Preprint draft from 2015

Algorithmic Spatialisation

> "We must stress an important distinction concerning [the] spatial dimension in acousmatic art. The 'internal space' is formed within the work itself, made of reflections of the sonic contours, of the movement of entities, presenting itself to the hearing as a sensation of composed volume. To this we contrast 'external space', with completely different effects, no longer concerned with the work but with the configuration of the space wherein it is heard, with its particular peculiarities (often undesirable or from time to time exploited)." (Bayle 2007, 243)

This article approaches sound spatialisation in musical practices that use algorithms as process and structure generators. The topic presents some complexity because we are dealing not just with a single domain but with a number of intertwined layers that are situated between acoustics and perception, between architectural spaces (Blesser and Salter 2007) and the sound-events situated therein. In addition, the practice of spatial audio is a wide-ranging one: it begins for example with a recording engineer's concern with reproducing the sound stage, continues with 'acousmatic' and electro-acoustic multi-channel compositions, and finally includes artistic applications in games and installations that construct artificial sound-spaces. Algorithms as a source of structure or process may only be used within a limited number of these activities but the implications in these contexts of using spatial audio processes remain critical.

This chapter attempts to give a very brief historical summary as well as an overview over perceptual and technical issues of spatial audio and music, then discusses the use of algorithms as compositional and performance tools for spatialised sound, in order to finally look at the difficulties and pitfalls of spatialisation.

With this sequence we hope to provide the anchor-points necessary to explore the question of how to fruitfully use algorithms for audio spatialisation and spatial music.

One of the central, yet sometimes ignored aspects of electro-acoustic and electronic music is that it needs to be heard in an actual space through loudspeakers or be delivered to our ears through headphones. Although the dominant mode of playback of music in everyday situations remains the stereo field (and 5.1 the new standard for films), to use two speakers in order to mirror our two ears is by no means compulsory. Since the beginnings of electrically amplified music the number of speakers used for spatial (re-)constitution has been one of the aspects experimented with. With the advent of electronics the number of channels used has increased, going from one to an arbitrary number. All of these arrangements attempt to mitigate the fact that the inherent spatial and enveloping quality of sound in the lived world collapses into 'flat' representations through loudspeakers, which need to be read/heard as if they were a two-dimensional image. Recording, encoding and diffusion techniques have evolved sufficiently in tandem with the acquisition of listening skills in particular for recognising acoustic spaces, in order for the illusion of spatial sound to become credible in many musical and acoustic situations. Nevertheless, the suspension of disbelief remains a necessary pre-condition for this effect to work.

In many musical practices the spatial disposition and in particular room acoustics have always played a role, but in a circumstantial rather than deliberate fashion, often dictated by the acoustical spaces where the music was performed. In recorded music for instance, with the aforementioned limitations, the notion of sound-stage has been used extensively to emphasise instrumental relationships, for example between the instruments of a band and the singer, the different instruments of an orchestra, in cinema between the dialogue, the music and the sound-scape within which the narrative is located, or in electronic music between sound and artificial reverberation. These practises can be called spatialised audio, but not necessarily spatialised music, since they deal with the space in an auxiliary manner, not as a core-element of musical composition work. Nonetheless, the technical developments made by sound-engineers for music recording and film-sound (nowadays blending over into video-game sound) are a big contributing factor to the increased focus on space as musical dimension in electro-acoustic and electronic music.

The availability of multi-channel diffusion systems beyond stereo has led to a musical appropriation not just with the goal of perfectly simulating the way the natural world sounds but in order to use space and its attributes as an additional musical dimension to compose with. The convergence of techniques for dealing with the two complementary aspects of sound can be observed in both fields of spatial audio and music, in surround audio's use in video-games as well as in the newly invigorated virtual reality field. Spatialisation means to work on the one hand with acoustic spaces or rooms, which are perceived both via direct and reverberant cues (Bregman 1994), through inter-aural time- and level-differences as well as spectral filtering due to the interaction of the sound waves with our head's and ears' morphology. And on the other hand it means to work with sound-scenes and object-based scene (re-)construction methods, which enable, through symbolic operations and a modelling approach, the generation of synthetic spatial audio.

Spatial sound concepts

Sound spaces and spatial sound diffusion are central topics of 'acousmatic' music, electro-acoustic music and composed 20th century contemporary music, as seen for example in early works by Charles Ives (Cowell and Cowell 1969), Edgar Varèse (Varèse 1966), or in Xenakis' 'Polytopes' (Serken 2001), and in the spatial distribution of orchestral groups in Stockhausen's 'Kontakte' (Stockhausen 1995), Boulez' 'Répons' (Boulez and Damiens 1998) and Luigi Nono's 'Prometeo' (Oehlschlägel 1985). "In these traditions, the localisation of sounding physical and perceptual space, as well as the creation of senses of virtual space and sonic spatial movement and evolution both between and within sound-objects (Chowning 1977), are harnessed to aesthetic ends either as part of the desired musical effect or as a primary element in compositional imagination. Like 'pitch space' formalism, this ... discourse of space prominent in electro-acoustic and computer music invokes notions of spatial and musical autonomy." (Born 2013, 11-12)

In addition to compositional musical work using sounds in space, the development of the sound-scape perspective of acoustic ecology in the 1970's (Schafer 1993) had a profound impact not just on sound-art (Neuhaus 2000) but also electro-acoustic music (Truax 1999; Westerkamp 2002). Converging with this development are the compositional processes of the stochastic synthesis methods defined by Xenakis 1992 and the expanded sonic possibilities in different time domains that constitute what is now known as granular synthesis (Roads 2001). Despite the rise of a spatial audio diffusion practice since the 1970's, proper formalisation has only been achieved in recent years. The categorisations of sound types, as proposed by Lachenmann for contemporary music (Lachenmann 1966), can be seen as a complement to Schaeffer's 'objets sonores' (Schaeffer 1966). Ihde's phenomenology of listening (Ihde 1976) in turn provides the foundations for Smalley's understanding of sound-shapes (spectromorphology) (Smalley 1997), which finally lead to the concepts of sound-spaces (spatiomorphology), which are essential for a spatialised music practice (Smalley 2007) (see Born (2013) for a more comprehensive overview).

The spatial concepts offered by Smalley range from the gestural, the ensemble, and the arena spaces, to the proximate and distal spaces that generate the listening perspective by defining the fore-, the mid- and the background, to the social perspectives of the intimate, the personal, the social, and public spaces (Hall 1966). Particularly interesting is Smalley's statement that "sounds in general, and source-bonded sounds in particular, ... carry their space with them – they are space-bearers. ... Source-bonded spaces are significant in the context of any acousmatic musical work ... in musical contexts where I imagine or even invent possible source bonds based on my interpretation of behavioural space." (Smalley 2007, 38) The multimodal entwinement of these spaces leads to a perception of the aesthetic configurations of the music through the 'enactive' capabilities provided by our sensori-motor skills (Gallagher 2005) and through "underlying spatial attributes: texture has space, gesture operates in spaces integrated into the gestural task, cultural and natural scenes are spatial, the highs and lows and motions of sound spectra evoke space. But sense experiences are also rooted in the physical and spatial entity of the human body, which is always at the focal centre of perception – as utterer, initiator and gestural agent, peripatetic participant, observer and auditor." (Smalley 2007, 39)

Milestones of Spatialisation

A look into the past permits us to examine concepts, technical achievements, and milestone applications of spatial audio and music in order to better understand current practices.

