PD10 Omnidirectional Dodecahedron Loudspeaker

ECE 499

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University
of Victoria

Group Information

Group ID: 22

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Co-supervisor (if any): TA Xiangyu Ren

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Acknowledgment

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Contents

Executive Summary

As social engagement and freedom of expression become increasingly sought after in the modern world, it is important to acknowledge the role of music. This project is geared toward enabling artistic expression so that people may enjoy music in new ways. More specifically, we have created a dodecahedron loudspeaker system capable of three-dimensional spatial effects. Effectively we wanted to create a sound source capable of moving audio in any chosen direction for a unique and pleasurable listening experience. On top of that, we have set up the speaker system to be capable of reproducing spherical recordings of various instruments so that listeners are able to discern the timbral shifts that occur as they wander around an instrumentalist.

We went about this by constructing a 12-sided speaker housing, with a speaker on each face. Through software we were able to control where a soundsource appears to be emanating from, utilizing multi-directional panning and volume control. The end product is a system of 12 individually-controlled drivers reproducing audio in all directions. This allows listeners to choose where they would most enjoy to hear a performance from, given that some spots will have more or less of various parts of the frequency range. This system could be employed at social gatherings in clubs, at festivals, and in stadiums, with the speaker array hanging atop the crowd, projecting sound in all directions.

I Introduction

Typical listening experiences for audiences in the modern era are either monophonic or stereophonic depending on the venue in which they are listening. There are very few exceptions to this (most notably movie theatres and a select few electronic concerts with live surround sound mixing). However, even these 4- or 5-channel listening experiences are different from hearing a single point source array that can send audio in any direction the artist desires. In fact the closest thing to a sound source with omnidirectional firing capabilities such as this would be rotary speakers (such as those produced by Leslie to be used in conjunction with Hammond organs [1], and the Fender Vibratone which was intended for use with guitars [2]).

The first purpose of this project was to design and construct an omnidirectional dodecahedron loudspeaker capable of offering fully three-dimensional spatial sensation to its listeners, capable of dispersing audio in any direction, changing direction with time and/or external control. The second was to reproduce acoustic instruments that have been recorded using spherical microphone configurations. A dodecahedron was chosen as it is functionally the closest feasible object to build that resembles a sphere (which would be a perfectly omnidirectional point source if such a thing were somehow able to be covered in infinitesimally small speakers in order to send audio in any possible direction).

Construction was accomplished using a dodecahedron shell made out of MDF, with backing boxes and faceplates for 12 speakers. The speakers are powered by 12 separate amplification channels fed by a USB audio interface whose outputs are controlled by Reaper, a highly customizable DAW.

This most applicable EGBC code to the project is Principle 3, which states, “Registrants must have regard for the common law and any applicable enactments, federal enactments or enactments of another province [3].” Typically in a performance venue (eg. clubs, pubs, churches, outdoor festivals) certain decibel levels are mandated via noise bylaws. Our project addresses this issue with appropriately amplified speakers whose mean sound pressure level (SPL) is 86dB at a distance of one metre, whereas typical Canadian noise bylaws (including Victoria’s) dictate an SPL of 90dB at the front of house audio mixing position. Since a doubling of distance leads to a quarter of the power, assuming any sort of reasonable distance between the speaker system and would-be complainants, there is little to no risk that these bylaws will be exceeded. In this way, we are also directly implementing Principle 13, which states, “Registrants must conduct themselves with fairness, courtesy, and good faith towards clients, colleagues, and others [3].”

Generally speaking, the user base for this product will be musicians, either monophonic instrumentalists seeking unique ways to reinvent their sounds (this would be particularly relevant to psychedelic bands and envelope-pushing bands who are prone to heavy use of effects seeking to create unique sonic tapestries, similar to the ways that acts like The Grateful Dead, Pink Floyd, The Mars Volta, and Tool have done in previous decades).

II Objectives

- To study the workings of an omnidirectional dodecahedron loudspeaker configuration as both a 3 dimensional sound source and effects unit
- To construct a dodecahedron with 12 individually controlled drivers (one in the centre of each face)
- To use a digital audio workstation (DAW) to create spatial effects for the dodecahedron speaker configuration
- To create 3 dimensional listening experiences for listeners based on their location relative to the dodecahedron
- To allow the study of individual instruments recorded using spherical microphone configurations

III Design Specifications

A digital audio workstation would need to be the brains of the operation, so choosing an appropriately programmable software was the aim.

The speakers would need to be individually amplified, so there would need to be a USB audio interface with a minimum of 12 output channels to go into the amplifiers. The corresponding 12 amplifiers would need to be power-matched to the speakers.

The speaker housing itself was already in existence, with the enclosures set up to take 4-inch speakers. As such it would need to have twelve 4-inch speakers. In keeping with the aforementioned Principle 3 of the EGBC code, with appropriate respect for noise bylaws, the speakers would need to have a mean SPL of not more than 90dB.

Most public address systems have subwoofers to take care of the lowest frequencies, and given that we were to use small speakers, it was specify that speakers below 100Hz (a typical crossover point between subwoofers and low-mid drivers on public address systems) would be taken care of by a separate subwoofer for most applications. As such, we were seeking speakers with a frequency range of 100Hz to 20kHz in order to match the human hearing range.

Additionally, we were concerned with the overlapping of frequencies between one driver and the next. Since the angle between any two adjacent speakers in a dodecahedron is 72 degrees, we would need to find speakers that had a pattern of no less than 72 degrees and as little as possible above that metric.

