurora* as a way to demonstrate the effectiveness of a wide bandwidth tactile frequency response, which would require a series of experiments to validate the feasibility of the large format installation.

Chapter two covers five experiments that assess the feasibility and limitations of developing the wide bandwidth vibration-based sound technology necessary for performing *Aurora*. The experiments covered the activities of a team consisting of various graduate and undergraduate students and eventually the EDGE Sound Research R&D members who helped me with each experiment.

The team first created a tactile stage bass floor-panel unit and combined it with a distributed mode loudspeaker (DML) high frequency stereo system to evaluate acoustic parity with traditional loudspeakers. They found that higher frequency vibrations could be interpreted as a feeling and created a chair prototype to further immerse a user in the sensation. The team applied for a university grant program and formed a startup company to apply for several other opportunities aimed at student startups. The technology was modularized so it could be attached to other types and form factors of chairs. The researchers used gaming chairs as a target substrate since the new startup company performed user interviews to identify gamers as a likely early adoption candidate of the technology. The team was able to successfully build five working prototypes that were eventually used for the *Aurora* Installation.

Chapter three covers the design, composition, installation build and execution of the *Aurora* installation. With *Aurora*, I aimed to share my fear and despair about the climate crisis and to make the message accessible to a wider audience. I incorporated physical sensation to *Aurora* to address hearing capabilities and used my background in audio engineering to create a successful commercial piece.

In the self-review, I critically examine how well I achieved certain aims of the project stated in the prospectus document. Overall, I was pleased with the outcome of the project, but hope to revamp certain parts to meet my envisioned standards. I share plans to release an EP of Aurora after graduation, and the student musicians who helped with the project are planning a remix album. The impact of *Aurora* on embodied sound technology is significant and will continue to inspire future installations and premieres.

Discussion

Ultimately, it is not a novel idea that individuals can feel sound or music. However, I propose that through proper presentation, the intelligibility and fidelity of felt sound can be increased. This can lead to a better understanding of nuances in sounds and subtle relationships between instruments in music. Researchers like Maria Karam have written that the complex harmonic content of mixed music is not possible to isolate:

> "…unlike feeling voices when we speak, feeling music that is comprised of multiple instruments and voices as individual sets of vibrations is not possible. This is because the audio signal originating from the voice, drums, bass, guitars, and piano are combined into an extremely complex wave-form intended for perception through the hearing organ. While our ears can discriminate the individual sounds from the combined signal, our skin cannot."[134]

I agree with the difficulty in perceiving a complex harmonic signal through the skin. However, in the same document she acknowledges the main reason why this may not be possible:

> "if we try to feel the sounds with our hands, we can only access the vibrations resulting from the combined stronger, low frequency signals, which mask the weaker, higher tones."[135]

Her team's approach is to separate bands of frequencies to multiple drivers. While I understand their reasoning, I think they should have attempted to create support for higher frequencies to provide a test platform for intelligibility first to see where more fidelity could be achieved.

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134. Karam et al., "Short The emoti-chair: an interactive tactile music exhibit." 3071.

135. Karam et al., "Short The emoti-chair: an interactive tactile music exhibit." 3071.

I understand that discourse around my claims will continue, as my methods were not specifically intended to provide a definitive, quantified baseline of various performant and perceptual parameters. I indicated that such parameters are imperative to determining effectiveness, and I maintain that a weakness of this dissertation is in the lack of comprehensive investigation into all of the parameters.

A common fallacious approach for vibrotactile or vibroacoustic experiments is to transmit the signal purely through a single sense and conclude that the additional mode is an ineffective factor in increasing intelligibility. However, just like the discussion on the importance of preserving signal integrity along the transmission pathway, the perception of intelligibility is influenced by many factors as well.

In her study on highly musical Cochlear Implant (CI) users, Kate Gfeller mentions several compensatory methods used to exploit the body's natural alternatives, including bimodal hearing.[136]

During a visit to Dr. Goldsworthy's office, he shared that the ResonX technology helped him with beat perception. Dr. Goldsworthy, a former drummer who now uses a CI, introduced me to a former pianist who now uses a CI and is a member of his study. She mentioned that she occasionally turns off her CI when playing the piano to feel the notes more accurately, which is consistent with Gfeller's observations.

