Exploring Design Patterns for Spatial Instruments: User-Driven Strategies, Spatialized Synthesis and Loudspeaker Topologies

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ABSTRACT

This paper investigates the field of spatialization tools and controllers within the context of immersive sound formats. After examining conventional approaches, we redefine spatialization tools as musical instruments challenging prevailing views of digital musical instruments confined to interface and synthesis components. Our exploration encompasses the projection, movement, and control of sound objects in diverse loudspeaker setups, emphasizing the reconnection of synthesis and space-related modulations. Addressing the multidimensional challenges associated with sound spatialization, we highlight some observed mapping strategies for the control of gestural and spatial information. In particular, we examine user-driven strategies, such as 'repurposed' controllers, 'interpreted' instruments, custom interfaces, and spatialized synthesis algorithms. Additionally, we introduce design patterns emphasizing an aesthetic standpoint, positioning *music as space*, advocating for the integration of loudspeaker topologies in the design process, and recoupling synthesis and spatialization. Illustrating our theoretical framework, we present three case studies of spatial digital musical instruments. These examples showcase the integration of spatialization with synthesis, offering a comprehensive approach to sound design. In conclusion, our exploration advocates for spatialization controller design strategies urging a transition to a more user-centric, adaptable, and holistic paradigm.

Author Keywords

NIME, spatialization, controllers, spatial synthesis

CCS Concepts

•**Applied computing** → **Sound and music computing;** •**Human-centered computing** → *Interaction design theory, concepts and paradigms; Interaction design process and methods;*

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1. INTRODUCTION

Sound spatialization reaches back to the beginnings of electroacoustic music [3] and has since then been considered a central feature of musical performance. With the rise of accessible and budget-friendly multichannel loudspeaker systems, there's a growing interest in developing interaction tools for immersive sound formats. While artistic concepts surrounding the discourse of sound and space are predominant, the study of corresponding spatialization instruments in musical performance and interactive live practice has received considerably less attention. In our opinion, spatialization tools can be viewed as musical instruments, given they fulfill "*certain aspects of instrumentality, immediacy, liveness, and learnability*" [18].

Within the scope of this paper, spatialization of sound is understood as a) the projection of sound objects either in a surround or periphonic loudspeaker setup (eg. Ambisonics, Wave Field Synthesis) or the binaural playback of virtual sound sources via headphones, b) the control of sound object trajectories in a three-dimensional soundfield, c) the control of other space related parameters such as intensity, presence, timbre, duration, virtual room acoustics, etc.

Sound spatialization techniques have been approached from different perspectives in recent decades. While some authors sketch the evolution of technologies from a historical and musicological perspective [4, 9], others discuss compositional and aesthetic strategies [2, 1], or propose classifications focusing on spatialization systems and rendering frameworks [10, 16, 15]. Only a few authors have specifically discussed spatialization controllers for real time interaction [13, 8, 18]. Interestingly, all these cited scholars see a contemporary trend in electroacoustic composition and acousmatic performance to consider space not only as an additional compositional material, but as a core feature of musical performance practice. However, only a few [18, 15] note a general lack of standardized evaluation criteria for defining constraints in spatialization controller design. They attribute this issue to the extremely diverse and idiosyncratic realizations of composers and instrument designs.

In a web-based survey on individual needs and preferences concerning spatialization[1], Peters et al.[17] elaborate that in most cases sound spatialization is done using "no hardware". Preferred controllers were mixing consoles, fader boards, touchpads, joysticks and motion tracking systems. The same survey describes that, on the software side, spatialization is mainly done using DAWs (Digital Audio Workstations) and audio sequencers (75 percent) with built-in panning tools. According to the survey, only a small per-

[1] Of the 52 participants, 85 percent were male and predominantly from Europe and North America.

centage of the participants were familiar with the use of custom-made interfaces.

Pysiewicz and Weinzierl [18] have provided the most comprehensive classification of spatialization controllers to date. The authors have pinpointed distinctive solutions based on their affordance characteristics (touch, extended, augmented, mixed) and in terms of their control scope (exclusive spatial control or inclusion of sound synthesis control parameters). Their inventory of around three dozen instruments and controllers include analog and digital mixing consoles as well as virtual and hybrid instruments for both sound production and spatialization. Although the majority of controllers rely on touch, only a few of them are wearable or handheld. The authors emphasize a historically grown split between sound production and spatialization[2] and conclude that, if spatialization controllers were to be understood as musical instruments, "new design strategies would be required".