IV Literature Survey

In preparation for this project, several literature sources were reviewed to understand the variety of existing approaches to spatial audio auralizations. A report concerning the “directional patterns and recordings of instruments in auralizations[4]” was studied to learn about prior implementations of sound source modelling in a three-dimensional spatial audio scenario. This report discusses the difficulties of omnidirectional sound sources which can conflict based on frequency and varying directional factors in time. A solution is proposed to produce a better model for spatial audio by simulating multiple virtual sound sources in a room setting. Each virtual sound source is set to radiate a directional output corresponding to the orientation relative to the original source. This means to divide the 360 degree playback by the number of speaker drivers to create an even dispersion of directional audio which results in a listening position output that creates a more accurate reproduction of the multi-track anechoic recordings. For example, this technique was used in modelling our dodecahedron using the angle of each speaker relative to a 0 degree centre point, resulting in approximately 72 degrees of rotation between each speaker. The virtual sound sources exhibited in this report resulted in our decision to choose the ReaSurroundPan plugin within Reaper to model our own 3D space using virtual sound sources, such as was suggested in this literature which was reviewed.

We took a different approach for the playback of a classical quartet (two violins, a viola, and a cello) which was recorded with the musicians in the centre of a spherical 12-microphone configuration with microphones placed equidistant from the instrument [5]. In practice, there have been developments on measuring the directional sound emanating from an acoustic instrument (such as a 32-microphone spherical array [6]) which have given the somewhat predictable result that while we may conceptualize a sound source as omnidirectional and radiating in all directions, in practice there are acoustic interactions within the instrument itself as well as the room it is recorded in that will have magnitude and phase interactions that differ from one frequency to the next. These interactions contribute toward the listener's perspective on the timbre of the instrument itself [7].

Even considering that the recordings were done in an anechoic chamber, we note that there is still interaction between the instrument and the player which would in all likelihood result in an attenuation of higher frequencies as they would be absorbed by the musician's body. Playing back the individual instruments from the quartet allows for a listening experience wherein this effect can be examined across most of the audible range that we humans can hear at. Interestingly enough, most of the literature we were able to find focuses on the measurement of instruments using some form of array rather than reproducing such a source in order for a wider range of listeners to be able to discern the intricacies using their ears. We feel that this is a more interesting goal as even though the people who are more likely to care about such acoustical properties are musicians and audio professionals, being able to quickly and easily educate listeners on various intricacies is likely to have a large impact on how they listen to music as well.

V Team Duties & Project Planning

Our project was hampered initially by an attempt to begin working on a project which we ultimately determined was not a good use of time and resources (as existing products are already in the marketplace) after doing a survey of such products. Initially, Brett Faulkner was in charge of researching DMX coding, Morgan Cave was in charge of researching lighting control driver coding, and Samuel Akpan was in charge of researching MIDI coding. While researching DMX coding, it was discovered the other products were discovered and determined to already be adequate toward the project goal.

After the next project was chosen, Brett was in charge of sourcing the workspace, loudspeakers and leading the assembly. Additionally, he used his CNC router to manufacture some parts for assembly. After it was assembled he arranged for training and oversight in the use of testing equipment and Smaart V8 software [8] with John Blythe of Pacific Audio Works. He was responsible for compiling the data from the session and determining what corrective processing (mainly equalization and volume adjustment) will need to occur in order for smooth transitions to occur between speakers as the signal moves. He configured the audio interface to map the Reaper channels to the appropriate amplifiers. Additionally he mapped the audio channels of the spherical recordings.

Morgan Cave was in charge of researching audio control methods in Reaper to provide a playback Reaper file for the speaker array demonstration. Morgan compared the possible tools available within Reaper such as ReaScript coding [9] and surround sound plugins to decide upon ReaSurround [10] as our preferred method of implementing 5.1 surround sound (this was selected as a typical path that travels around the speaker system before returning to its origin is comprised of 5 faces, and correspondingly 5 speakers). Morgan also assisted the assembly process by documenting speaker testing and working to maintain quality standards for wiring and construction. Finally he oversaw the addition of documentation to the project website constructed from a previous HTML website designed by Morgan and modified by the group.

Samuel Akpan was in charge of liasing with Dr Driessen and his lab technician Levente Buzás to procure and transport the dodecahedron frame and shells as well as 12 output amplifiers. He played a substantial part in completing the construction of the dodecahedron, soldering speakers to cables and completing other electrical requirements for the project. He was also responsible for the CAD model of the speaker configuration.

To achieve these deliverables, we have set up meeting times weekly to touch base and account for progress during the course of this project. Due to time sensitivity and deliverables, the foreseeable bottleneck will be acquiring 12 identical speakers in a costly manner and access to a shop with after hours availability for construction and testing. Filtering via equalization for audio interference will be a big hurdle to overcome as well.

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VI Design Methodology & Analysis

The first task was to source appropriate speakers so that they could be shipped and received in a timely manner. We found Visaton 4899 speakers that had a frequency range of 95Hz to 22kHz that are 30W at 8 ohms.

In the interim, we secured a workshop at Pacific Audio Works and negotiated the use of some amplifiers that they had on hand, each capable of producing well over 30W at 8 ohms so that they could be matched to the speakers when running in an attenuated state.

We also selected Reaper as an appropriate digital audio workstation to control the setup given that it has advanced scripting and customizable programming capabilities.

The Behringer X32 Rack USB audio interface was loaned to us by a former colleague who was interested in the project and wanted to help out.

VII Design & Prototype

We began the construction of our prototype by sanding and painting the speaker unit cones to prepare them for installation into the dodecahedron shell. The exterior of all parts was painted black for aesthetic choice. Figure 1 below shows a speaker cone housing unit before being painted. Once dried, wiring holes were widened to accommodate our speaker units and the speakers were then tested before being added to the cone housing unit held by the shell frame.

In order to confirm which terminals of each speaker were negative and positive we conducted a polarity check. This test involved placing a 9V battery in contact with the terminals and observing if the speaker moves forward or backward in its housing. We ensured that polarity was consistent for each speaker. The leads of each speaker were soldered (white to positive and black to negative) using 16 gauge speaker wires as seen in Figure 2.