To evaluate the intelligibility of a known song, I provided the former pianist with a ResonX device to hear the piano music. She first listened with her implant, then turned it

136. Gfeller et al., "Practices and Attitudes that Enhance Music," 8.

off. She was impressed with the level of detail she could hear with the prototype unit, but acknowledged that the CI could provide additional information in the higher registers.

In our in-house subjective tests, our team of engineers - who are also music producers and audio engineers - reported that they could better interpret individual instruments with the use of ResonX in addition to the studio monitors in the same room. I have taken the development of this technology as an opportunity to train myself to recognize vibrations from acoustic sources. Although not certain, I believe that I can now perceive more from acoustic sources because I can more easily recognize patterns of interference present in the harmonic interplay between instruments mixed together into a single audio file.

One issue that arose from a recent keynote presentation of the research to a group of deaf and hard of hearing individuals was the difference of meaning of this technology between deaf and Deaf culture. Deaf culture, differentiated by using a capital D, centers around an identity of non-participation with hearing norms. Most of the population who identifies as Deaf are pre-lingually deaf, which has resulted in a rich culture without the need to interface with the acoustic world.[137]

That is why it is more accurate to use the term "hard of hearing" instead of "deaf" to describe the subset of the hearing population that the technology and composition could potentially help. Although this dissertation addresses the greater "deaf and hard of hearing"

137. "Community and Culture – Frequently Asked Questions," National Association of the Deaf, accessed March 26, 2023, https://www.nad.org/resources/american-sign-language/community-and-culture-frequently-asked-questions/.

population, some Deaf individuals may not be willing to consider this solution as relevant to their situation and may be offended to see this technology labeled as accessible in a large venue.

While my observations and interactions may not be completely scientifically defensible, they have led me to believe that there is a compelling argument for the combination of multiple senses, which is what made *Aurora* such a significant accomplishment in the field of audio reproduction and composition. Although we did not achieve complete parity with a comparable loudspeaker system in terms of frequency response, we reached a level of reproduction that met my stringent requirements for presenting this multimodal composition and achieved it with about 1/10th of the power usage.

Aurora was composed and designed to take advantage of as many senses as possible to immerse the audience in the composition. Every moment was designed to be simultaneously heard, felt, seen, and read. This could be perceived as overstimulation, as one child left the stage crying during one of the experience's darker and intense moments during "Furiosa". Perhaps the commentary here is an acknowledgement of a world full of stimulus, that keeping every sense fully engaged is necessary to capture attention for even fifteen minutes.

For example, a simple 16x9 screen is not enough, I needed a wraparound screen around the audience. A sound system is not enough, the stage the audience sits on and the screen the audience views should both be the source of the sound that also delivers vibrations through their body. The content can't be just lyrics matched to music, every word must immerse the audience by being painted with melody, harmony, sound design, color, and a visual representation projected around the audience. Perhaps I thought "only then will they hear every word of this piece".

The fight for audience's attention may be the reason for groups like COSM, a technology and content conglomerate whose deep integration allows the realization of a hyper-immersive remote venue, with a list of first-of-their-kind technologies designed for immersing their audience.[138] Their huge flexible wraparound mini-LED screen allows the COSM Studio team to produce content that literally wraps around their audience.