In the development of DMIs for spatialization, Lopez-Perez [15] advocates for a "holistic" approach encompassing a wide array of design considerations, such as questions of agency, mapping possibilities, accessibility, and compatibility with existing spatial rendering frameworks, along with state-of-the-art HCI design constraints.

Many of the discussed taxonomies can be useful in defining design patterns for the development of future spatialization DMIs. In our view, it is crucial to extend these classification systems toward other characteristics which are often overlooked. For instance, synthesis-spatialization couplings and the integration of loudspeaker topologies. These factors require a comprehensive approach, along with tailored solutions to address highly individualized problems.

2. MULTIDIMENSIONAL CHALLENGES

Conventional approaches to composing and performing spatialized music, as outlined by Marshall [10], typically involve a two-step process. Initially, sound elements are recorded or synthesized, typically in mono or stereo format. Subsequently, these audio tracks are spatialized. The crucial aspect is that analog or digital audio can be sent directly to loudspeakers via routing hardware, or it can be rendered for a virtual space using spatialization algorithms (e.g. panners, Ambisonics, Wave Field Synthesis, and others). With this approach sonic materials transform into spatial sound objects encompassing attributes such as position in a soundfield. The core technical challenge lies in devising mapping strategies between control mechanisms (whether hardware or software) and the parameters offered by the spatialization algorithm used. Since each sound source can be characterized by numerous parameters and the number of sound sources may also vary, this results into a multidimensional control issue. This complexity makes the real-time control of spatialization a cumbersome task.

The second challenge linked to sound spatialization involves the gestural control of these spatial parameters. For instance, position trajectories can take on a highly gestural nature. Ideally, an effective spatialization controller should offer the flexibility to effortlessly create or draw various types of movements in a 3D space. However, designing hardware controllers to meet this demand is challenging. While some sensors can capture specific gestures, they may not cover all possibilities. As a result, GUI applications are frequently employed to draw and animate trajectories in space.

[2]The problem of performing both sound synthesis and spatialization simultaneously has also been addressed by Marshall et al. who discuss different degrees of responsibility depending on the „cognitive load" of the performers [10].

As outlined in the preceding section, there is a relatively small number of spatialization controllers documented within the context of NIME. In the field of acousmatic music, the mixing desk emerged as the default control surface, despite its inherent gestural limitations. Nevertheless, this choice established the necessary conditions for the development of a stable practice. Practitioners in sound diffusion have crafted impressive musical techniques for gesturally controlling sound in space using mixing desks, passing down this knowledge from scholars to students. In contrast, other spatialization strategies lack the same stability. In our view, conceptualizing spatialization merely as the parametric control of audio sources poses a significant challenge in creating stable controllers. Breaking down the musical process into two stages — initially sound design and later spatialization — improves the efficiency of the computational workflow. However, this approach poses technical challenges in designing practical spatialization controllers for live performance. In the following section, we explore some of these issues and see how different artists have come up with various solutions.

3. USER-DRIVEN STRATEGIES

Over the past three years, we have collaborated within the group of technologists and artists established around the open immersive audio platform OTTOsonics[3]. We have worked together in artist in residence periods with around a dozen composers[4] with extensive experience in spatialization. We have also enabled an Ambisonics Summer school[5] with twenty participants, and we have organised two editions of a yearly festival dedicated to immersive audio with more than thirty artists in total. Through these events, we have identified a list of the strategies taken to address the multidimensional mapping issue. To illustrate these solutions, we would like to introduce here a 'user-driven classification'. Instead of being an exhaustive taxonomy, this type of classification recognizes that users often discover innovative or unintended ways to use devices beyond their original design. In this context, spatialization devices are categorized based on the diverse ways users adapt and repurpose them for different applications. The focus of this classification lies in understanding user behaviors and applications rather than adhering strictly to the device's original intended use. In our approach to tackling this issue, we have observed the following design strategies:

1. Repurposed controllers: they consist in using existing controllers which are not initially intended for spatialization. For instance, a 2D touchpad or tablet can be repurposed to determine the azimuth and elevation values of a sound source within a loudspeaker hemisphere. Typically, only minor adjustments of input values to software parameters ranges are needed to achieve their use. The primary challenge lies in mapping physical gestures to control parameters of the spatialization algorithm. The challenge then shifts to

[3]An open hardware and software platform for the development of affordable and accessible loudspeaker systems, multichannel amplifiers, etc. Link: https://tamlab.kunstuni-linz.at/projects/ottosonics/ (accessed 6 May 2024)

[4]There were no formal contributions by any of these artists to the contents of this paper, but we acknowledge that their practice has shaped and informed this section. The names of these artists can be found in the Ethical Standards section.