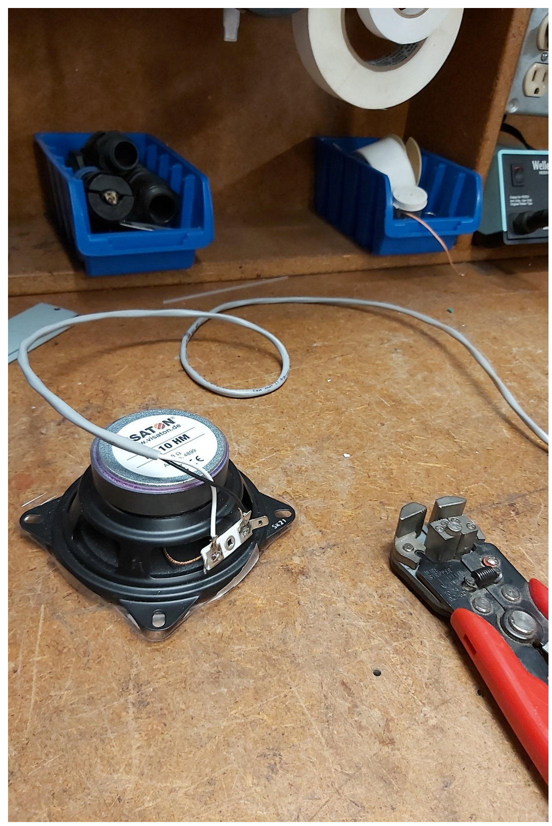


Figure 1 & 2 : A speaker unit before being painted and assembled (left), and Soldered speaker wires (right)

After soldering the speaker with 1 meter long wires, we had to test each speaker and make sure they were working with similar audio output given the same input. This preliminary test was achieved by connecting them to a 2-channel amplifier, playing a song and listening.

We encountered a few challenges on our final design prototype: the first was the assembly of the dodecahedron. The initial design, which we CAD-modelled as seen in Figure 3, was a solid shape which theoretically should have held together with minimal additional fastening required.

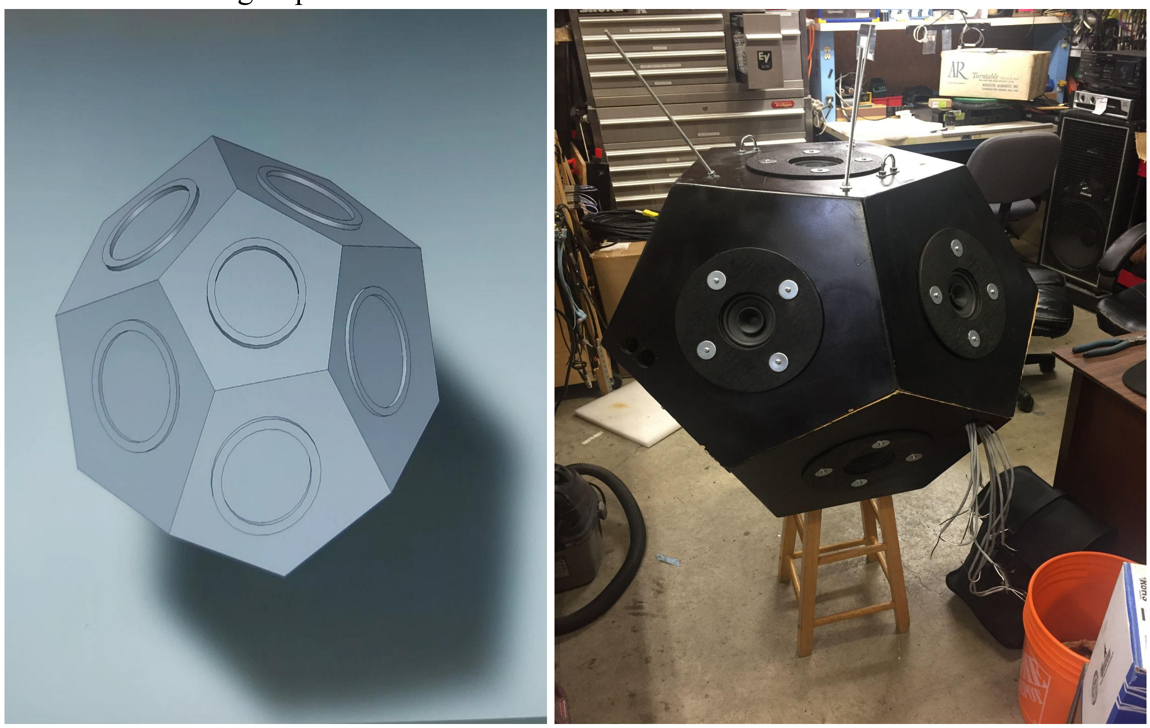


Figure 3 & 4 : CAD Generated dodecahedron (left), and Actualized prototype (right)

The physical enclosure was a previous construction that we recovered from storage at the University of Victoria, consisting of two large pieces that would make up the outer shell, 12 speaker enclosures that would reside in the shell, and 12 faceplates. The first challenge was that the enclosure itself was splitting on one of its seams and as a result the two halves did not fit together all that well. In order to bolster this and cause it to be solid enough to hang in the air, we added three threaded rods going through the enclosures at angles so as to dodge the speaker enclosures after they were mounted in the shell.

Figure 5 & 6 : Dodecahedron prototype hanging test (left), and measuring 1m distance between speakers and microphone for Smaart equalizer testing (right)

Secondly, it was clear that in its previous iteration, the enclosures had been adhered to the shell using tape and the faceplates would have either not been used or would have been stuck on using a non-permanent adhesive. We determined that the best method for attaching the enclosures to the shell would be to place the enclosures inside the shell from the back and then attach the faceplates onto the front.

This necessitated modifying the faceplates in order to put screws through them, which was accomplished using a CNC router in order to make them as uniform as possible. To get the speakers to sit flush with the faceplates in this configuration, we needed to screw them to the enclosures using spacers. Rather than using traditional spacers, we manufactured them out of pneumatic tube that we cut to length, which would have two benefits: it would somewhat dampen vibrations so that adjacent speakers would affect each other to a lesser degree, and it was also a more readily-available solution than ordering spacers as there were none matching the thickness we needed at the hardware store.