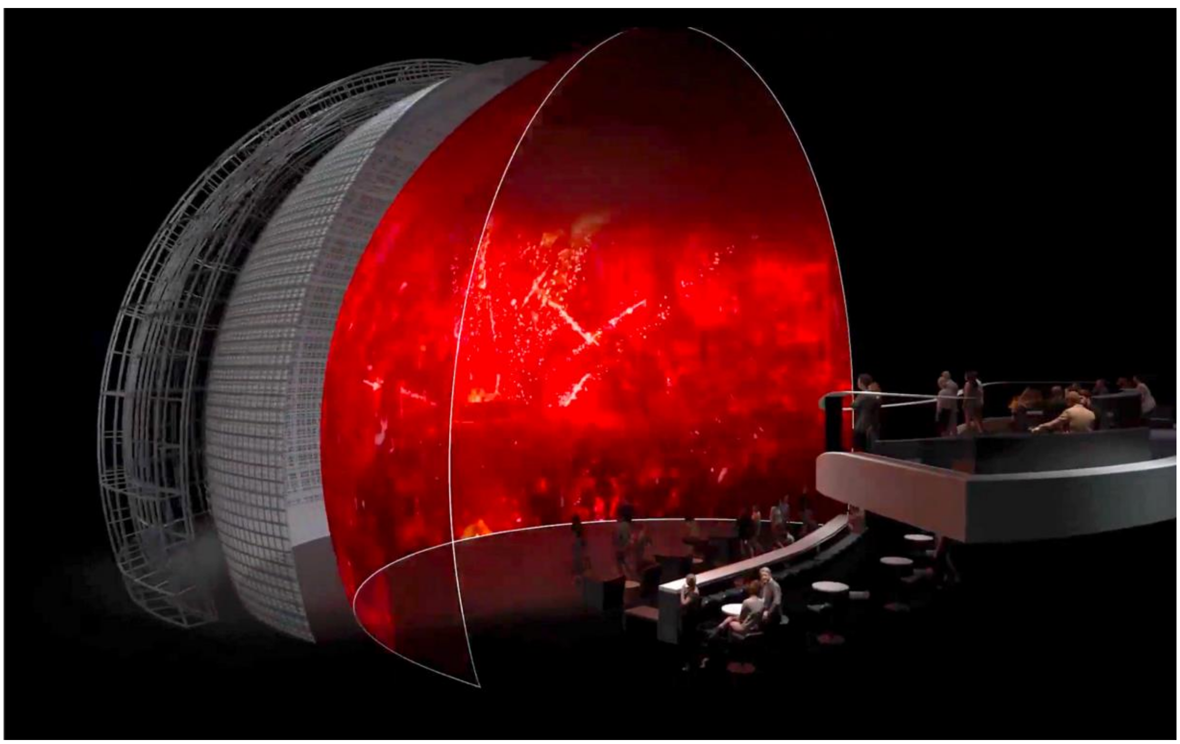

Figure 153: COSM Los Angeles planned 2023 immersive venue space

138. "COSM," COSM, 2023, accessed March 26, 2023, https://www.cosm.com.

Another large scale venue planned for the ultimate immersive experience is the Madison Square Garden (MSG) Sphere, a sphere-shaped immersive music and entertainment venue with a capacity of 17,500. The Sphere would feature the worlds largest LED screen (as of April 2023) wrapping around the entire curved surface of the venue. This venue features beamforming acoustics, an audio format that uses phased arrays to ‘steer’ the acoustic signal towards a certain area, and greatly attenuating the signal outside of the steered area.

Figure 154: MSG Sphere in Las Vegas promotional photo – MSG

Although *Aurora* does not offer the same level of immersion as these large-scale venues, it is a viable and cost-effective option for preparing future immersive works. This is especially relevant given that the MSG Sphere costs over $2 billion to create.[139]

139. "New Content Unwrapped for MSG Sphere in Las Vegas," Behind the Screen, The Hollywood Reporter, updated April 11, 2023, 2023, accessed March 26, 2023,

The *Aurora* installation ultimately proved to be successful, with the ability to sustain a high volume of traffic and constant performances. Although there were a few minor hiccups, the transition to and from the standby state was smooth and seamless for almost every performance.

Further Investigation

This section describes limits of this dissertation and possible avenues of future research to further the ideas presented within these pages. Some restrictions are due to scope, resource availability, and researcher qualifications. For example, mapping perception of vibration intensity versus frequency for sense of touch. It is possible to re-create the format of Bell Labs' widespread survey of hearing intensity versus frequency is necessary to accurately generate an average perceptual threshold level of the sense of touch for various frequencies. This could be used to evaluate effectiveness of any vibration-based system that delivers frequencies beyond the narrow frequency range stated in literature.