[5]Organized by Phonon Crew in Ústí nad Labem in July 2023. More info: https://www.phonon.cz/ambisonics-summer-school/ (accessed 6 May 2024).

finding suitable controllers that offer enough parameters and enable swift control of the specific spatialization technique.

2. Interpreted controllers: they consist in utilizing existing controllers alongside custom intermediate software applications to operate at a higher level. Given that controlling numerous sound sources and spatial characteristics involves specifying extensive sets of parameters, one approach could be to employ higher-level models. This method entails using a reduced number of control variables to affect a large number of parameters at lower levels. The approach involves computationally extending physical controllers and instruments through multiple layers of mapping, potentially incorporating machine learning. Intermediate programs are essential to translate arbitrary physical gestures into higher-level musical strategies or semantic values, such as trajectories, sonic gestures, sequences, etc. As an example of this type of controllers, the composer Åke Parmerud has described us through personal conversations the use of a MIDI piano to control spatialization trajectories. The composer has developed an intermediate Max/Msp patch which animates these movements and creates smooth transitions between trajectories.

3. Custom GUI and TUI interfaces: these are controllers crafted to interact with existing spatialization software, typically highly individualistic and tailored for executing a specific sound piece. The goal is to develop a unique tangible controller that interfaces with the existing parameters of a spatialization application. Recent examples would be the controllers created by Johnson, Murphy and Kapur [9] or Bukvic, Sardana, and Joo among many others[5]. Typically, these controllers incorporate OSC or MIDI protocols to communicate with a spatialization software. In our view, they often mirror the complexity found in such environments through physical interaction. However, due to the constraints of the physical world, these controllers offer a restricted set of features compared to their software counterparts.

4. Spatialized synthesis techniques: algorithms created to inherently synthetize spatialized sounds. With this approach, the spatialization process involves synthesizing sound, or digital sound is inherently spatialized during synthesis. The aim is to develop synthesis methods that directly incorporate spatialization or spatial distribution. Interestingly, there are examples of such solutions in various synthesis domains. Firstly, in the realm of granular synthesis[12][23] and corpus-based concatenative synthesis[6], studies have demonstrated the feasibility of assigning distinct spatial attributes to individual grains. This enables the linkage of spatial behavior to audio features, controllable through gestures or programmed trajectories. Secondly, in physical modeling, wave field spatialization solutions have been proposed [14]. This approach combines physical modelling synthesis with wave field renderings for performing sound diffusion. An example would be the sound propagation simulation and control of virtual string instruments. Thirdly, highly abstract sound textures can be synthetized using modulation through spatialization. Rapid movements of virtual sound sources lead to frequency modulation, accompanied by the appropriate Doppler shift. If a sound source is modulated through high-speed movements, especially within periodic trajectory orbits, abstract sonic textures can be created. Using this technique, called *spatial modulation synthesis* [11], listeners have the impression that space and timbre get unified. On the one hand, sound velocity determines timbre. On the other, we perceive these abstract sounds at the exact positions where they get modulated.

With the exception of spatialized synthesis approaches, these solutions adhere to the conventional two-phase model of synthesis followed by spatialization. In the next two sections of this paper, we present guidelines and examples which aided us at creating controllers toward rejoining both processes.

4. DESIGN PATTERNS

4.1 Point of departure: Music as Space

Gerriet K. Sharma [19] explains the fundamental premise that electroacoustic space-sound composition for loudspeaker sculptures embodies *music as space*, akin to an art form that shapes space by itself. Specifically, reproduced sound phenomena have the capacity to constitute 'space' even without spatialization. This concept contrasts with the traditional approach of *music in space* or *sound in space*. For Sharma, "space, here, is not conceived as something existing that must be filled with sound, but rather constituted topographically as a three-dimensional entity by means of sound". This concept can aid in framing live spatialization with controllers as a process that should align with a) the intrinsic spatial characteristics of the sound material being used; b) the sculptural sonic effect created by the loudspeakers; and c) the acoustics and other properties of the room where the sound is perceived. From this perspective, spatialization controllers could be conceptualized from an aesthetic standpoint, rather than solely as physical extensions of the parameters existing at spatialization software.