In order to get signal to the speakers, we set up a Reaper file with 12 output channels, using a Behringer X32 Rack as an audio interface, sending its outputs to 12 amplifier channels and onto each individual speaker, thus giving us individual control over the output to each speaker. Inside the DAW we used an equalization plugin on each output channel to flatten the frequency response (see the Testing & Validation section for further detail on equalization methodology).

For the objective of listening to a 3-dimensional sound source with multiple instruments occurring in the space, we first needed a 12 channel recording wherein microphones had been set up in a spherical/dodecahedron configuration. Following that, it would be a question of mapping each of the microphone positions to a corresponding speaker location, functionally preserving the configuration in reverse. In other words, wherever the recording engineer had placed a microphone facing inward toward the musicians, we would be placing a speaker facing outwards toward the audience whose output was an amplified version of the microphone's input.

VIII Testing & Validation

In order to ensure accurate reproduction of audio in all directions, we set up measurement microphones in various locations and captured impulse responses with varying amounts of speakers turned on in order to determine what sort of frequency interaction would be occurring when more than one speaker was reproducing sound that the listener would be hearing. This was accomplished using Smaart[5] software by sending pink noise from the computer via the audio interface to amplifiers and then finally to the speakers. Measurement microphones were connected to the audio interface to capture the impulses back into the software.

Figure 7 : Measuring the Smaart testing 1m distance

Once the microphones were set up, we first took an on-axis response of a single speaker:

Figure 8: Phase and magnitude responses of a single speaker across the human hearing spectrum.

Then we captured the response at the midpoint between two speakers with them both on to determine the interaction that would happen if a sound source were to pan from one to the next or a listener were to step from being mainly in front of one to part way in between speakers:

Figure 9: The green trace is the original on-axis single speaker response while the pink trace is the response of two speakers interacting at their midway point.

The phase response was in good agreement up until approximately 7kHz, while the magnitude response showed significant additive behaviour until approximately 3.5kHz after which point there is a loss in volume when compared to a single on-axis speaker. In order to have a more complete picture of what might happen, we considered that due to the geometric placement of the speakers, a listener will be directly receiving sound from three speakers most of the time (if audio is coming out of all speakers). This led to choosing a point one metre away from three speakers, taking an impulse response with first one, then two, and finally three speakers turned on:

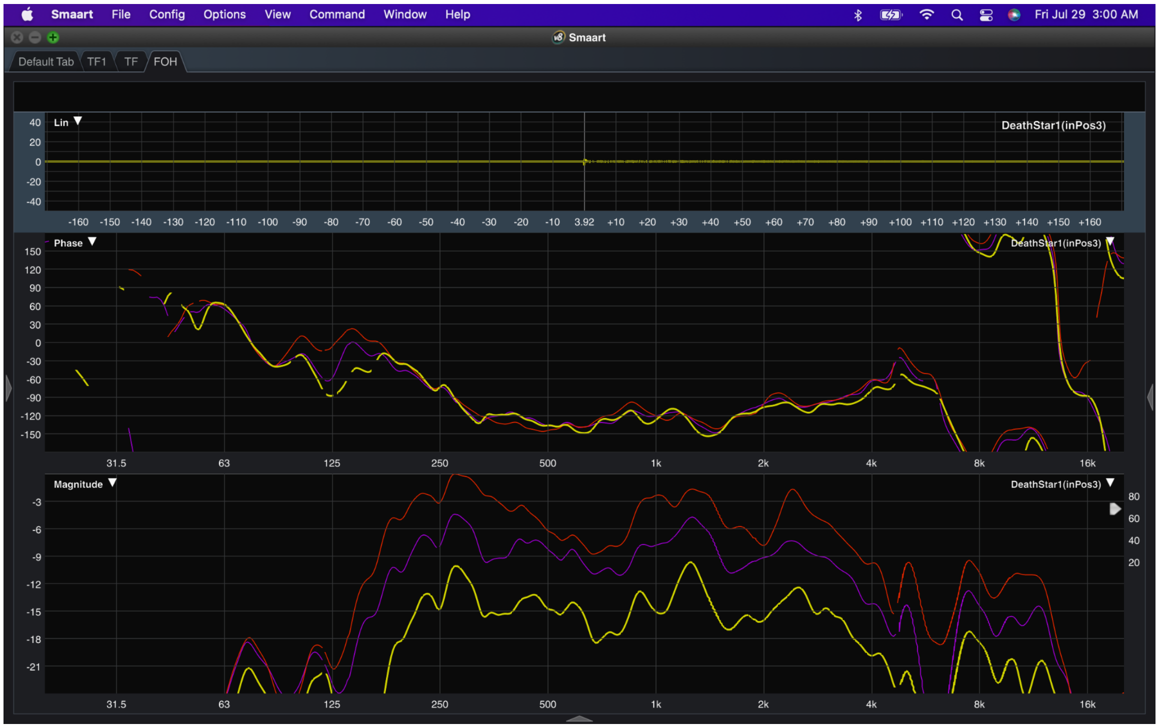


Figure 10: Taken at a spot equidistant from three adjacent speakers, the yellow trace is the output of a single speaker, the purple trace is two speakers, and the red trace is all three.

The phase coherency between all three was quite good throughout the spectrum, and the magnitude response showed fairly reasonable increases (we would expect a maximum of 12dB and saw an average increase of between 6 and 9dB), indicating that the speaker interactions were mainly constructive rather than destructive. We decided that for the majority of use cases, it would make the most sense to approach the frequency equalization from an average of one, two, and three speaker responses. To determine the equalization curve that would get a consistent, reasonably flat response, we used the built-in averaging function that Smaart has of these three traces.

Figure 11: The average frequency response of 1, 2, and 3 speakers. Note that for the sake of seeing the entirety of the frequency response, the average was scaled up in magnitude evenly across all frequencies.