Additionally, this section touches on limitations and improvements to the *Aurora* installation as previously mentioned in the chapter three conclusion section and earlier in the discussion of this conclusion chapter.

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https://www.hollywoodreporter.com/business/business-news/msg-sphere-las-vegas-experience-postcard-earth-1235370782/.

Embodied Sound Technology

Mechanical

To control unintended vibrations while allowing constructive ones to pass through a separate substrate, the transducers must be suspended in a semi-solid material that provides a solid connection with the enclosing substrate. This allows vibration to transfer through the substrate without the hard exterior of the transducers coming into contact with it. The substrate, in turn, must also have a solid connection with the transducer array to be excited, effectively turning the enclosure into a giant full-frequency exciter. In the case of a gaming chair, the material of the chair cannot interact with the device. Additionally, for our purposes, the device must be easily removable, which negates many reliable permanent methods of attaching substrates that would otherwise be satisfactory.

Electrical

Generating the amplified signal that transducers need in order to create the desired experience requires a large amount of electrical energy to push vibrations through the enclosure and, in turn, the target substrate. Although current Class-D amplification technology found in most affordable modern audio solutions boast an efficiency of 90% or greater, they still generate quite a bit of heat when pushed at higher levels.[140] To improve efficiency and reduce inefficient heat waste within the same size or smaller system

140. "Class D Audio Amplifiers: What, Why, and How," Analog Dialogue, Analog Devices, updated June 2006, 2006, accessed March 26, 2023, https://www.analog.com/en/analog-dialogue/articles/class-d-audio-amplifiers.html.

capacity, Gallium Nitride (GaN) power and switching components could be used to increase power density.[141] This is necessary for embodied systems that are likely to be in condensed areas near a person and need to operate within a safe temperature range.

Having all necessary components on a single PCB is an obvious future research plan. Our team encountered numerous challenges due to inter-board connections with poorly made cables as well as issues including poor PCB design in some modules, lack of heatsinks, inadequate testing, among others. We discovered issues with radio frequency (RF) interference affecting our Bluetooth module on the Raspberry Pi, which made wireless connections unreliable. Additionally, we found that using the Raspberry Pi as a multi-purpose computing device instead of a dedicated digital signal processing (DSP) resulted in higher latency when processing audio on the fly.

Software

The code that we ran on the Raspberry Pi performed exactly as we intended. However, the latency prevented us from using it in mission-critical situations, such as in *Aurora*. As a result, we had to create a direct connection into the exciter's amplifier. Early alpha testers noted a significant delay between the visual and acoustic events from ResonX. Improvements are needed in DSP to fully realize the potential of embodied sound. Germani et al. have opened the door for texture simulation via embodied sound, while Hayes has

141. A. S. Augustine Fletcher and D. Nirmal, "A survey of Gallium Nitride HEMT for RF and high power applications," *Superlattices and Microstructures* 109 (2017/09/01/ 2017), https://doi.org/10.1016/j.spmi.2017.05.042.

paved the way for new "embodied relationships with new musical instruments" in her 2013 dissertation and subsequent research.[142,143,144]

The most significant DSP improvement to be made is the calibration method detailed in Chapter 2. The ideal vibrotactile/vibroacoustic device should reproduce a flat frequency response in detectable acoustic and physical realms simultaneously. However, reproducing the latter presents a unique challenge since there is currently no mapping of the perceptual tactile response of sound through the body (similar to the Fletcher-Munson curve for acoustic perception). This mapping is essential to accurately reproduce the embodied signal.

Psychology + Physiology of Sound

Although this dissertation shared many studies exploring vibrotactile stimulation at lower frequencies, much remains to be discovered about embodied signals at higher frequencies. Specifically, there is a need to understand how the user's mind interprets signals related to force over time, instantaneous peak, and other areas that can be

142. Germani et al. Michele Germani, Maura Mengoni, and Margherita Peruzzini, "Electro-tactile device for material texture simulation," *The International Journal of Advanced Manufacturing Technology* 68, no. 9 (2013/10/01 2013), https://doi.org/10.1007/s00170-013-4832-1.