4.2 Embodiment of loudspeaker topologies

In our view, if the loudspeaker topology gets embodied into the design of spatialization controllers, potentially, there will be more chances to create meaningful relationships between the performer and space performed. This affordance will inspire and limit the performer's gestures, shaping its movements and proposing compositional ideas. Indeed, in electronic music, loudspeakers go beyond being neutral transmitters. They function as electroacoustic instruments that impart color to sound. But their structural and sculptural configuration may also inspire musical concepts and interactions. When designing embodied synthesis and spatialization tools, if we have to draw on the concept of DMIs and expand them toward spatial instruments, this design pattern can assist and inspire controller designs, especially when the speaker layout lacks symmetry in space or it is custom-made. For instance, in a live performance where sound travels through the topology of a long and narrow corridor, it would likely make sense to integrate this spatial factor into the controller.

4.3 Recoupling synthesis and spatialization

As discussed in the previous section, spatial synthesis algorithms exemplify the reconnection of the traditionally separated processes of synthesis and spatialization. Typically, these strategies involve the individual spatialization of single sound components at an early stage of the synthesis process. The aim is to incorporate sound spatialization into the realms of timbre, amplitude, and frequency without relying on the parametrization of virtual audio sources. This notion was anticipated by Stockhausen in his "*Concept of Unity in Electronic Music*" [20], where the composer articulated the idea of unity between timbre, pitch, intensity, and duration. To achieve this unity, Stockhausen reduced pulse trains to extremely short durations. The drawback is that phenomenological processes intended to demonstrate this synthesis often lead to very artificial soundscapes due to the extreme FM or granular synthesis used. For example, spatial audio modulation[11] works at micro levels and with extremely rapid trajectories: sound spatialization modulates the sound to create a new timbre. On the other hand, the advantage is that the spatial and timbral attributes of sound can be coherently controlled through spatial movements in the instrument. There is also no spatial parametrization. The sound appears as a unit that is both synthesized and equipped with a spatial characteristic. Controllers following this design pattern could be inspired by higher level musical metaphors: spatial spread, elasticity and periodicity of spatial trajectories, noisiness and chaos, etc. These metaphors could result into tangible artifacts exploring the physical attributes of interesting materials: viscosity, plasticity, flow, magnetism, etc.

5. EXAMPLES

5.1 Tangible granular spatialization

This project involves granular spatialization of an existing tangible interface instrument driven by concatenative synthesis. Since 2013, the first author has been designing digital instruments called 'tangible scores'[21][22]. They are objects and surfaces that he transforms into improvisatory musical instruments using concatenative synthesis. The author engraves surfaces, and through contact microphones, he captures the sound activity produced after tangible interaction, mostly playing them with his hands[6] (figure 1).

Using mathematical descriptors, specifically Mel-frequency cepstral coefficients (MFCCs), the sound created by the author is objectively annotated. The concatenative synthesis software is fed with a corpus of sound grains previously analyzed and indexed with the same mathematical descriptor process. Similar to the projects developed by Einbond and Schwarz [6], and von Coler[23], the live audio MFCC values array from the instrument is employed as a multidimensional weight to determine the 3D position of each synthetized audio grain. The 3D position is limited to the surface of a hemisphere above the listeners. This real-time process automatically routes each synthetized sound grain among 30 audio sources, all equally separated within the 3D virtual surface. The outcome is a 3D spatialized synthesis process driven by the timbre produced on the physical object. In other words, sound grains with similar timbre occupy the same location in the virtual 3D space. These audio sources can be then rendered and assigned to various spatialization techniques: Ambisonics, Wave Field Synthesis, etc. In our case, we have mostly played it with 4th and 5th order Ambisonics loudspeaker hemispherical arrays. The experience of playing the instrument becomes an intriguing experiment. Performers synthesize spatial sound while they can also perceive how the slightest change in timbre is perceived as a spatial change too. Therefore, timbre exploration results into spatial trajectories. This converts a physical gesture on the object into synthesized sound with inherent spatial character.

Figure 1: A tangible score. Photo Elisa Unger.