In order to get a flat frequency response, we simply implemented an equalization curve that is the upside down version of this, using a VST plugin in Reaper:

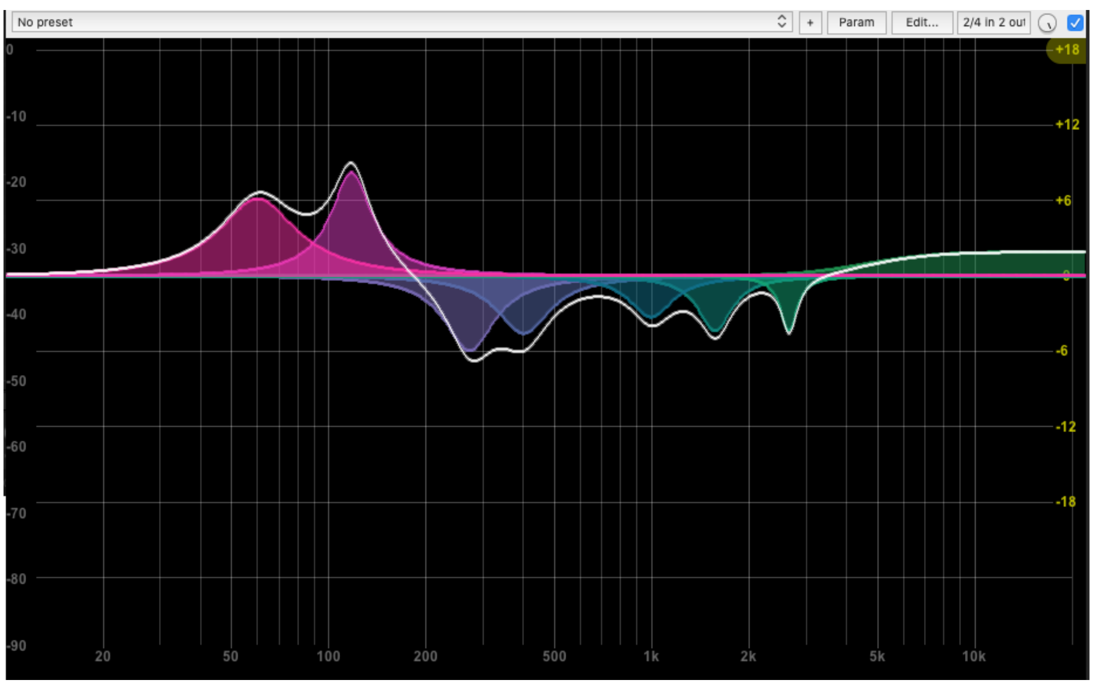


Figure 12: The equalization applied to speaker outputs in order to get a flat frequency response.

Note that at the top of the frequency spectrum we see a simple shelf eq rather than boosts corresponding to each peak. This is due to the high likelihood that the nulls in this region are being caused by acoustic properties that are caused by cancellation, whether due to a lack of coupling between speakers or due to bouncing off of a nearby surface. The boosts in the low end, however, are making up for the driver size being small enough that there is a significant dropoff of output. Note that this equalization curve is for use when there is not a subwoofer present as it brings in lower frequencies. The lowest boost would be omitted for use with a subwoofer.

To process the output of our dodecahedron, we began by choosing a suitable DAW for us to apply our desired effects. Reaper was our immediate choice due to ease of access for any possible user, as Reaper is a free DAW with full functionality across the 60 day evaluation period and beyond. Reaper has many VST plugins included in the DAW which we can use to process the sound and control the outputs of each of the 12 dodecahedron drivers. Reaper also offers ReaScripts[9], Reaper's own API code editor which can write and read scripts in various programming languages such as EEL2, Lua, and Python. After setting up the dodecahedron speaker output, it was found that ReaScript offers the most customizable control over the system by programming each specific change in volume to imitate the natural movement of a sound source across the dodecahedron. However after testing the stock VST plugins within Reaper, we determined that the ReaSurround[10] and ReaSurroundPan plugins[11] were optimal for our particular demonstration of the sound source movement.

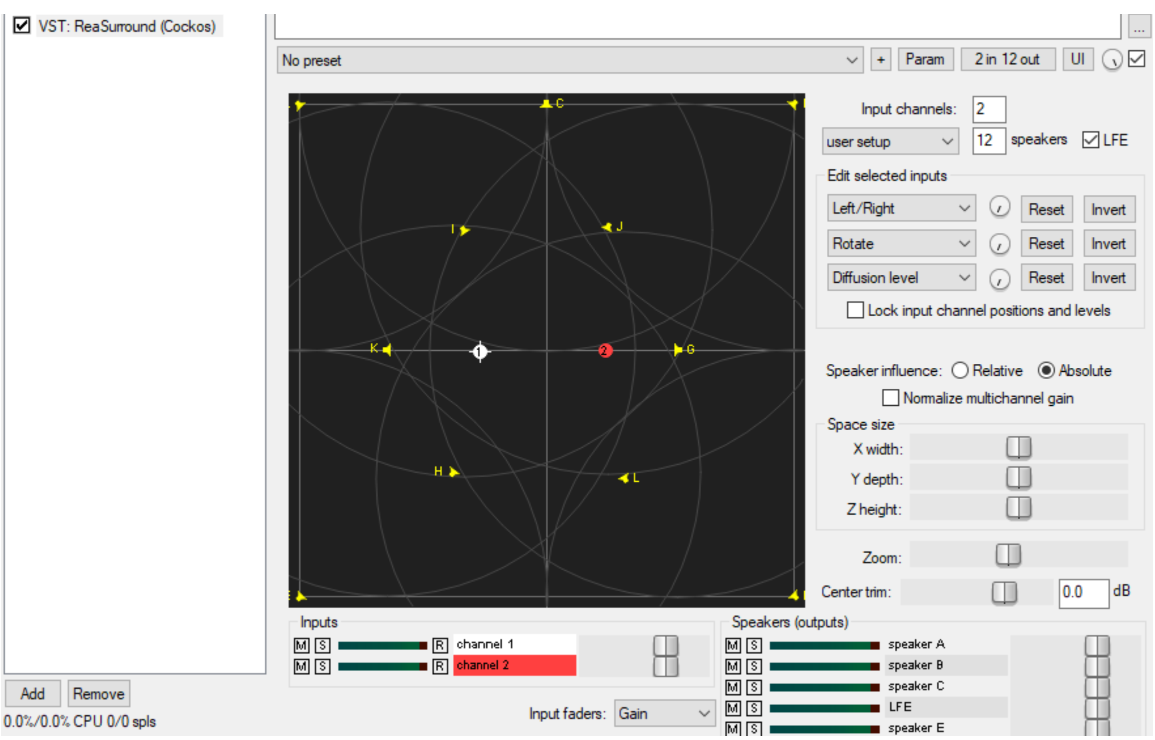


Figure 13: The ReaSurround plugin in Reaper. Used to control 2-dimensional sound source movement and resulting output from the 12 dodecahedron drivers.