Spatialisation or spatial sound diffusion with any practicality became feasible in the late 1950's and 1960's and was tied to the development of more sophisticated electronics, mainly through the advent of magnetic tape machines and ultimately the development of semiconductors. Earlier applications were tied to sound-scene transmissions via telephone-lines (Rumsey 2001, 10).

One of the first examples of a large channel-count sound diffusion system was Edgard Varèse's 'Poème électronique' in the 1958 Brussels world fair. Here, within the parabolic architecture of the Phillips Pavilion designed by Xenakis, the Phillips-built multichannel sound diffusion system complemented the architectural space and visual projections (Zouhar et al. 2005). In 1959 electronic music pioneer Karlheinz Stockhausen developed the rotation table, a mechanical device used to generate rotating sounds (Braasch et al. 2008). A decade later, he presented a spherical auditorium in the German pavilion of the Osaka world fair in 1970 with 50 speakers surrounding the space in vertically arranged layers. The audience was seated on a lattice floor in the median plane of the sphere, the conductor was placed at the centre and ensemble positions were dispersed around the space (Stockhausen et al. 1978).[1] In 1971, the 'Experimentalstudio' of the German Südwestrundfunk, which was and still is in charge of performing live-electronics for Luigi Nono's pieces, developed the 'Halaphon', a controllable signal matrix used for spatial sound diffusion (Parra Cancino 2014, 39). In 1974 François Bayle designed the 'Acousmonium', an 80 speaker 'orchestra' located at the french radio's research laboratory 'Groupe de Recherche Musicale' GRM, which is still in use today (Bayle 2007).

In San Francisco, a historical multichannel sound diffusion theatre called the 'Audium' exists in a dedicated space and has been in operation since 1967 (Shaff 2014). More recent multi-channel musical spaces are located in Karlsruhe with ZKM's 'Klangdom'

(Brümmer et al. 2014), at UC Santa Barbara with the 'Allosphere' (Amatriain et al. 2007), in Belfast's QUB with SARC's sonic laboratory space[2], a.o. (for a survey of these spaces, please refer to Normandeau (2009)). In Paris at IRCAM the 'Espace de Projection' concert hall provides varying spatial modes through movable panels that can modulate the room acoustics, and is equipped with a hemispherical speaker-dome that is combined with a large wave-field synthesis array (Noisternig et al. 2012), in Graz the IEM-Cube (Zmoelnig et al. 2003) and the 'Mumuth' concert hall provide regular and irregular multi-channel speaker arrays and dedicated spaces for spatial audio (Eckel 2011). There are wave-field synthesis arrays at the Technical University in Delft in the Netherlands (Boone and Verheijen 1993), where this technique originated, at the Technical University in Berlin (Baalman 2010), as well as at an increasing number of venues worldwide.

Principles of Spatialisation

Spatialisation could be defined as the act of placing sounds in a – both virtual *and* real – acoustic space or room, or the act of creating, extending and/or manipulating a sound space. The process therefore needs to deal with the spatial attributes of sound sources, but also with the acoustical properties of the space itself. Some practices focus exclusively on the former, building on the notion of an abstract sound-scene that is populated by sound objects, while others focus mainly on the latter, modelling the perceived acoustic properties that carry the spatiality of the sounds. In any practical musical situation, both domains need to be taken into account.

In the 'acousmatic' practice of speaker orchestras, the sounds are routed directly to actual speakers distributed in space, either as single source channels or grouped in so-called "stems [that] constitute the submixes or – more generally speaking – discretely controllable elements which mastering engineers use to create their final mixes." (Wilson and Harrison 2010) The speakers can have different sonic qualities, thereby influencing the colouring of the diffusion; they are given the role of different instruments in an orchestra. This channel-based placement is also the technical method of cinema surround sound, where the content, in particular the dialogue, is routed to a dedicated speaker. Only with the recent advent of object-based audio in systems such as 'Dolby Atmos' (Dolby 2012) has this mode of operation been extended.

Object-based or abstract sound placement methods can be considered to simulate a sound-scene. These simulation methods are built on the premise that all the elements of an acoustic scene can be constructed one by one, and that by assembling the abstract elements, a convincing acoustical space can be generated. We will see that this is not always the case, since by working with sound-objects in an abstract space, a geometric mode of thinking is emphasised whose visual paradigm doesn't always translate to perceivable auditory results (Couprie 2004).

Sound-objects in a sound-scene are conceptually independent from the specifics of the audio reproduction system. They are modelled first in the abstract space before being rendered into the concrete venue. As soon as a sound-source needs to be placed at a location that falls *between* the diffusing speakers, the term phantom imaging (Lennox 2009, 261) or virtual source is used. In the simplest case this involves panning a source between a stereo pair (pairwise panning) but this can be extended to an arbitrary number of speakers and even pass through a simulation of an entire wave-front of a sound, as is the case in Ambisonics or Wave-Field-Synthesis.

Sources in sound-scenes have geometric properties such as position, orientation, and size. They are often considered as mere points in space, sometimes with added spatial extension. Sources in a scene also have acoustic qualities and spatial attributes such as directivity or diffusion pattern, i.e., the way sound is projected into space, for example the narrow sound-beam exiting the bell of a trumpet versus the diffuse sound-waves originating from the drum-heads of the timpani. Sound objects in a scene are also subjected to the acoustical properties of space. These affect spatial perception and are modelled using acoustic cues such as distance attenuation (falloff of sound intensity with increasing distance), spectral air absorption with distance (high-frequency components of sounds are filtered by air-moisture), doppler shifts of moving sound sources (pitch changes due to compression or dilation of sound-waves when moving towards or away from the listener) and reflections from elements in the sound-scene such as walls.

In addition to these source-bound properties, certain spatialisation processes introduce additional cues that reconstruct either psychoacoustic effects such as inter-aural time-difference, pressure difference and filtering effects by the anatomy of the head, or other processes that add global spatial effects such as reverberation, components of which might be localised or which might reconstitute the acoustics of an actual space by convolving an impulse response obtained in a real space, or might reconstruct the field of the sound-wave as it existed in real acoustics.

An entirely different mode of musical thinking with spatiality of sound is the deconstruction or combination of sounds in an artificial manner, which doesn't intend to simulate an existing sounding space. The aim of these techniques is to generate different senses of envelopment and engulfment of the listener (Paine et al. 2007; Lynch and Sazdov 2011). Through blending or fragmentation (decorrelation) of sound-elements spatial effects are generated that have no correspondence in the natural world. This can occur in the temporal, spectral or spatial domains. In the temporal domain the construction of auditory cues is manipulated by placing events close together on the temporal threshold of the auditory system. In the spectral domain the spatial coherence of a sound gets extended or suppressed by splitting and displacing frequency components of the sound (Parry 2014). In the spatial domain sounds can be spread across groups of speakers, usually combined with some manipulation of the signal such as filtering. The listener's auditory processes provide the basis for this creative play with the boundaries of perception. More subtle processes that fall into this category are also applied when manipulating spatial properties of sounds via traditional sound-engineering techniques such signal matrixing.

Many electro-acoustic composition and diffusion practices involve the use of techniques that deal with the distribution of pre-produced sound-elements on speaker arrays (Wilson and Harrison 2010) through a variety of compositional principles (Lyon 2008).

Since these sound-groups carry their own spatial imagery (Kendall 2010), even through metaphorical connections (Bayle 2007), overlaying these sub-spaces and combining their gestural presence generates a different sense of spatiality and tangibility (Barrett 2015).

Spatialisation Algorithms

There are two meanings of the term 'algorithm' that need to be distinguished in a discussion about algorithmic spatialisation.

