speaker.motion: A Mechatronic Loudspeaker System for Live Spatialisation

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ABSTRACT
This paper provides an overview of a new mechatronic loudspeaker system: speaker.motion. The system affords automated positioning of a loudspeaker in real-time in order to manipulate the spatial qualities of electronic music. The paper gives a technical overview of how the system's hardware and software were developed and the design criteria and methodology. There is discussion of the unique features of the speaker.motion spatialisation system and the methods of user interaction, as well as a look at the creative possibilities that the loudspeakers afford. The creative affordances are explored through the case study of two new pieces written for the speaker.motion system. It is hoped that the speaker.motion system will afford composers and performers with a new range of spatial aesthetics to use in spatial performances, and encourage exploration of the acoustic properties of physical performance and installation spaces in electronic music.

Author Keywords
Spatialization, Live Electronics, Interface Design, Musical Mechatronics

ACM Classification
H.5.5 [Information Interfaces and Presentation] Sound and Music Computing, H.1.2 [Information Systems] User / Machine Systems

1. INTRODUCTION
Throughout electroacoustic music's history there can be found a connection with an exploration of space in composition. Spatial engagement can take many forms in electronic works. Much research has been conducted into creating spatialisation systems that allow composers to create three-dimensional sound fields that give the illusion of fully immersive real-world spatial environments. Techniques such as VBAP, Ambisonics, and Wave-Field Synthesis have been at the forefront of this research over the past few decades. However, hand in hand with the idea of creating spatial environments through sophisticated panning systems is the aesthetic use of the unique acoustic properties of a performance space. For many years speaker orchestras such as BEASTS [1], The Gmebaphone [2], The GRM Acousmonium [3] and the ZKM Klangdom [4] (to name a few) have afforded a way for electroacoustic performers to incorporate a live spatial element to their works. The speaker orchestra and the act of the live diffusion have often been seen as a way for the composer to interpret their piece into a new performance space [5]. The unique spread of the loudspeakers throughout the room ensures that each piece will vary depending on the performance setting. Thus the physical space of the room can inherently be viewed as a compositional element to be manipulated.

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Often, electroacoustic composers have very specific desires in terms of the placement of loudspeakers in the venue, particularly regarding the direction the loudspeakers are facing. After many years watching performers spend time slightly adjusting the angles of loudspeakers' directions to get the response they desire, the concept of a loudspeaker that could not only be repositioned in terms of its angle but also its vertical tilt became the starting point for further exploration of the aesthetic affects of loudspeaker directionality. Further, this idea that subtle changes in the loudspeakers' positions would greatly affect the way a piece resonated through space raised two questions: firstly why should one position be considered perfect for the entirety of the performance, and secondly why not be able to use these resonant qualities and the spatial trajectories created by moving between set directions as a further expressive layer in the piece?

Based upon these motivations the speaker.motion system was conceived to allow composers to dynamically use the spatial aspects of the room and trajectories created within the room in a dynamic way throughout the piece. It was also hoped that by building a system that had both a compelling visual aspect and that made it clear to the audience that the spatial aspects were also being manipulated throughout the piece, it might draw the listeners attention to consider the wider space as the stage rather than the point source of the loudspeaker as the instrument.

This paper will begin by looking at spatialisation aesthetics and trends in extending the standard loudspeaker. It will then go on to provide an in-depth discussion of the speaker.motion system, how it was built, and how the hardware and software work. Section 5 provides a discussion of two new pieces that were written and performed for the speaker.motion system; the discussion includes compositional goals and how spatial elements were achieved through use of the speaker.motion system. The paper concludes with a discussion about future plans for the speaker.motion system.

2. RELATED WORKS
Diffusion systems and speaker orchestras are not the only way electronic composers have engaged with physical space. Another interesting way of using space creatively is through using the physical acoustics of the performance space to create spectral content. The most famous example of this is Alvin Lucier's 'I am sitting in a room' (1969). Toward the end of the piece the connection to the original recording of speech is semantically lost, instead we hear the frequencies of the room with some rhythmic intonations. In this piece it could be said that not only is the physical space the main signal processing effect, but indeed it is the aesthetic output for the piece. A great deal of research has been conducted on how we can build 'idealistic' performances spaces, ones that allow the sound to travel large distances with minimal colouration from the physical space. However, in Lucier's piece, and in the speaker.motion system presented in this paper, the idea of using the physical space is not in an attempt to correct for the inaccuracies of the room but

rather to embrace its unique physical qualities and to use them for aesthetic engagement and compositional exploration.