The ReaSurround plugin offers a 2-dimensional plane to model the left-to-right stereo spread by placing sound sources and listening points which only output sound if the sound source node is placed within the listening points' sphere of influence. The size of the sphere of influence and overall gain of each output can be controlled in the settings of the ReaSurround plugin. ReaSurroundPan is simply a 3-Dimensional version of ReaSurround, offering a Z-axis and tri-pane view mode to monitor the movement of a sound source in three dimensions. This 3-D approach was found to be optimal for our system because we can place the listening points within the plugin to match the outputs of the dodecahedron; 5 upper listening points circling around the centre point, 5 lower listening points around the centre point, and one upper middle and one lower middle point for the top and bottom of the dodecahedron respectively. Another reason we chose the ReaSurroundPan plugin was the ability for us to control sound source positioning via MIDI using a small MIDI keyboard. We relate the X, Y, and Z positioning of the ReaSurroundPan sound source to 3 separate mixing dials on the MIDI controller, allowing users to demonstrate the sound source movement themselves by easily modifying the sound positioning and observing the results sonically as well as visually on the ReaSurroundPan plugin window. The MIDI mapping and room model was saved as a preset in Reaper for repeated use.

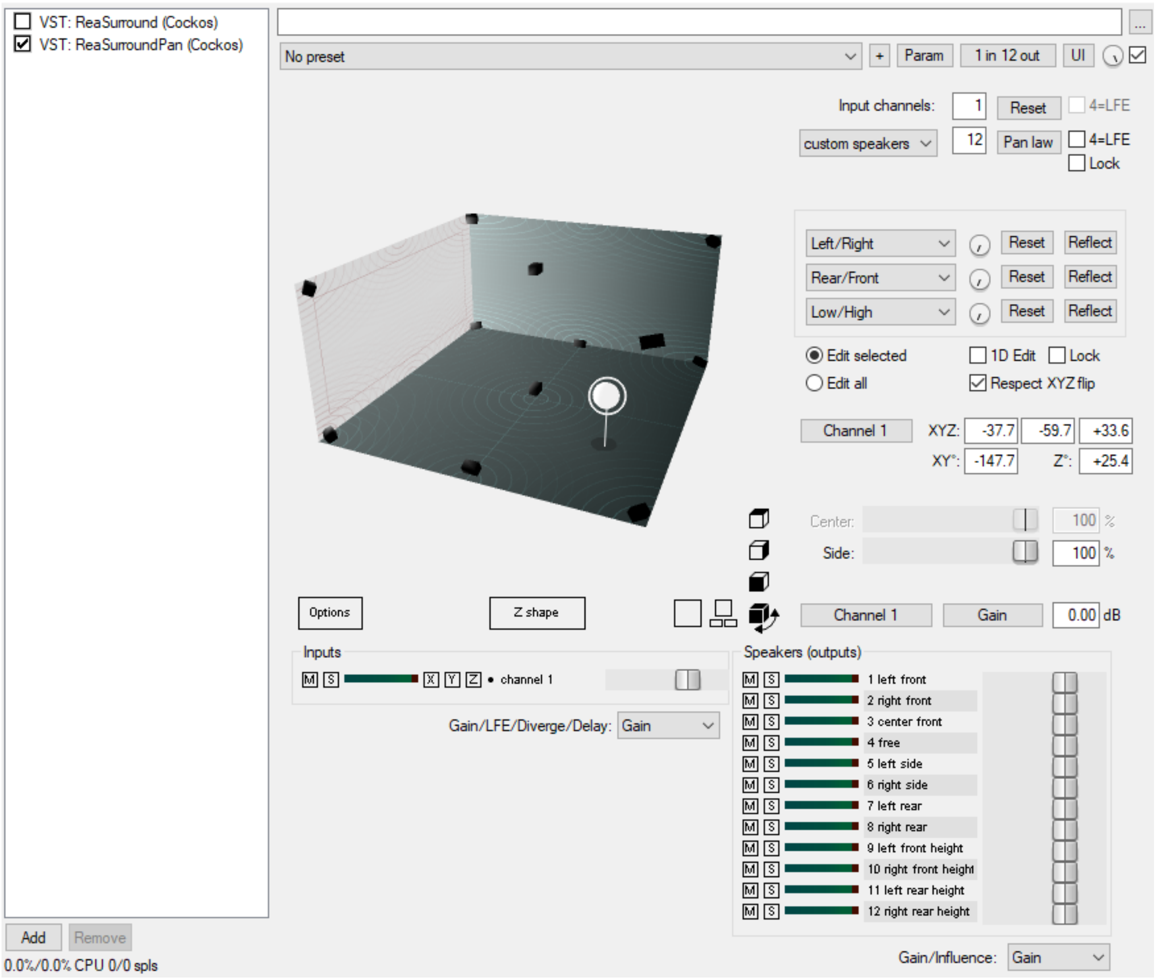
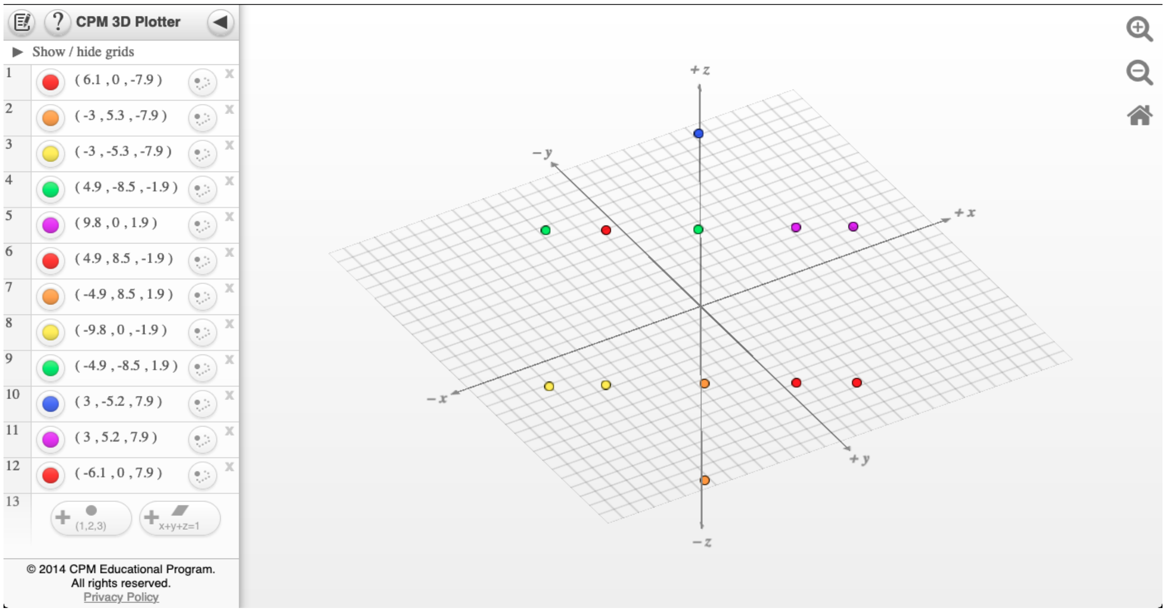