The first is applied to mathematical formulas that process and synthesise those audio signals that carry spatial information to the listener's ears. They are called spatialisation algorithms or in analogy with computer-graphics spatial audio *rendering* algorithms.

The second meaning is used to denote rule-based operations that generate structure from (sometimes) symbolic elements. These algorithms are used in compositional operations with elements that are part of an abstract sound scene or a symbolic space.

This separation is not always strictly enforceable, in some rendering processes there are parameters that can also serve for symbolic operations (see Fig. 1, processing layers 3 and 4).

Within the first category, the 'rendering' algorithms sometimes represent mere multichannel panning processes but at other times involve many layers of sound processing in order to generate the acoustic and psycho-acoustic cues necessary for convincingly simulating spatialised audio. Commonly used rendering algorithms are Vector Base Amplitude Panning VBAP (Pulkki 1997) and derived from that Distance Based Amplitude Panning DBAP (Lossius et al. 2009), the more complex and powerful Ambisonics (Gerzon 1985) and Higher Order Ambisonics (Daniel 2000), Wave Field Synthesis WFS (Berkhout et al. 1993), the virtual microphone techniques ViMiC (Braasch 2005) and binaural rendering (for headphones) (Bedini 1985; Noisternig et al. 2003). Each one of these audio processing algorithms offers specific controls over the spatiality of sound. Some of the controls of these signal processing methods may even become part of a composition system's parameter space, for example the spread factor offered by VBAP that changes apparent source-width, or the order factor used in Ambisonics that describes the angular resolution of the sound image.

In a blending of the two paradigms, spatialisation needn't only be concerned with objects in a sound-scene, it could equally be dealing with creating sound-spaces in general with a mix of acoustic elements coming for example from field-recordings or artificial spaces. To some extent all (electro-acoustic) music inherently takes the spatial effect of its sound elements into account since there is no dissociation possible between the sound-space and the sound-image (Bayle 1993; Kendall 2010).

In general, the topic of using sonic environments is a less explored area of electro-acoustic composition and by extension of musical forms developed with algorithms. In most spatial audio practices the acoustical properties of a chosen space are configured once and left static for the duration of the piece and the performance. We will present a few examples where the configuration of the acoustic spaces themselves become compositional operations, and are done with the aid of algorithms.

When working with spatialisation the first task is to decide which dimension of spatial sound, audio, or music generates the material for the compositional operations and/or provides the core elements of the musician's activity.

Spatialisation Process Layers and Domains

When looking at a workflow for spatialisation (Peters et al. 2009) making the following subdivisions can help to distinguish the domains we operate in and the types of representations and dimensions that are in play (see Fig. 1). The technical processing layers represent necessary steps of a workflow; a different category of a data flows from one layer to the next, and each layer contains conceptually similar and unique classes of functionalities. These provide "services to the layer above it and receive services from the layer below it." (Peters et al. 2009)

[**Place Fig. 1 approximately here.**]

- The Authoring Layer: This layer contains all software tools for the end-user to create spatial audio content without the need to directly control underlying audio processes.
- The Scene Description Layer: This layer mediates between the Authoring Layer above and the Decoding Layer below through an abstract and independent description of the spatial scene.
- The Encoding Layer: Here the source-signals are encoded acoustically for the first time. Some spatialisation algorithms process the encoding and decoding in one step, whereas other implement it in two or more steps. All the perceptually relevant sound cues are encoded here.
- The Decoding Layer: In this layer the sounds are assembled into a coherent virtual acoustical sound-space or scene. In this step additional acoustics modelling and simulation is applied to the source sounds.
- The Hardware Abstraction Layer is located with the operating system's audio-drivers.
- The Physical Devices are the speakers needed to make an audio-signal audible in a physical space.

Juxtaposing this technical model with the operations done in the compositional domain can help to clarify how these operations are related to each-other. This is particularly relevant when reflecting on the distinction between operations that modify a sound-scene and those that modify the acoustic space. The two main sections differentiate between symbolic operations in an abstract (parameter) space applied to discrete properties of abstract sound-objects, and signal operations directly affecting the acoustic qualities and properties of the sounds that will be projected and heard. As with all categorisations, there are exceptions that straddle the divide as we will discuss further on with regard to spectral operations.

Authoring processes deal with placements, movements and groupings, as well as with time-organisation of the scene. The processes themselves are embedded in the algorithms that are used to shape the evolution of sound-objects over time within the sound-scene. The scene-model is an abstract representation of a space evolving over time. This space can maintain its state as a container for spatial audio operation, but can also become the object of operations itself (Wozniewski et al. 2007).

Acoustic space simulation deals with all the processing necessary to produce the audio-signals that we will hear as containing spatial audio. This includes positioning a source around the listening position, giving it distance cues, movement cues and directivity cues, in short, constructing all the necessary auditory cues for the perceptual encoding of a source in space. In addition the processes may include the acoustical modelling of a space, for example by simulating the reflections a sound source would produce in an architectural space.

Finally, working with the physical devices themselves i.e., working with the speakers, is a necessary part of controlling the effect of the actual physical space on the simulated acoustical space that is being projected. In some practices this is leveraged for interesting creative effects, e.g., in 'acousmatic' interpretations on a speaker orchestra, whereas in other settings the influence of the actual space is eliminated as much as possible in order to obtain as 'pure' a simulation of a virtual space as possible (this is of course only really possible in anechoic conditions).

Storage and Transmission

One of the challenges of working with spatialised audio is the storage and transmission of pieces, and in particular of in-progress and non-fixed sound compositions. Traditionally, an 'acousmatic' composition is either stored as a rendered version for a dedicated speaker-setting (an 8-channel circle, a 5.1 mix for DVD etc.) or, the same way as work in progress, the components of the composition are stored individually. The spatial placements, transformations and manipulations that constitute the piece are stored in the session formats of the DAW software that was used, and as sound-files containing single tracks or stems (grouped tracks). However, storing a sound-scene and all its constituting elements so that all the relevant aspects remain editable is only beginning to be possible in commercial environments (e.g., Dolby-Atmos, MPEG-H) and still represents an important hurdle in a composer's workflow. Several initiatives have tackled this issue in the past, including standards-bodies such as the MPEG group (Scheirer et al. 1999), the production format "Audio Definition Model" endorsed by the EBU (2014), and software projects intended to generate a unified framework for audio-spatialisation (Geier et al. 2010).

The SpatDIF project group, of which the author forms part, approaches this task in a pragmatic manner by defining and implementing the Spatial Sound Description Interchange Format. "SpatDIF provides a semantic and syntactic specification for storing and transmitting spatial audio scene descriptions ... a simple, minimal, and extensible format as well as best-practice implementations." (Peters et al. 2013) In this syntax, the sound-scene and its embedded entities are described by descriptors that represent as many relevant properties as necessary in order to describe and at a later stage reconstruct the scene. The descriptors with their values are stored in human readable form in text-files or transmitted in network packets for realtime applications and joined with the sound files or streams that make up the content of the work. In the SpatDIF concept the authoring and the rendering of spatial scenes may occur at separate times and places using tools whose capabilities are unknown. It is a syntax rather than a programming interface or file format and can therefore be represented in any of the structured mark-up languages or message systems that are in use today or in the future.

In addition to specifying the syntax and format, the SpatDIF group is developing reference implementations that show best-use applications, and also provides a software library for easy integration in various audio software (Miyama et al. 2013). This library has been embedded in code-plugins (externals) for the MaxMSP and Pure Data environments, and is currently being integrated into a new version of the 'Zirkonium' software (Wagner et al. 2014), providing it with SpatDIF import and export capabilities and opening up possibilities of interchanging compositions between different software environments and venues.