While the speaker.motion system has many novel qualities, it is not the first extended loudspeaker performance tool. In 1940 Donald Leslie began selling his 'Leslie' loudspeaker that was designed to simulate the spatially resonant qualities of the pipe organ on an electric organ by rotating a speaker at such speeds as to create a Doppler effect. The original loudspeaker could only be run at one speed, but a later version was able to run in both 'Chorale' and 'Tremolo' modes, that allowed either a slow or fast rotation speed. The audio effect created by the Leslie has since inspired a number of musical effects systems that were very popular in the 1960s and 1970s and are still in use today. The Sharma speaker, by Keith Hitchcock, was sold in the 1960s and 1970s was designed in direct competition with the Leslie. The cabinets that enclosed these loudspeakers meant that the sound coming from them was still very much localised to one point in the same way a standard amplifier would be. The use of these rotating systems was to process audio and create interesting timbre rather than to create spatial effects. While these systems are still available, guitar pedals and other similar tools were able to simulate the same affects as the rotating speaker; therefore the speaker units themselves had a significant drop in popularity[1].

Bahn and Trueman [6] created hemispherical speaker arrays as a way to simulate the complex radiation patterns created by traditional musical instruments. These loudspeakers also allow electronic musicians to create the same point source localisation when collaborating on stage that would be experienced through localising different sounds to specific instruments in an orchestra or band. The hemispherical loudspeakers have been used extensively in laptop orchestras and robotic ensembles. Whilst not necessarily the original intention, the shape of these speakers does allow musicians to conceive of spatial trajectories by creating specific panning patterns throughout the individual cones of the loudspeaker unit. In fact, the spatial elements of these hemispherical speakers has been explored by Sharma et al. in more depth in [7]. These researchers have explored the use of their icosahedral loudspeaker system as a way of spatialising sound through the creation of complex spatial trajectories as well as positioning the icosohedral loudspeaker in the specific areas of the room to allow the composer to manipulate the room reflections.

The speaker.motion system presented in this paper aims to further the research being conducted in the field of spatial composition by giving composers a new way to manipulate the spatial directionality of sound, and therefore also to dynamically manipulate physical acoustic qualities of the performance space.

3. SPEAKER.MOTION HARDWARE DESIGN

Speaker.motion is a mechatronic instrument that has been designed to allow real-time manipulation of spatial positioning of a loudspeaker for electronic music performance. There are four identical mechatronic loudspeaker units that make up the full spatialisation system.

3.1 Design Criteria

There were a number of things considered in the design of the speaker.motion system. As the most important consideration was to afford an extensive range of possible spatial trajectories, it was deemed that the loudspeaker must be able to continuously rotate in either direction indefinitely. Also, the loudspeaker must not only be able to rotate but to feature a further degree of freedom achieved by the vertical tilt parameter. The quality of audio reproduction was of great importance, the loudspeakers needed to be capable of reproducing a high fidelity audio output with a wide frequency response. However, in choosing the loudspeakers, weight was also a consideration. For the initial designs we were looking for a loudspeaker that was as lightweight as possible to allow relatively lower cost components to be used for the mechanics needing to hold and tilt its weight.

The overall cost of the system was also taken into consideration: whilst there was no set budget for the project it was hoped that the loudspeaker system could be utilized by a range of institutions researching spatial composition, therefore keeping the system at a relatively low-cost whilst not hindering audio quality or potential trajectories was an important aspect of the design. The system should also require minimal disturbance to the loudspeaker itself so as to not significantly change the resonance and frequency response of the loudspeaker. The system needed to be easily controlled by composers, and should be intuitive enough that composers without a technical or engineering background are able to fully explore the aesthetic potential of the system. It should also be controllable in real-time so that composers may explore spatial characteristics of new spaces on the fly. The loudspeaker system should not link to any particular type of audio reproduction, instead be capable of the same playback options as a regular loudspeaker. It was also deemed important that the loudspeaker system had a strong visual element that would draw the attention of both listener and composer to the spatial aspects of any piece.

Speaker.motion is part of a larger body of research, the goal of which is to provide a new range of tools that encourage a heightened sense of spatial engagement for the composer, and spatial awareness for the listener [8] .