143. Lauren Sarah Hayes, Michael Edwards, and Martin Parker, "Audio-haptic relationships as compositional and Performance Strategies" (Doctor of Philosophy Dissertation, The University of Edinburgh, 2013), 1.

144. Hayes, Edwards, and Parker, "Audio-haptic relationships as compositional and Performance Strategies," 2.

determined once perceptual thresholds are established for frequencies beyond the lower range.[145]

Scale Manufacturing

Scaling the production of components such as Gallium Nitride (GaN) components, PCBs/integrated circuits (ICs), and high-powered transducers to become cost-effective is a challenge due to the current limited demand for these items. However, as companies like EDGE Sound Research develop more reliable use cases for these components, it is expected that prices will decrease, creating more affordable options.

Transducer Efficiency

Efficiency can be improved by radically redesigning transducer mechanics. As previously stated, most common tactile transducers rely on motors that are variations of the voice coil, which was originally designed to translate signals to cones that push air towards a user. However, since embodied audio involves pushing vibrations through a solid substrate, it is reasonable to assume that a radical redesign of the motor structure could significantly increase efficiency in translating signals into detectable vibrations. This could result in a device like the Clark Synthesis all-frequency single transducer or a

145. Qiang Liu et al., "Study on perception threshold for whole-body vibration," *Vibroengineering PROCEDIA* 14 (2017/10/21 2017), https://doi.org/10.21595/vp.2017.19165.

series of smaller drivers in an array, similar to the UltraHaptics system, but for direct physical embodiment.[146]

Aurora

As stated in the conclusion of chapter three, I foresee significant improvements to the design, composition, sound design, visuals, and build quality of both the stage and the control electronics.

Generally, I was satisfied with the outcome of *Aurora*, but I recognize that there were areas that need improvement. I am pleased with the musical composition; however, I plan to reprocess my own voice in the "Prelude" and possibly add another female voice to replace the demo vocals.

To enhance the project's visual component, I plan to rebuild the Unreal Engine map with UE5 and take advantage of its new features to improve lighting, fog refraction, physics modeling, and realistic landscape sculpting. Future attempts will hopefully add atmospheric effects, such as fog and temperature controls, using thermoelectric modules.

Regarding the project's physical component, I aim to improve the ResonX technology for better tactile frequency response, making it stronger and capable of creating high-fidelity immersive audio systems. I also plan to enhance the stage build by selecting thinner plywood or a combination of flooring and wooden structure to create an even distribution of vibrations across the floor.

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146. Tom Carter et al., "UltraHaptics: multi-point mid-air haptic feedback for touch surfaces" (Proceedings of the 26th annual ACM symposium on User interface software and technology, St. Andrews, Scotland, United Kingdom, Association for Computing Machinery, 2013).

These improvements will ensure a more reliable delivery of the same feeling that our first audience experienced from *Aurora* in the garage of Riverside Studios during the hot summer of 2021.

As a composer, I have made previous audiovisual compositions. I find that editing music videos to the song's transient events is emblematic of my composition palette. Bringing these elements into a space is a complex task that requires careful consideration of factors such as people flow, lighting, and guiding the audience's eye as they explore the space. By broadening my compositional vocabulary to include these elements, I can integrate a variety of modalities when presenting pieces in other mediums. For example, I could bring a ResonX system to a concert hall or a movie theater, offer images to be displayed during a concert, or design systems that maximize engagement and immersion of an idea within a confined space.

As our research into the possibilities of spaces such as Aurora, COSM, or MSG Sphere continues, I am confident that more composers will create immersive experiences. In the modern sense, the term "composer" will refer to individuals who combine sensory elements to create a meaningful impression.

Further details about specific improvements were provided in the self-review and conclusion of chapter three.

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