Spatialising with Algorithms

Spatialisation as defined earlier deals with placing sounds in an acoustic space and/or creating and modifying such a space. Evidently algorithmic spatialisation does this by using rule-based processes. Selecting which of the elements are generated, controlled or transformed between the abstract sound-scene and the simulated room determines which algorithmic operations are possible. Since algorithms in this context are defined as being rule-based processes organising elements and structures of a musical work, in the case of composition, or as processes that directly affect the timbral, temporal and spatial qualities of the music, those two domains need first to be considered separately before we can find overarching processes that affect both simultaneously.

Point Sources

As discussed earlier, the objects in a sound-scene as well as the scene-defining acoustic elements possess various parameters useful for creating musical work. The most immediate and spatially most intuitive aspects of the objects are their locations and displacements in space. Algorithms for generating, controlling and transforming the movement trajectories are quite common and are closely related to traditional panning automations. Beginning with the earliest multichannel works based on computational processes, working with point sources and transforming their geometrical as well as acoustical properties has become the most common way of composing and transforming a sound scene.

The 1972 composition ‘Turenas’ by Chowning (1977) created at Stanford’s nascent ‘Center for Computer Research in Music and Acoustics’ CCRMA is a four channel piece that for the first time simulated several aspects of spatial sound diffusion beyond source-panning, such as doppler, reverb, and air-absorption. ‘Turenas’ represents an important step in the context of algorithmic thinking, since the source movements are derived from mathematical functions rather than subjective drawings or placements, and the model for connecting the perceptual and the compositional aspects are highly formalised (Chowning 2011). In this piece Lissajous formulas serve as algorithms that describe source movements, resulting in expressive trajectories (see top left of Fig. 2).

[**Place Fig. 2 approximately here.**]

Composing by choreographing sounds with geometric shapes and trajectories within the frame of space is further explored conceptually by Wishart (1996). He proposes an entire typology of movements oriented in the space around the listener. The spatial movements constitute (musical) gestures, and he investigates how the spatial motion of sound object relate to each other in what he calls ‘spatial counterpoint’ and how these “gestures can be used independently of other musical parameters or in a way which reinforced, contradicted or complemented other gestural features of the sound-object.” (195) The frame of reference formed by the listener enables the distinction between purely geometric and symmetrical spatial forms, orientations, and directions, which are biased by psychological and aesthetic aspects of spatial perception. Sounds are heard, for instance, most clearly when we turn our face towards them, which emphasises frontal positions, whereas a unidentifiable sound originating from a rear direction may have, for evolutionary reasons, a threatening or frightening effect. In his typology Wishart only considers continuous motion paths in two dimensions. His catalogue enumerates many direct paths: centre crossing straight lines, edge hugging straight lines, centre-crossing arc movements, forward or backward moving diagonal paths, centre-hugging diagonal paths, movements towards and away from the centre. For circular motions he distinguishes between cyclical (repeated), central or eccentric circular motion, spiral paths, figure-of-eight and s-curves. By combining and overlaying these shapes, various zig-zags and looping movements arise that exhibit progressing movement patterns through space and that range from oscillatory rotating loops to cloverleaf and butterfly pathways. Further elements are localised and unlocalised irregular motions generated by random or brownian processes, as implemented for example in the ICST's 'ambicontrol' methods (Schacher and Kocher 2006), that can be centre-bound or corner-bound and offer the possibility to be overlaid and combined into compound paths. For defining the behaviour of a motion in time as well as space, Wishart adds time-contours that define speed, acceleration and deceleration, and which generate perceptual forms that transport 'intent' or physical behaviour such as elastic, bouncing or throwing movements. These behaviours give rise to the perception of a sound-object's material properties or the type of handling by an (unseen) agent. He emphasises how changing the time-contours of a given spatial gesture can influence the aesthetic impact of a spatial motion. Of course all of the principles described by Wishart can be generated, controlled and transformed through algorithmic processes (See the bottom row of Fig. 2 for three examples of looping movements generated by applying different spline formulas).[3]

There are research projects developing terminologies, methods, and tools for the *notation* of spatial sound aspects. Thoresen's analysis of Schaeffer's sound objects (Thoresen and Hedman 2007) as well as the sound patterns and form-building patterns both in the temporal and spatial dimensions he categorises (Thoresen 2010), have led to an extension to GRM's 'acousmatic' music notation software, the 'Acousmographe' (Geslin and Lefevre 2004). The 'Spatialisation Symbolic Music Notation' project at ICST in Zurich also works towards defining a standard taxonomy of spatial motions (Ellberger and Perez 2013) and a set of trajectory 'gestalts' that are applicable both to sound sources and room-aspects, with the goal of representing them as symbols in standard music notation (Ellberger et al. 2014). In these systems the taxonomies of shapes, patterns and relations, and semantic organisation of discrete sound elements serve to identify those elements as compositional material that are equivalent to other musical parameters (in a mode of post-serialist compositional thinking).

Source Clusters

The method of dealing with discrete 'sound-pixels' in an abstract sound-scene is extended when working with clusters of sound elements, or 'ensembles' (Rumsey 2002). These sometimes large groups of objects follow general rules and might appear as more or less diffuse sound objects in the sonic space. Granular synthesis techniques are particularly apt for spatial distribution of large numbers of objects, where each grain potentially occupies a different location in space and form together a sound-mass that can occupy a sector or the entire sound-space (Wilson 2008).

A combination of these techniques with generative principles, for example by giving each cluster-element emergent spatial behaviours by using flocking concepts such as the perennial 'Boids' algorithm (Reynolds 1987), provides a higher level of handling the entities forming the cluster (Kim-Boyle 2006). These agent-based systems, thanks to their self-organisational properties, permit the generation of complex group or cluster behaviours with a reduced number of semantically relevant parameters. In the case of a 'Boids' flock, for example, moving the attractor-point will manoeuvre the entire cluster in a loose cloud whose spatial extension is controlled by the shared cohesion parameter. These agent-based algorithms represent a special case of control algorithms, by offering dynamic, self-organised domain-translations that are useful for spatialisation as *direct parameter mapping* since the agents can be modelled as objects in Euclidian space and their location therefore directly translated to spatialisation source-positions (Schacher et al. 2014, 52).

More generic algorithmic models can generate complex behaviours as well, even in interactive settings, for example through the use of hierarchical, nested swarms controlling both visual and sonic surround renderings (see Fig. 3) (Schacher et al. 2011) or the implementation of rules that operate not in the spatial domain but rather on the object's physical attributes, for example on spring forces, mass or damping parameters in physical models (Bisig et al. 2011).

[**Place Fig. 3 approximately here.**]

Particle systems provide a similar type of high-level cluster control for the dynamic distribution of large numbers of point sources with a few control parameters, in this case exerted as force-fields on particles. "One of the attractive qualities of particle systems is their ability to model or visually mimic natural phenomena." (Kim-Boyle 2005) Simulating natural phenomena within such a system generates emergent properties for clusters of sound-objects, for example by implementing spatial evasion through sensing of the proximity of another particle or by exerting forces along directional lines, thus orienting the movements of the objects.

An example of the combination of a traditional synthesis technique with a dynamic spatialisation is shown by Schumacher and Bresson (2010) in their "spatial additive synthesis: (a) a harmonic spectrum is generated ... and additional partials (micro-clusters) added around each harmonic; (b) a set of envelopes is used to control both sound synthesis and spatialisation parameters; (c) two manually defined ... trajectories are interpolated over the number of partials. Each partial is assigned an individual trajectory." A similar method by Topper et al. (2002) describes a separation process for spatialisation purposes as "taking an existing synthesis algorithm and breaking it apart into logical components" and then "[assembling] the components by applying spatialisation algorithms." In this application the method consists of "separating the modes or filter the output of a physical model and applying individual spatial processing on each component."