Figure 14: The ReaSurroundPan plugin in Reaper. Used to control 3-dimensional sound source movement and resulting output from the 12 dodecahedron drivers.

In this way, we were able to program the DAW to achieve the desired three-dimensional sound effects via a combination of panning, velocity and volume control.

After this, we set up Reaper to play back a recording done with a classical quartet, listening to it first as individual instruments and then as a whole. Firstly we had to map out the microphone configuration that was used to record it. It was plotted as follows:



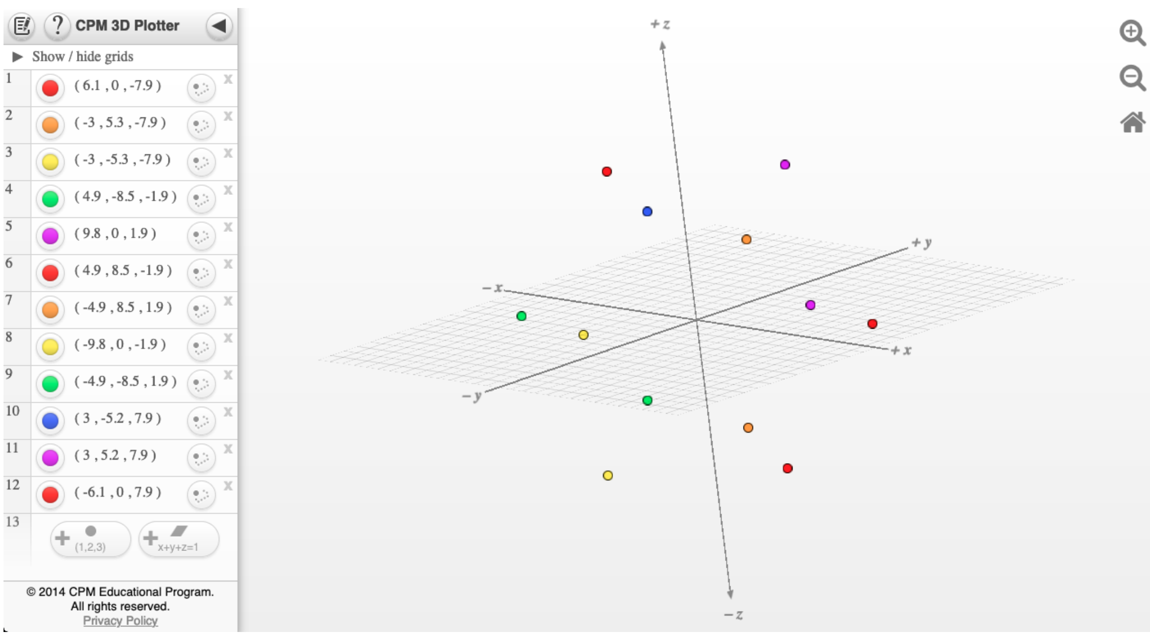


Figure 15 & 16: three-dimensional mapping of the microphone locations so that they could be mapped to the outputs of the reaper file.

The Reaper file is functionally a group of twelve channels that receive the outputs of the four instrument channels. These channels in turn are labelled and mapped to the corresponding speakers on the dodecahedron.