5.2 Spatial Entanglements

As part of his ongoing PhD project *Sonic Topologies* [7], our second author presented *Spatial Entanglements*, a spatial instrument[7]. The system (figure 2) includes a mobile and lightweight structure, designed as a tensegrity and shaped as an icosahedron, supporting a 12-channel loudspeaker array. A maximum of three portable interfaces, designed following the same structural principle and shape, as tensegrities, allow the audience to perform synthesis and spatialization with a single gesture. The interfaces (figure 3) consist of spring steel bands that carry flex sensors and are held together by nylon strings. ESP32 microcontrollers placed in the centre of the shapes are used to transmit additional motion data to a host computer via OSC and WiFi. The data is analyzed by Max/Msp and fed into a granular synthesis engine.

The same motion and flex sensor data is used for spatialization with High Order Ambisonics (HOA) and object-oriented panning, rendered in the Ircam spat environment with full periphonic (3D) resolution.

Due to their design as tensegrities, the interfaces are dynamically and organically responsive objects. By turning the interfaces around their Cartesian axes while stretching or squeezing them, performers can manipulate the sonic material and the spatial motion simultaneously. Allowing novice players to improvise with the interfaces yielded astonishing results in terms of the choreographic affordances of the interfaces while experimentally exploring the instrument's possibilities. Some performers have compared the handling of the interfaces to somatic body techniques such as Qi Gong or Tai-Chi. In fact, tensegrities have often been referred to in biomechanics and physiology to describe the interplay of tension and compression elements, such as myofascia and bones, in the human body.

5.3 Phonotosphere

The Phonotosphere is a light and sound installation by the artist Boris Shershenkov[8], affiliated to our department, the Tangible Music Lab. The Phonotosphere (figure 4) combines an instrument and a loudspeaker sound sculpture arranged as a dodecahedron. This project originates from lightscape recordings, where the artist deploys a light sensor to capture illumination values in cities. Instead of aiming

[6]Videos of performances with tangible scores can be watched in the link https://tamlab.kunstuni-linz.at/projects/tangible-scores/ (accessed 6 May 2024)

[7]A video of the Spatial Entanglements system can be watched here https://vimeo.com/838339681 (accessed 6 May 2024)

[8]More information can be found in the link https://shershenkov.com/ (accessed 6 May 2024)

for slow signals, the artist focuses on recording rapid pulsating lightscapes containing oscillations (e.g. street lamps or traffic lights). These signals are adjusted in amplitude and played back as light through small lamps suspended from the sound sculpture. In the center lies a smaller-scaled dodecahedron, equipped with light-sensitive sensors at its corners, precisely mirroring the loudspeakers positions of the larger dodecahedron.

Performers can grab a lamp and point it towards the central dodecahedron, translating electricity into sound through the corresponding speaker. The closer the lamp, the louder the sound in the corresponding loudspeaker. Performers can illuminate not only one corner but also its neighbors, distributing sound among speakers and creating a richer soundscape in space. Rapid trajectories of illumination around the central dodecahedron are possible, resulting in an intuitively controlled analog sound diffusion. This process draws parallels to the light-sensing instruments created by David Behrman and Frederic Rzewski in the 1960s. With 10 lamps incorporated into the dodecahedron, many performers can play it simultaneously, transforming the sculpture and the instrument into a social space for experimenting with spatial audio.