Spatial Spectral (De-)Composition

These decomposition techniques are also applicable to the spectral or timbral domain of (re-)synthesised sound. Different ways of cutting up the spectrum of a sound and spreading these components in the sound-space exist. By fragmenting the sound spectra amongst a network of speakers "the entire spectrum of a sound is recombined only virtually in the space of the concert hall. ... It is not a conception of space that is added at the end of the composition process ... but a truly composed spatialisation." (Normandeau 2009, 278)

Changing the temporal as well as the spatial location of fragments of a sound's spectrum further de-correlates it and leads to a different type of diffusion within the acoustic space. "Delaying the resynthesis of individual FFT bins of a short-time Fourier transform can create musical effects not obtainable with traditional types of delays. When those delays are applied to sounds reproduced through the individual channels of a multi-channel playback system, unique spatialization effects across spectral bands can be realized." (Kim-Boyle 2008)

This 'spectral splitting' as a decorrelation technique can also occur involuntarily when using non-homogenous speakers that emphasise certain frequencies and thus distribute the spectrum unevenly across a speaker-array's sound-space. Combining this effect with granulation approaches that determine routing in relation to the input amplitude or spectral characteristics has the potential to create an expanded perceived spatial size of the cluster, for example by spreading "from the front to the back of the space as the amplitude increases" (Wilson and Harrison 2010).

Manipulating Sound-Spaces

A different and subtle way of changing the timbre of sounds throughout the acoustic space is using different room-simulations for individual stems that are then overlaid and assigned to different sectors of the space. These artificial acoustic situations can suggest a volume of space through implied spatial occupation (Barrett 2002). Further creative use of spatial zones, as implemented for example with the virtual microphone techniques ViMiC might not even cover an entire venue homogeneously, but use overlapping virtual acoustic spaces in different parts of the physical space, thus leveraging the effect of the real acoustics to generate a hybrid spatiality (Peters et al. 2011, 180)

Similar concepts can be explored by employing rendering processes that do not necessarily generate a unified sound-field. In these processes stems can be assigned to sub-spaces or speaker-groups in what is effectively a hybrid between 'acousmatic' interpretation in the style of the 'Acousmonium' and signal-processing-based multi-channel diffusion methods. Using DBAP (Lossius et al. 2009) for example, in particular by using speaker-sub-sets and partial groups, non-realistic representations of distributed sounds can be created. In this pragmatic approach the perception of sound-*placements* and the local activities of sonic elements, rather than of *trajectories* provides the central characteristic (Baltazar and Habbestad 2010).

The Ambisonics spatialisation processes offer yet another way of algorithmically manipulating virtual acoustic space. In this concept all sound-events are first encoded into an intermediate abstract sound-space – the B-format stream – which consists of the spherical harmonics of a sonic wave-field that covers the full 'periphonic' space, i.e., the entire three-dimensional sphere around the listener. This technique originates from a microphone technology that is used to record a full 3D sound-field, but the mathematics of this process have subsequently been implemented for virtual sound encoding and decoding as well. Ambisonics enables the placement of sound-objects in the 'periphonic' space (on the unit sphere), but more interestingly permits the manipulation of the sound-field itself (Lossius and Anderson 2014). By changing aspects of the algorithm and introducing transformation of the signals within the intermediate B-format domain, manipulations such as zooming in, pushing out, emphasising and rotating the entire sound-field become possible (see Fig. 4).

[**Place Fig. 4 approximately here.**]

Spatialisation in Live-situations

Manipulating spatial audio distribution in real-time during live-performance poses a few unique problems. To begin with, the musician's listening position is not always centred, and therefore does not always provide the ideal sound image. In 'acousmatic' concerts with surround-sound the mixing-desk position will be centred in the hall to avoid this problem. In a frontal performance situation however, surround monitoring is necessary to provide the performer with the same spatial perception as the audience. Replacing this by pre-listening over headphones is difficult, unless an additional binaural simulation is implemented in the monitoring paths.

Controlling spatial distribution of a large number of sound-sources in real-time (with or without the aid of algorithms) demands a representation of parametric controls that can be understood and handled directly. The challenge and limitation of parametrically controlling a large number of sound-sources in real-time is one of the reasons for using higher-level algorithms for control. A mapping strategy that implements one-to-many connections (Arfib et al. 2002) represents the first type of algorithmic control structure. For live situations, higher-level abstracted controls need to be implemented that can be manipulated with lower dimensional controls; be it directly on single-dimension controllers such a faders, or on compound controllers that encapsulate spatial information such as joy-sticks or camera-based gesture recognition systems. Algorithms that contain autonomous, independent components and provide high level control such as agent or particle systems are particularly suited for real-time control. But any algorithm that is capable of being manipulated through a few variables works. By overlaying several dimensions of control, for example by combining spatial and temporal control variables, e.g., in granular or spectral processes, the overall 'gestalt' of the sounds can be performed with relatively few interactive controls.

This applies to studio and off-line processes as well. When composing with algorithms that shape any aspect of a sound-scene, be it through placements and trajectories, clustering, and spectral and temporal processes, the composer needs simple methods to interact with rule-based processes in order to judge the results. The principal difference is that these processes can be repeated, layered and edited in ways which are not possible during performance.

Depending on the context, be it an electro-acoustic concert, a live-coding session, a theatre production with real-time sound processing, or a gestural performance (Schacher 2007) in a club or festival, a strategy needs to be devised to maintain expressive control over the spatialisation without getting overwhelmed by the complexity of the spatial and algorithmic processes.

'Impacts' – an interactive algorithmic composition

In order to show how some of the aspects described above can be applied in practice, an interactive and algorithmic composition provides us with an example. The musical and visual composition 'Impacts' forms part of the 'Flowspace' installation (Schacher et al. 2011). Within a dodecahedral frame the sound is spatialised on twenty speakers that sit in its corners. The upper faces of the four metre platonic solid serve as rear-projection screens for the real-time graphics, and a touch-sensitive surface provides the interaction modality to the visitor (See Fig. 3).

The algorithms at the heart of this piece explore hierarchical relationships between three flocks, and represent their interdependence within the ecosystem of the piece. Three types of entities are present in an abstract algorithmic domain: the first are attractor 'touch' points that are controlled by the visitor's actions; the second are agents in a flock and react to the attraction forces of the 'touch' agents as well as those of their own kind; the third flock is subjected to the forces exerted by the second swarm and those of its own peers. The behaviours of the agents within the second and third swarms are based on the classic attraction, evasion, alignment paradigm (Reynolds 1987), and are parameterised to create dynamic motion patterns.

In a next step, perceptually significant events are extracted from the continuous motions of flocking agents in order to provide key impulses for the music. The impacts or (near)-collisions between agents are treated as expressive events in the scene that trigger the musical events. In contrast, reaching the farthest points on the escape trajectory from the point of impact triggers a second type of event. The collision events trigger piano samples on impact and granular echoes of the same pitches at the escape points, and thus constitute the musical 'gestalt' of the composition.