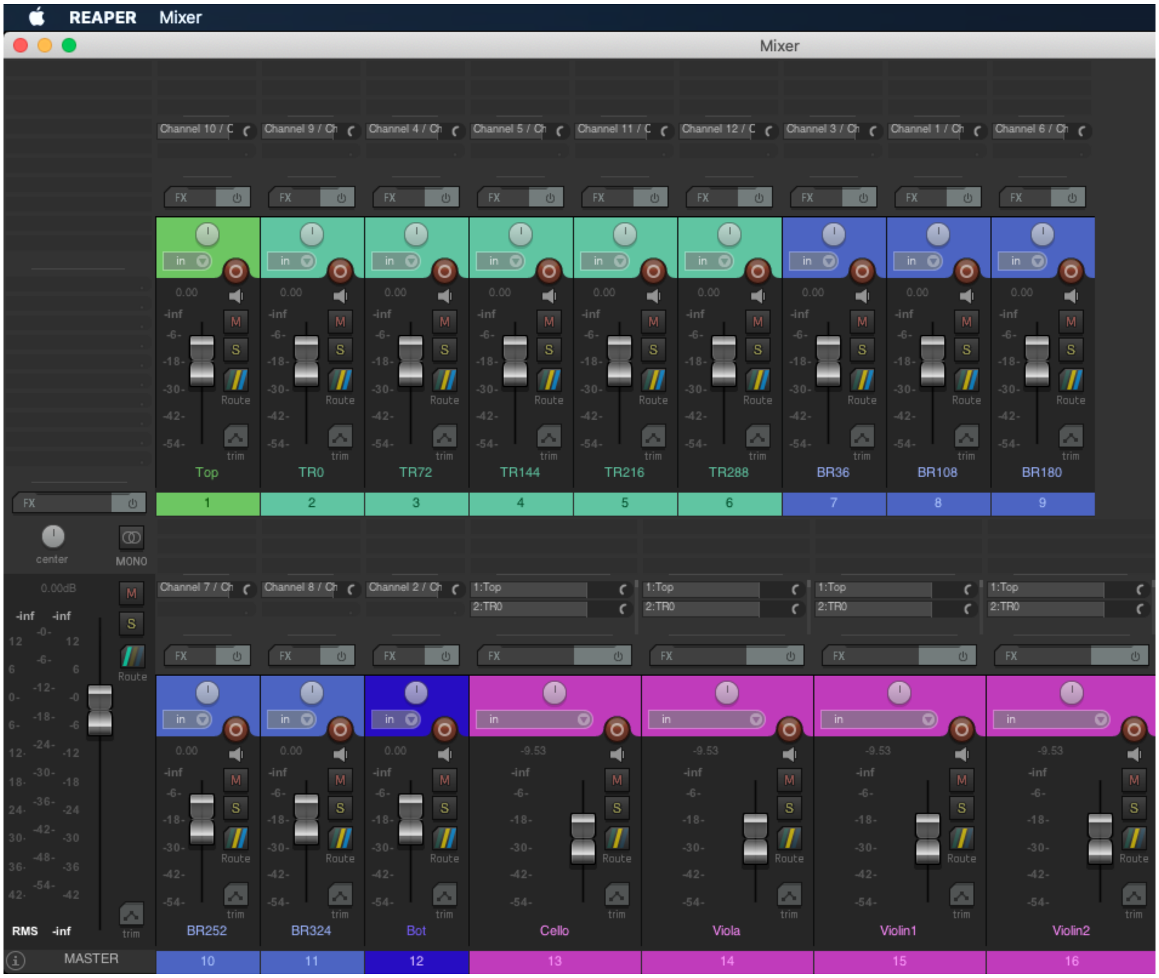


Figure 17: Reaper's mixer window, configured to send the audio from the instruments in the last four tracks to the outputs listed in the first twelve tracks.

Note that the output channels were named corresponding to the top speaker, then the top row (TR) of five, the bottom row (BR) of five, and the bottom speaker. The instrument tracks were all 12-channel .wav files. The listening experience was certainly interesting, both for single instrument listening, but especially when listening to multiple instruments as they were placed on top of each other in a way that would be impossible in a traditional setting. This led to some interesting masking and blending effects in terms of the overall balance of the sound.

IX Cost Analysis

Direct costs:

- 12 x Speakers = $194.87
- Construction materials (Black paint, screws, spacers, mounting) = $79.20

Funding

- University of Victoria ECE 499 reimbursement amount = $120.00
- Dr. Peter Driessen's research fund = $154.07

Indirect costs: B**rett**

- Assembly time = 28 hours
- Testing time = 12 hours
- Programming time = 20 hours
  Above are estimated time spent for Brett, feel free to add yours and then we can put in the total amounts

- **Morgan** - Shared testing time ~12 hours
  Shared Assembly time ~20 hours
  Reaper research ~4 hours
  Reaper preset design ~4 hours
  Literature review ~4 hours
  Meetings ~4 hours
  Website ~6 hours

- **Samuel** - Omnidirectional speakers literature ~5 hours
  Shared Assembly time ~10.5 hours
  Shared testing time ~ 9 hours
  CAD(Solidworks) research ~4 hours
  CAD mock up design build ~ 5 hours
  Initial paper writing ~3 hours
  Meetings ~4 hours
  Equipments procurement ~4 hours
  Equipments Return ~ 2 hours

Total Indirect costs:

- Approximately ~100 hours of work researching and implementing the desgin

X Conclusion & Recommendations

This project culminated in a successful build of an omnidirectional dodecahedron loudspeaker system, configured to function as a software-controlled effects unit. In addition to that, we were able to play back recordings of individual instruments recorded using spherical microphone arrays in order to listen to the differences in timbre and unique changes in characteristics depending on the listener's location. During our public demonstration, the sheer depth and space of the listening experience drew vast attention as people were able to experience these things.

While previous iterations of dodecahedron speakers have mainly been used for acoustic testing in construction, there have been some previous incarnations where they were used as a spherical sound source. However, being able to add customized spatial effects to a musical performance via the use of a speaker hanging over a crowd has not been done previously in any of the literature we found.

We would recommend that future work focus on constructing a sturdier dodecahedron, as well as the possibility of integrating a subwoofer into the array. On top of that, we think it would be interesting to explore multitrack mixing possibilities given that the speaker may be divided into groups of two or three quite easily in order to create areas with different sound sources as the listener walks around the speaker.

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[11] *How to use ReaSurroundPan for Spatial Audio in REAPER (Part 2)*. (2021, November 13). [Video]. YouTube. https://www.youtube.com/watch?v=vg28Dok2vqQ

Appendix

1. Project Website
   https://ece499-2022.github.io/OmniSpeaker/index.html

   Website coded in HTML and hosted through github source repository below https://github.com/ece499-2022/OmniSpeaker

2. Code of ethics of EGBC
   https://www.egbc.ca/Complaints-Discipline/Code-of-Ethics/Code-of-Ethics

3. Project source - Peter Driessen 499 projects page
   https://www.ece.uvic.ca/~peterd/499/499music3.html