Figure 2: Spatial Entanglements. Photo Florian Goeschke

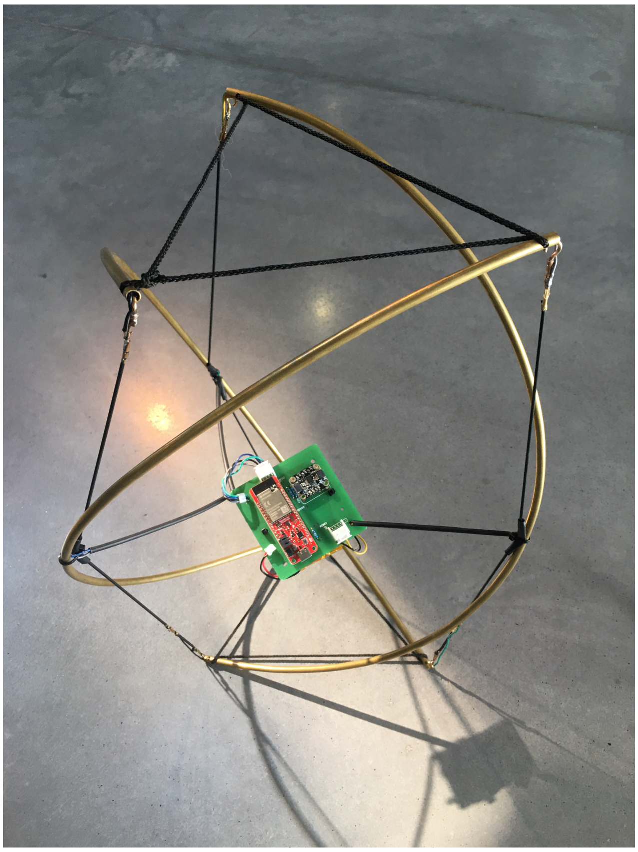

Figure 3: Controller of Spatial Entanglements. Photo Florian Goeschke

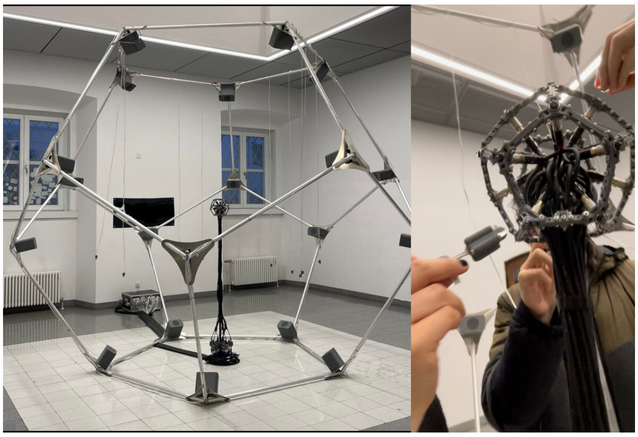

Figure 4: B. Shershenkov's Phonotosphere. Photo E. Tomás

6. CONCLUSIONS AND FUTURE WORK

In this section, we aim to summarize the key contributions of this paper:

- We have reconceptualized spatialization tools as musical instruments, challenging the traditional perspective that confines digital musical instruments to interface and synthesis components.
- Our contribution includes a user-driven classification of spatialization instruments, derived from observations of how practitioners have adapted existing tools or proposed new designs. This classification can help in understanding the motivations and challenges that musicians and designers face.
- We have introduced a number of design patterns to approach spatialization instrument design, emphasizing music's inherent spatial dimension. These patterns reframe spatialization interface design from an aesthetic viewpoint. Specifically, we advocate for embodying loudspeaker topologies into the physical affordances of instruments, and reuniting synthesis methods with spatialization.

- Finally, we advocate for transitioning towards a more user-centric, adaptable, and embodied paradigm for spatialization instrument design. As technology continues to advance, these insights can contribute to the development of more intuitive and expressive tools for artists and performers working in the realm of immersive sound.

Our future work focuses on three main areas. Firstly, we plan to develop software frameworks to facilitate the use of spatialization synthesis methods, particularly Spatial Modulation Synthesis as discussed by McGee [11], and spatialized concatenative and granular synthesis, as we described in section 5.1. These frameworks will help musicians to compose new works with these methods and explore the proposed design patterns. Additionally, we aim to conduct user studies involving composers and performers specializing in immersive audio to validate our design pattern assumptions and enhance user experience in this domain. Finally, we plan the further development of the open platform OTTOsonics to facilitate the use of loudspeaker arrays in artistic projects.

7. ETHICAL STANDARDS

This project has been entirely funded by Austrian public money through our institution, the University of Arts Linz, Tangible Music Lab, as well as through the publicly funded project OTTOsonics. The user-driven classification of instrument design strategies we have introduced in Section 3 was developed from informal observations of works presented by a number of composers and performers who visited the OTTOsonics project and the Tangible Music Lab during the last two years. These authors have been Mariam Gviniashvilli, Åke Parmerud, Amélie Nilles, Theodoros Lotis, Britt Hatzius, Ida Hiršenfelder, Polina Khatsenka, Ursula Winterauer, Rojin Sharafi, Boris Shershenkov, Robert Schwarz and Enrique Mendoza.

8. REFERENCES

[1] M. A. Baalman. Spatial composition techniques and sound spatialisation technologies. *Organised Sound*, 15(3):209–218, December 2010.