A simple state machine tracks the level of engagement of the visitor and controls the choice of pitches accordingly: the higher the level of interaction, the fuller and more dissonant the pitch-sets will be. These sets are divided into eight groups, one for each agent in the primary 'touch' flock. The secondary swarm activates the lower register notes on impact whereas the third swarm initiates the higher pitches at the escape points. Being repeatedly triggered during the escape trajectory, the expanding granular 'shadows' engender a noticeable perceptual widening of the pitch- and surround-space. Since the note-events are spatialised according to the geometrical positions of agents, the swarm clusters are perceivable as note-clusters in different sectors of the surround field. Vertically, the spatial positions of the swarm agents are stretched onto the surround sphere in order to make height perception more evident.

The mixture of all of these elements, arising from the dynamics of events that the agents encounter, generates the sonic texture which is characteristic of this piece. The ebb and flow of density found in the musical domain reflects the state of the underlying model, and even if no global control is applied to the sound producing algorithms directly, the way visitor interactions propagate through the layers of algorithms influences the overall musical result.

A third principal element of the piece, the real-time graphic visualisation, re-interprets the idea of impacts and escape points by connecting points into dynamically changing and triangulated 'Delaunay' meshes, and by triggering concentric, rippling circles for each of these events. The graphical language works with rules of its own that affect colours, scaling and visibility of elements. These algorithms are also controlled by the visitor's engagement level, and provide through graphical means an interpretation of the processes occurring in the underlying hierarchical ecosystem of the piece.

Challenges, Misconceptions and Pitfalls of Spatialisation

It is important to be aware of the subtle and not so subtle ways sound spatialisation can fail to fulfil expectations. Since acoustic space represents a complex environment with many factors at play, getting everything right in (re-)creating a *believable* spatial sound scene is quite challenging. The degree to which this needs to be achieved depends on the desired outcome. If the perfect simulation of a sonic environment is the goal, criteria come into play that are harder to fulfil than if the goal is compositional work in a creative manner. In the former case great care has to be taken to reconstitute the acoustic space with all the correct localisation cues, whereas in the latter case completely artificial spatial combinations are possible. In both cases the sound processes are subjected to the laws and principles of our spatial auditory perception.

Kendall and Cabrera (2011) investigate and explain in detail why things don't always work as expected. They give "three reasons why the spatial potential of electro-acoustic music is not always realised: 1) misconceptions about the technical capacities of spatialisation systems, 2) misconceptions about the nature of spatial perception, especially in the context of such systems, and 3) a lack of creative engagement, possibly due to the first two issues." According to them, some of the elements responsible for these problems are: the precedence effect (Wallach et al. 1949; Brown et al. 2015), sweet-spot misalignment (Peters 2010), plausibility and comprehensibility issues, time-delay differences from the speakers between small and large venues, image dispersion dependant on transient and spectral characteristics of the source, cross-talk when playing back binaural signals over speakers, and the failure for spectral decomposition to be recognised as separate objects, which can only be achieved by de-synchronising the partials, or adding contradictory vibrato patterns on the individual components (Kendall and Cabrera 2011).

A conceptual problem which is often ignored is the fact sounds and sound-objects are not pixels or abstract points in space. The dominant thinking in spatialisation is based on a purely geometrical conception in Euclidian space and most software tools provide a visualisation in that paradigm, be it through points or trajectory paths on a visual display. This is misleading for several reasons: our spatial perception and the way sounds are embedded within an acoustic space does not provide by default the sharp point sources imagined; the grouping and stream-segregation principles applied both spatially and temporally by our auditory system (Bregman 1994) do not provide separation of sources in the same way a visual display does; the spatial resolution of our auditory system is not homogenous in all directions: on the horizontal plane, the frontal localisation blur covers +/-1 degree at certain frequencies with a more typical blur of +/- 5 degrees, to the sides the blur increases to +/- 10 degrees, and above or below the listener and slightly to the back this blur reaches up to +/- 22 degrees (Blauert 1983); a further problem is the front-back confusion, in particular with binaural headphone-rendering without head-tracking, as well as the cone of confusion on which it is impossible to determine where a sound is located (Röttger et al. 2007); phantom-images on the side have a tendency to collapse which leads to confused spatial perception, and finally, without the correct environmental cues, we have limited capabilities for judging the distance of sound objects (Oechslin et al. 2008).

It is fair to say that geometrically constructed sound-scenes that operate with abstract point sources rarely produce a coherent or convincing spatial scene; for this to occur additional acoustic and psycho-acoustic cues need to be introduced. Therefore those algorithmic processes that merely manipulate symbolic sound-objects without respecting the psycho-acoustic reality might not produce the desired effect. The auditory system's 'fault-correction' is capable of presenting the most plausible element as relevant, even if it is not mathematically correct or compositionally intended. Nevertheless, for creative applications that do not expect to produce a 'natural' sounding scene and space, algorithmic spatialisation processes can generate interesting and sometimes surprising results.

Notes

[1] http://www.medienkunstnetz.de/werke/stockhausen-im-kugelauditorium/bilder/4/ all URIs were accessed in July 2015.

[2] http://www.sarc.qub.ac.uk/sites/sarc/AboutUs/TheSARCBuildingandFacilities/TheSonicLab/

[3] The paths were generated using the icst.spline external for MaxMSP that is part of the ICST max-tools: https://www.zhdk.ch/index.php?id=icst_toolsmaxmsp

References

Amatriain, X., J. Kuchera-Morin, T. Hollerer, and S. T. Pope. 2007. "The AlloSphere: Immersive Multimedia for Scientific Discovery and Artistic Exploration," *IEEE Computer Society* 16, no. 2 (April): 64–75.

Arfib, D., J. M. Couturier, L. Kessous, and V. Verfaille. 2002. "Strategies of mapping between gesture data and synthesis model parameters using perceptual spaces." *Organised Sound* 7 (02): 127–144.

Baalman, M. A. 2010. "Spatial Composition Techniques and Sound Spatialisation Technologies." *Organised Sound* 15 (03): 209–218.

Baltazar, P., and B. Habbestad. 2010. "Unruhige Räume – Spatial Electro-Acoustic Composition Through A Collaborative Artistic Research Process." In *Proceedings of the International Computer Music Conference.* New York, USA.

Barrett, N. 2002. "Spatio-musical composition strategies." *Organised Sound* 7 (03): 313–323.

———. 2015. "Creating tangible spatial-musical images from physical performance gestures." In *Proceedings of the International Conference on New Interfaces for Musical Expression.* Baton Rouge, USA.

Bayle, F. 1993. *musique acousmatique: propositions... ...positions.* Paris, France: Institut National de l'Audiovisuel INA & Editions Buchet/Chastel.

———. 2007. "Space, and more." *Organised Sound* 12 (03): 241–249.

Bedini, J. C. 1985. *Monaural to binaural audio processor.* US Patent 4,555,795, November.

Berkhout, A. J., D. de Vries, and P. Vogel. 1993. "Acoustic control by wave field synthesis." *The Journal of the Acoustical Society of America* 93 (5): 2764–2778.

Bisig, D., J. C. Schacher, and M. Neukom. 2011. "Flowspace – A Hybrid Ecosystem." In *Proceedings of the Conference on New Interfaces for Musical Expression.* Oslo, Norway, 30 May - 1 June.

Blauert, J. 1983. *Spatial Hearing: The Psychophysics of Human Sound Localisation.* Cambridge, MA, USA: The MIT Press.

Blesser, B., and L.-R. Salter. 2007. *Spaces Speak, Are You Listening?: Experiencing Aural Architecture.* Cambridge, MA, USA: The MIT Press.

Boone, M. M., and E. N. G. Verheijen. 1993. "Multichannel Sound Reproduction Based on Wavefield Synthesis." In *Audio Engineering Society Convention 95.* October. `http://www.aes.org/e-lib/browse.cfm?elib=6513`.