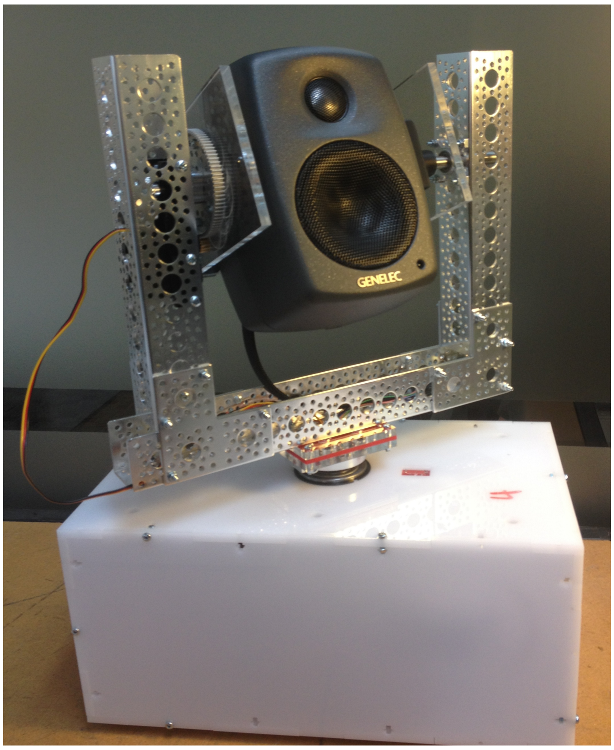

Figure 1. A single speaker.motion unit capable of real time directionality changes across two axes.

[1] http://theatreorgans.com/hammond/faq/mystery/mystery.html Accessed 22.12.15

3.2 System Overview

Each speaker.motion unit features a Genelec 8010 loudspeaker mounted in a custom built mechanical structure. The loudspeaker itself is mounted inside a gimbal like structure that gives the loudspeaker the desired rotational and tilt control parameters. A servomechanism mounted on one side of the cage controls the loudspeakers tilt, and the rotation of the entire cage occurs via a stepper motor. By rotating the full cage structure speaker.motion is able to adjust both the tilt and the rotation simultaneously, it also gives the greatest range to the directionalities able to be achieved by the system. Where possible the moving parts are all mounted inside the enclosure underneath the cage. This design helps with structural stability, protection of the mechanical parts, and safety of limiting access to moving parts, as well as visual aesthetics.

The speaker.motion system was designed utilizing a number of rapid prototyping techniques, and an iterative design methodology. A number of smaller iterations were first developed that led to the current speaker.motion model.

3.3 Hardware Implementation

The majority of functionality is achieved through use of a NEMA 23 stepper motor to achieve the rotation, and a servomechanism to achieve the vertical tilt. Both devices are geared down to achieve a higher torque level allowing more smooth and accurate control of the loudspeaker and compensate for the loudspeakers physical weight. The stepper motor is geared through a timing-belt and pan drive system that also help distribute the weight of the loudspeaker, and the servo is geared down with a high ratio involute gear. The wired rotation is achieved through use of a slip ring. The slip ring connects the audio cables from the loudspeaker amplifier to the loudspeaker cone, and runs the power up to the servo so the servo may rotate with the rest of the structure. The slip ring allows for continous 360 degree rotation without any wires becoming tangled. The slip ring informed many design decisions in the system, including the decision to modify the loudspeaker and remove the power board so that only audio signals would be required to pass through the slip ring to the loudspeaker, instead of 240V power lines.

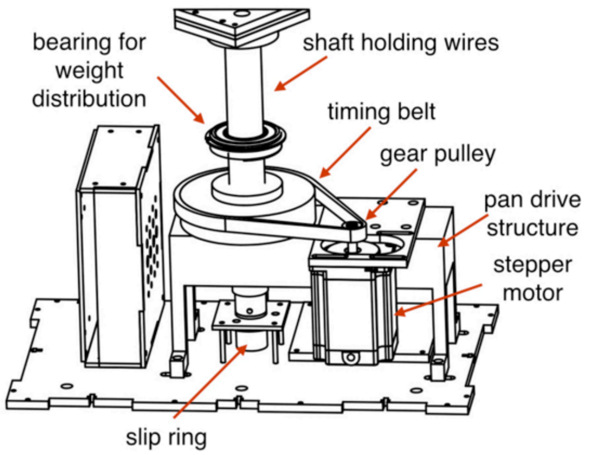

Figure 2. The rotation system and internal mechanical structure of speaker.motion. This diagram shows the parts inside the enclosure shown in Figure 1.