[2] N. Barrett. Spatio-musical composition strategies. *Organised Sound*, 7(3):313–323, June 2002.

[3] M. Battier. Recent discoveries in the spatial thought of early musique concrète. *Kompositionen für hörbaren Raum / Compositions for Audible Space: Die frühe elektroakustische Musik und ihre Kontexte, edited by Martha Brech and Ralph Paland, Bielefeld: transcript Verlag*, pages 123–136, 2015.

[4] M. Brech and R. Paland. *Kompositionen für hörbaren Raum / Compositions for Audible Space: Die frühe elektroakustische Musik und ihre Kontexte, edited by Martha Brech and Ralph Paland, Bielefeld: transcript Verlag.* transcript publishing, Bielefeld, 2015.

[5] I. I. Bukvic, S. Disha, and W. Joo. New interfaces for spatial musical expression. In *NIME 20: Proceedings of the International Conference on New Interfaces for Musical Expression, Birmingham, 2020*, pages 249–254, 2020.

[6] A. Einbond and D. Schwarz. Spatializing timbre with corpus-based concatenative synthesis. In *International Computer Music Conference (ICMC), Jun 2010, New York, United States.*, 2010.

[7] F. Goeschke. The ioscahedron: developing a hybrid spatialization instrument. *AM '22: Proceedings of the 17th International Audio Mostly Conference*, 2022.

[8] B. Johnson, J. Murphy, and A. Kapur. Designing gestural interfaces for live sound diffusion. In *Proceedings of the 39th international computer music conference*, pages 271–276. ICMC 2013, August 2013.

[9] B. Johnson, M. Norris, and A. Kapur. Diffusing diffusion: A history of the technological advances in spatial performance. In *Proceedings ICMC/SMC/2014*, pages 126–132. ICMC/SMC, September 2014.

[10] M. T. Marshall, J. Malloch, and M. M. Wanderley. Gesture control of sound spatialization for live musical performance. In *Gesture-Based Human-Computer Interaction and Simulation*, pages 227–238. 7th International Gesture Workshop, May 2007.

[11] R. McGee. Spatial modulation synthesis. In *In Proceedings of the International Computer Music Conference (ICMC)*, 2015.

[12] A. McLeran, C. Roads, B. L. Sturm, and J. J. Shynk. Granular sound spatialization using dictionary-based methods. In *5th Sound and Music Computing Conference (SMC2008), Berlin, Germany*, 2008.

[13] J. Mooney. *Sound diffusion systems for the live performance of electroacoustic music.* University of Sheffield, Sheffield, 2005.

[14] A. Mueller and R. Rabenstein. Physical modeling for spatial sound synthesis. In *In Proceedings of the International Conference on Digital Audio Effects (DAFx)*, 2009.

[15] A. Perez-Lopez. 3dj: A supercollider framework for real-time sound spatialization. In *21st international Conference on Auditory Display*, pages 165–172. ICAD, July 2015.

[16] N. Peters. *Sweet [Re] production: Developing sound spatialization tools for musical applications with emphasis on sweet spot and off-center perception.* McGill University, Montreal, 2010.

[17] N. Peters, G. M. andd, and S. McAdams. Current technologies and compositional practices for spatialization: A qualitative and quantitative analysis. *Computer Music Journal*, 35(1):10–27, March 2011.

[18] A. Pysiewicz and S. Weinzierl. *Instruments for Spatial Sound Control in Real Time Music Performances. A Review.* Springer Nature, Singapore, 2017.

[19] G. K. Sharma. Composing with sculptural sound phenomena in computer music. doctoral thesis. September 2016.

[20] E. B. K. Stockhausen. The concept of unity in electronic music. *Perspectives of New Music*, 1(1):39–48, September 1962.

[21] E. Tomás. Musical instruments as scores: a hybrid approach. *Proceedings of TENOR 2016, International Conference onTechnologies for Music Notation and Representation, Cambridge*, 2016.

[22] E. Tomás and M. Kaltenbrunner. Tangible scores: Shaping the inherent instrument score. *Proceedings of NIME 2014, New Interfaces for Musical Expression Conference, London*, 2014.

[23] H. von Coler and S. Weinzierl. User-defined mappings for spatial sound synthesis. In *Proceedings of the International Conference on New Interfaces for Musical Expression*, pages 464–469, 2020.