Born, G. 2013. *Music, Sound and Space: Transformations of Public and Private Experience.* Cambridge, UK: Cambridge University Press.

Boulez, P., and A. Damiens. 1998. *Répons: Dialogue de l'ombre double.* Berlin, Germany: Deutsche Grammophon.

Braasch, J. 2005. "A loudspeaker-based 3D sound projection using Virtual Microphone Control (ViMiC)." In *Audio Engineering Society Convention 118.* Audio Engineering Society.

Braasch, J., N. Peters, and D. L. Valente. 2008. "A loudspeaker-based projection technique for spatial music applications using virtual microphone control." *Computer Music Journal* 32 (3): 55–71.

Bregman, A. S. 1994. *Auditory scene analysis: The perceptual organization of sound.* Cambridge, MA, USA: The MIT Press.

Brown, A. D., G. C. Stecker, and D. J. Tollin. 2015. "The Precedence Effect in Sound Localization." *Journal of the Association for Research in Otolaryngology* 16 (1): 1–28.

Brümmer, L., G. Dipper, D. Wagner, H. Stenschke, and J. A. Otto. 2014. "New developments for spatial music in the context of the ZKM Klangdom: A review of technologies and recent productions." *Divergence* 1, no. 3 (December).

Chowning, J. 1977. "The Simulation of Moving Sound Sources." *Computer Music Journal* 1, no. 3 (June): 48–52.

———. 2011. "Turenas: the Realization of a Dream." In *Proceedings of the 17es Journées d'Informatique Musicale (JIM'11).* Saint-Etienne, France.

Couprie, P. 2004. "Graphical representation: an analytical and publication tool for electroacoustic music." *Organised Sound* 9 (01): 109–113.

Cowell, H., and S. R. Cowell. 1969. *Charles Ives and his music.* Oxford, UK: Oxford University Press.

Daniel, J. 2000. "Représentation de champs acoustiques, application à la transmission et à la reproduction de scènes sonores complexes dans un contexte multimédia." PhD diss., University of Paris VI.

Dolby. 2012. *Dolby Atmos: Next-Generation Audio for Cinema.* White paper. Dolby Laboratories, Inc. http://www.dolby.com/us/en/technologies/dolby-atmos/dolby-atmos-next-generation-audio-for-cinema-white-paper.pdf.

EBU, E. B. U. 2014. "Tech 3364, Audio Definition Model." *Geneva, January.* https://tech.ebu.ch/docs/tech/tech3364.pdf.

Eckel, G. 2011. *Random Access Lattice.* "http://iem.at/~eckel/download/RAL-description.pdf".

Ellberger, E., and G. T. Perez. 2013. *SSMN Taxonomy.* "http://blog.zhdk.ch/ssmn/files/2012/10/SSMN_Taxonomy.pdf".

Ellberger, E., G. T. Perez, J. Schütt, G. Zoia, and L. Cavaliero. 2014. "Spatialization Symbolic Music Notation at ICST." In *Proceedings of the Joint International Computer Music and Sound and Music Computing Conference.* Athens, Greece, September.

Gallagher, S. 2005. *How the Body Shapes the Mind.* Oxford, UK: Clarendon Press.

Geier, M., J. Ahrens, and S. Spors. 2010. "Object-based audio reproduction and the Audio Scene Description Format." *Organised Sound* 15 (03): 219–227.

Gerzon, M. A. 1985. "Ambisonics in multichannel broadcasting and video." *Journal of the Audio Engineering Society* 33 (11): 859–871.

Geslin, Y., and A. Lefevre. 2004. "Sound and musical representation: the acousmographe software." In *Proceedings of the International Computer Music Conference.* Miami, USA.

Hall, E. T. 1966. *The Hidden Dimension.* 1990 paperback. New York, USA: Anchor, Doubleday.

Ihde, D. 1976. *Listening and Voice: Phenomenologies of Sound.* 2nd 2007. Albany, NY, USA: SUNY Press.

Kendall, G. S. 2010. "Spatial perception and cognition in multichannel audio for electroacoustic music." *Organised Sound* 15 (03): 228–238.

Kendall, G. S., and A. Cabrera. 2011. "Why Things Don't Work: What You Need to Know about Spatial Audio." In *Proceedings of the International Computer Music Conference.* Huddersfield, UK.

Kim-Boyle, D. 2005. "Sound spatialization with particle systems." In *Proceedings of the 8th international conference on digital audio effects (DAFX-05),* 65–68. Madrid, Spain.

———. 2006. "Spectral and Granular Spatialization with Boids." In *Proceedings of the 2006 International Computer Music Conference,* 139–142. New Orleans, USA.

———. 2008. "Spectral Spatialisation - An Overview." In *Proceedings of the International Computer Music Conference.* Belfast, Ireland.

Lachenmann, H. 1966. "Klangtypen der neuen Musik." In *Musik als existentielle Erfahrung,* 1–20. Wiesbaden, Germany: Breitkopf & Härtel.

Lennox, P. 2009. "Spatialisation of Computer Music." In *The Oxford Handbook of Computer Music,* edited by R. T. Dean, 258–273. Oxford, UK: Oxford University Press.

Lossius, T., and J. Anderson. 2014. "ATK Reaper: The Ambisonic Toolkit as JSFX plugins." In *Proceedings of the Joint International Computer Music and Sound and Music Computing Conference.* Athens, Greece.

Lossius, T., P. Baltazar, and T. de la Hogue. 2009. "DBAP - Distance-Based Amplitude Panning." In *Proceedings of the International Computer Music Conference,* 489–492. Montreal, Canada.

Lynch, H., and R. Sazdov. 2011. "An Ecologically Valid Experiment for the Comparison of Established Spatial Techniques." In *Proceedings of the International Computer Music Conference.* Huddersfield, UK.

Lyon, E. 2008. “Spatial Orchestration.” In *Proceedings of the Sound and Music Computing Conference.* Berlin, Germany.

Miyama, C., J. C. Schacher, and N. Peters. 2013. “SpatDIF Library – Implementing the Spatial Sound Descriptor Interchange Format.” *Journal of the Japanese Society for Sonic Arts* 5 (3): 1–5.

Neuhaus, M. 2000. “Sound Art?” In *Liner notes for Volume: Bed of Sound.* New York, USA: P.S. 1 Contemporary Art Center, July.

Noisternig, M., T. Carpentier, and O. Warusfel. 2012. “ESPRO 2.0-Implementation of a surrounding 350-loudspeaker array for sound field reproduction.” In *Proceedings of the Audio Engineering Society UK Conference.* York, UK.

Noisternig, M., A. Sontacchi, T. Musil, and R. Hóldrich. 2003. “A 3D ambisonic based binaural sound reproduction system.” In *Audio Engineering Society Conference: 24th International Conference: Multichannel Audio, The New Reality.* Banff, Canada: Audio Engineering Society.

Normandeau, R. 2009. “Timbre Spatialisation: The medium is the space.” *Organised Sound* 14, no. 03 (December): 277–285.

Oechslin, M., M. Neukom, and G. Bennett. 2008. “The Doppler Effect – an Evolutionary Critical Cue for the Perception of the Direction of Moving Sound Sources.” In *International Conference on Audio, Language and Image Processing (ICALIP 2008),* 676–679. Shanghai, China: IEEE.

Oehlschlägel, R. 1985. *Klanginstallation und Wahrnehmungskomposition. Zur 'Nuova Versione' von Luigi Nono's Prometeo.* Köln, Germany: MusikTexte.