The stepper motor was chosen for its ease of precision movements. Being able to achieve predictable and repeatable speaker angles is of the utmost importance to the system. Therefore, a photo-interrupt sensor is also used in order to 'home' the motor on start up. Whenever the speaker.motion unit is first turned on the motor and servo will both search for their home positions, and once achieved will then be ready to accept communications. The servo has an internal homing function so no extra hardware was required. The stepper motor is driven by a Pololu DRV8825 Stepper Motor Driver, which allows the motor to operate in micro-stepping modes. These modes have been employed for smoother movement and acceleration patterns, and because they cause the motor to operate with a lower output of mechanical noise.

The choice to remove the audio driver board from the Genelec loudspeaker was made to both reduce the physical weight of the loudspeaker, and so that the 240V power input for the amplifier power supply was not being sent through the device. It was also decided that the power and PCB for the speaker itself should remain entirely separate from that of the mechanical side of the unit. By decoupling the speaker electronics from the mechatronics subsystem, the loudspeaker remains insensative to any mechatronic faults and may be easily reverted to its off-the-shelf configraution. A separate enclsure was built to house the Genelec loudspeaker PCB, that both protects the board from any damage and provides safety from human contact with live power.

4. SPEAKER.MOTION FIRMWARE AND SOFTWARE

The speaker.motion mechatronics are controlled by an ATMEGA328 microcontroller and an implementation of MIDI spec. The firmware is very simple: its main job is to receive MIDI messages and decipher those relevant to its particular unit based on the MIDI channel. Each individual unit is on a separate MIDI channel. The messages sent for other channels are ignored by the unit and passed on to other units via the MIDI THRU. This allows multiple loudspeaker units to be daisy-chained together. Once messages are received, the desired rotational and tilt movements are derived from the message contents. The firmware also implements the homing function that runs on startup, to make sure the messages result in accurate positioning throughout the performance.

4.1 Operation Modes

The stepper motor can be run in two modes that the user may switch between on the fly. The first is a positional mode. In this mode the user gives the motor new desired position and the motor will move to that position as quickly as possible. To ensure that all motions remain smooth, the motor employs an acceleration and deceleration in this mode. The acceleration/deceleration is implemented with the AccelStepper Library[2].

The second mode results in continuos azimuthal rotation. The user is then able to adjust the speed of rotation on the fly. This mode has two sub-modes to allow rotation in either clockwise or counterclockwise direction. Again these modes can be constantly changed throughout the performance.

4.2 Methods of Interaction

One of the reasons the MIDI protocol was chosen was how easily it allows communication out of a number of different software apllications. Many of the pieces that have so far been written for the speaker.motion system implement the MIDI output from Ableton Live because it is particularly easy to sync gestures to the loudspeakers with gestures in the audio. However, any DAW or other such software that is capable of sending MIDI may be used to control speaker.motion. For real-time control of the speaker.motion units, MIDI can be easily mapped from any MIDI controller via music software. The modular design of the system allows a great deal of freedom for

[2] http://www.airspayce.com/mikem/arduino/AccelStepper/

the composer/performer to interact with they system however they are most comfortable. This ensures that a wide range of performers can use the system.

An iPad application for live interaction has also been developed. The iPad gives the user a graphical representation of the spatial area surrounding each of the four loudspeakers and allows the user to drag an object around the space to indicate where the loudspeaker should point to. Three concentric circles represent the space; rotating the object around the circles controls the angle. Dragging the object from the centre of the space to the outer ring controls the tilt. When the object is placed in the very center circle it will point directly towards the ceiling, the middle circle causes the speaker to tilt with a flat response straight ahead, and the outer ring causes a tilt towards the floor. The app then wirelessly sends OSC [9] messages that pertain to the desired angle and tilt of the speaker that can be received in Max/MSP. A communication patch has been built in Max/MSP to receive these messages and translate then to MIDI that can be sent either directly to the speaker or to a DAW that is running. Whilst the author has chosen to implement this communication translation in Max/MSP, one could use any program capable of receiving OSC and sending MIDI to do the same.

These interaction modes were chosen because they are simple and intuitive. They open up the system to use by a wide range of live electronic musicians by ensuring that anyone with some familiarity with a DAW can use the system to its full potential without needing a deep understanding of how the electronics or the firmware works.

5. CASE STUDIES

The following section will outline two pieces performed with the speaker.motion system, focusing on the way specific audio qualities were linked to spatial movements and how these aspects were used to heighten the compositional elements of the pieces. There is also discussion of how the loudspeakers where used to highlight characteristics of the physical performance space.

5.1 Tidal.Motion

Tidal.Motion is made of filtered field recordings from a water pump in New Zealand's Cook Strait. The original drone has interesting timbral content but very little movement. The idea for the piece was to constantly play similar audio through the loudspeakers to draw heightened attention to the way the speakers' positions caused perceived movement in the audio. The piece is approximately 6 minutes long.

Each audio channel features slightly different filtering allowing it to to draw attention to the characteristics of the room at specific resonant peaks in the audio. All four speakers were set to start spinning gradually in one direction and over time their speed increased. All four speakers also slowly raised their tilt angle until directed almost straight up at the climax of the piece. Two of the speakers were set to spin clockwise and two counerclockwise. This was done to create spatial relationships not only between each loudspeaker and the space, but also between pairs of loudspeakers themselves. At times the two loudspeakers that spun in the same way appeared to be working together to activate the space in similar ways, a phenomenon heightened to their relatively close proximity. At other times throughout the rotation, two loudspeakers spinning in opposite directions would meet to be facing each other causing pair-like relationships and momentarily, would work together to create phantom source images that would last briefly before dissipating and causing the localisation to return for a moment back the the physical loudspeaker, and then out to the speaker's wider trajectory path, and then to the room itself.

Figure 4. All four speaker.motion units on stage at the National Library of New Zealand. For the tidal.motion performance all four loudspeakers were placed in a horizontal line on stage approximately 1.5 meters apart.

The specific speeds of the motors and the frequencies drawn out by the filtering of the drone are designed to sync together to create rich timbres in the piece. This can cause an affect where the listener is unaware which sounds are mechanical ones coming from the device, and which sounds are audio coming from the loudspeaker. The timbre of the drone and the motor align together to create deep and rich harmonies. The gestural motion created through the filtering is mimicked and livened by the both the physical gesture of the rotation, and the spectral gestural motion of the units' mechanical sounds.

5.2 Lines and Distances

Lines and Distances is an electroacoustic piece by Douglas Lilburn, originally intended as one of his four channel works with a spatialised element. The spectromorphology of the piece allows for an extensive spatiomorpholgy to be explored with it heightening the physical space of the concert hall, the immediate perceived space of the stage, and the spectral space of the piece [10,11]. Lines and Distances was reinterpreted to be spatialised through the speaker.motion system.

The beginning of the piece features a number of short phrases with a small amount of space between each that allow the listening palette to be reset. This was further emphasized by having each speaker move to a different direction before the beginning of the phrase, and reset to a new location at the end of the phrase. For example, the first phrase featured the speakers as shown on the top line of the figure below. The speakers then re-arrange in the break between phrases to be positioned as in the bottom line. For these phrases the physical distance from the walls combined with their particular angle re-positions the space for the audience to interpret each phrase as unique, though related, in the same way the phrases are musically presented.

As the piece continues, the segmented phrases evolve into longer sustained gestural content. At this point the speakers were programmed to begin spinning all at slightly different speeds drawing attention to both the trajectories being created by the movement, and the way those frequencies cause the room to respond. The speeds are synced to follow the gestural motion created in this section of the piece. They emphasize faster spectral movement by mimicking that with their speeds. A sudden severe drop in speed is triggered with a rhythmic element of the piece suggesting a change back to ore phrase based movement.

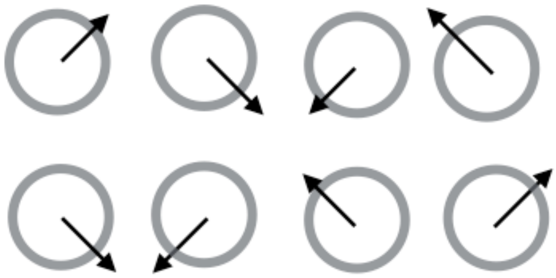

Figure 5. Diagram of speaker positions for Lines and Distances

With the resurgence of this more phrase-based sonic material, the speakers return to their positional mode where they all move together to target different areas of the room as the phrases occur, however in this case the changing of position occurs before the end of the phrase, to emphasize the more intensive spectral movement present at this point in the piece.

Following a melodic line that quickly ascends, the speakers then return to rotational movements one at a time working at differing speeds but all quickly ramping to spin almost to their full capacity with the climax of the piece, and then suddenly stop, and reset to end the piece's bird-like phrases with a more gentle and subtle positioning of the speaker.

The timbral qualities of this piece lent itself well to a fuller exploration of the space in many ways. This was the first attempt at having the speakers change modes of use, but it ran without any glitches and the spatial results perceived very positively by audience members and other composers present at the concert. For this piece the spatial movement while obviously done by someone after the fact, quite successfully worked with the space, and the piece to help portray the composers original intentions for the piece.

6. CONCLUSIONS AND FUTURE WORKS

The speaker.motion system has now been used by a number of composers in a number of concerts in different physical locations. The ability to dynamically adjust the directionality of the loudspeakers has afforded the composers with a new range of ways to interact and engage with the physical space of the concert room. While the design is very stable and is working very well, small iterations on the infrastructure are constantly been made to improve the loudspeakers capabilities.

A user study is currently being conducted to assess the composer's use of the speaker.motion system and how well the system is able to meet its goals. The initial findings are very promising, however more findings will be released at a later date. The MIDI implementation is proving to be very successful at allowing composers a variety of options in choosing how they interact with the system. A recent concert included composers using a variety of MIDI controllers and mapping their control parameters in different ways for live control of the speaker system, as well as the use of a custom hand gesture controller, and some fixed MIDI sent from Ableton Live. The variety of control methods used for this one concert exemplifies the wide range of possibilities for spatial interaction afforded by the speaker.motion system.

The physicality of the moving speaker has also proved very popular from an audience perspective. The spinning gestures of the moving speaker can at times seem almost choreographed in a more dance-like fashion, and the character that becomes the loudspeaker has incited a great level of curiosity from the audience.

The Genelec 8010 loudspeakers themselves have worked very well for the context: they are surprisingly present in a space for their size, and many composers have been very happy with their response both as a standard loudspeaker and as dynamic spatialisation system. In the future there are plans to scale the system to work with larger loudspeakers that would allow more potential for use in larger concert venues. This should be possible with a few minor changes to the design structure in order to compensate for the larger weight of a bigger loudspeaker.

Overall, the system has so far shown itself to be a very expressive and engaging way to spatialize electroacoustic music.

7. ACKNOWLEDGMENTS

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8. REFERENCES

[1] J. Harrison, and S. Wilson. Rethinking the BEAST: Recent Developments in Multichannel Composition Birmingham ElerctroAcoustic Sound Theatre. *Organised Sound.* 15, 3 (2010), 239-250.

[2] C. Clozier. The Gmebaphone Concept and Cybernephone Instrument. *Computer Music Journal.* 25, 4 (2001) 81–90.

[3] S. Desantos, C. Roads, and F. Bayle, Acousmatic Morphology: An Interview with François Bayle. *Computer Music Journal.* 21, 3,(1997) 11–19.

[4] C. Pamakrishnan, J GoBmann, and L Brunmmer. The ZKM Klangdom. *In The Proceedings of the 2006 International Conference on New Interfaces For Musical expression (NIME'06)*, Paris. France.

[5] S. Emmerson. Diffusion Projection: The Grain of The Loudspeaker. *In Living Electronic Music.* Ashgate Publishing Limited. (2007)

[6] D. Trueman, C. Bahn and P. Cook. Alternative Voices For Electronic Sound: Spherical Speakers and Sensor-Speaker Arrays (SenSAs) *Journal of Acoustical Society of America*. 01/2000

[7] G. Sharma, F. Zotter, and M. Frank. Orchestrating Wall Reflections in Space by Icosahedral Loudspeaker: findings from the first artistic research exploration. *In The Proceedings of the Joint International Computer Music Conference and Sound and Music Computing Conference* (ICMC/SMC'14). Athens, Greece (2014)

[8] B. Johnson. Emerging Technologies For Real-Time Diffusion Performance. *Leonardo Music Journal.* MIT Press Vol 24 (2014)

[9] M.Wright, A. Freed and A. Momeni. OpenSound Control: State of the Art 2003. In The Proceedings of the 2003 Conference on new Interfaces For Musical Expression (NIME'03), Montreal, Canada.

[10] D. Smalley. Spectromorphology: explaining sound-shapes. *Organised Sound* 2, 2. (August 1997) 107-126

[11] D. Smalley. Space-form and the Acoustmatic Image. *Organised Sound*. 12, 1 (2007) 35-58.