Paine, G., R. Sazdov, and K. Stevens. 2007. “Perceptual Investigation into Envelopement, Spatial Clarity, and Engulfment in Reproduced Multi-Channel Audio.” In *Audio Engineering Society Conference: 31st International Conference: New Directions in High Resolution Audio.* London, UK, June.

Parra Cancino, J. A. 2014. “Multiple paths: towards a performance practice in computer music.” PhD diss., Academy of Creative and Performing Arts (ACPA), Faculty of Humanities, Leiden University.

Parry, N. 2014. “Exploded sounds: spatialised partials in two recent multi-channel installations.” *Divergence* 1, no. 3 (December).

Peters, N. 2010. “Sweet [re]production: Developing sound spatialization tools for musical applications with emphasis on sweet spot and off-center perception.” PhD diss., McGill University.

Peters, N., J. Braasch, and S. McAdams. 2011. “Sound Spatialization Across Disciplines Using Virtual Microphone Control (ViMiC).” *Journal of Interdisciplinary Music Studies* 5 (2).

Peters, N., T. Lossius, and J. C. Schacher. 2013. “The Spatial Sound Description Interchange Format: Principles, Specification, and Examples.” *Computer Music Journal* 37 (1): 11–22.

Peters, N., T. Lossius, J. C. Schacher, P. Baltazar, C. Bascou, and T. Place. 2009. “A Stratified Approach For Ssound Spatialisation.” In *Proceedings of the Sound and Music Computing Conference.* Porto, Portugal, July.

Pulkki, V. 1997. “Virtual sound source positioning using Vector Base Amplitude Panning.” *Journal of the Audio Engineering Society* 45, no. 6 (June): 456–466.

Reynolds, C. W. 1987. “Flocks, herds and schools: A distributed behavioral model.” In *ACM Siggraph Computer Graphics,* 21:25–34. 4. ACM.

Roads, C. 2001. *Microsound.* Cambridge, MA, USA: The MIT Press.

Röttger, S., E. Schröger, M. Grube, S. Grimm, and R. Rübsamen. 2007. “Mismatch negativity on the cone of confusion.” *Neuroscience letters* 414 (2): 178–182.

Rumsey, F. 2001. *Spatial Audio.* Oxford, UK: Focal Press.

Rumsey, F. 2002. "Spatial quality evaluation for reproduced sound: Terminology, meaning, and a scene-based paradigm." *Journal of the Audio Engineering Society* 50 (9): 651–666.

Schacher, J. C. 2007. "Gesture Control of Sounds in 3D Space." In *Proceedings of the Conference on New Interfaces for Musical Expression.* New York, USA.

Schacher, J. C., D. Bisig, and M. Neukom. 2011. "Composing With Swarm Algorithms – Creating Interactive Audio-Visual Pieces Using Flocking Behaviour." In *Proceedings of the International Computer Music Conference.* Huddersfield, UK.

Schacher, J. C., and P. Kocher. 2006. "Ambisonics Spatialization Tools for Max/MSP." In *Proceedings of the International Computer Music Conference.* New Orleans, USA, June.

Schacher, J. C., P. Kocher, and D. Bisig. 2014. "The Map and the Flock – Emergence in Mapping with Swarm Algorithms." *Computer Music Journal* 38 (3): 49–63.

Schaeffer, P. 1966. *Traité des Objets Musicaux.* Paris, France: Editions du Seuil.

Schafer, R. M. 1993. *The soundscape: Our sonic environment and the tuning of the world.* Rochester, VT, USA: Inner Traditions/Bear & Co.

Scheirer, E., R. Vaananen, and J. Huopaniemi. 1999. "AudioBIFS: Describing audio scenes with the MPEG-4 multimedia standard." *IEEE Transactions on Multimedia* 1 (3): 237–250.

Schumacher, M., and J. Bresson. 2010. "Spatial Sound Synthesis in Computer-Aided Composition." *Organised Sound* 15 (3): 271–289.

Serken, S. 2001. "Towards A Space-Time Art: Iannis Xenakis's Polytopes." *Perspectives of New Music:* 262–273.

Shaff, S. 2014. "Audium – sound-sculptured space." *Divergence* 1, no. 3 (December).

Smalley, D. 1997. "Spectromorphology: explaining sound-shapes." *Organised sound* 2 (2): 107–126.

———. 2007. "Space-form and the acousmatic image." *Organised Sound* 12 (01): 35–58.

Stockhausen, K. 1995. *Kontakte: für elektronische Klänge, Klavier und Schlagzeug.* Kürten, Germany: Stockhausen-Verlag.

Stockhausen, K., D. Schnebel, C. von Blumröder, and I. Misch. 1978. *Texte zur Musik 1970–1977.* Vol. 4. Köln, Germany: DuMont.

Thoresen, L. 2010. "Form-building patterns and metaphorical meaning." *Organised Sound* 15 (02): 82–95.

Thoresen, L., and A. Hedman. 2007. "Spectromorphological analysis of sound objects: an adaptation of Pierre Schaeffer's typomorphology." *Organised Sound* 12 (02): 129–141.

Topper, D., M. Burtner, and S. Serafin. 2002. "Spatio-Operational Spectral (SOS) Synthesis." In *Proceedings of the International Conference on Digital Audio Effects DAFx'02.* Hamburg, Germany.

Truax, B. 1999. "Composition and diffusion: space in sound in space." *Organised Sound* 3 (2): 141–146.

Varèse, E. 1966. "The Liberation of Sound." *Perspectives of New Music* 5, no. 4 (Autumn–Winter): 11–19.

Wagner, D., L. Brümmer, G. Dipper, and J. A. Otto. 2014. "Introducing the Zirkonium MK2 System for Spatial Composition." In *Proceedings of the Joint International Computer Music and Sound and Music Computing Conference,* 823–829. Athens, Greece.

Wallach, H., E. B. Newman, and M. R. Rosenzweig. 1949. "A Precedence Effect in Sound Localization." *The Journal of the Acoustical Society of America* 21 (4): 468–468.

Westerkamp, H. 2002. "Linking soundscape composition and acoustic ecology." *Organised Sound* 7 (01): 51–56.

Wilson, S. 2008. "Spatial Swarm Granulation." In *Proceedings of the International Computer Music Conference.* Belfast, UK.

Wilson, S., and J. Harrison. 2010. "Rethinking the BEAST: Recent developments in multichannel composition at Birmingham ElectroAcoustic Sound Theatre." *Organised Sound* 15 (3): 239–250.

Wishart, T. 1996. *On Sonic Art.* New and Revised Edition. Newark, NJ, USA: Harwood Academic Publishers.

Wozniewski, M., Z. Settel, and J. R. Cooperstock. 2007. "Audioscape: A Pure Data library for management of virtual environments and spatial audio." In *Proceedings of the Pure Data Convention.* Montreal, Canada.

Xenakis, I. 1992. *Formalized Music: Thought and Mathematics in Composition.* New expanded. Harmonolgia Series 6. Hillsdale, NY, USA: Pendragon Press.

Zmoelnig, I. M., A. Sontacchi, and W. Ritsch. 2003. "The IEM-cube, a periphonic re-/production system." In *Audio Engineering Society Conference: 24th International Conference: Multichannel Audio, The New Reality.* Banff, Canada: Audio Engineering Society.

Zouhar, V., R. Lorenz, T. Musil, J. Zmölnig, and R. Höldrich. 2005. "Hearing Varèse's Poème électronique inside a virtual Philips Pavilion." In *Proceedings of the International Conference on Auditory Display,* 247–252. Limerick, Ireland, July.

List of Figures

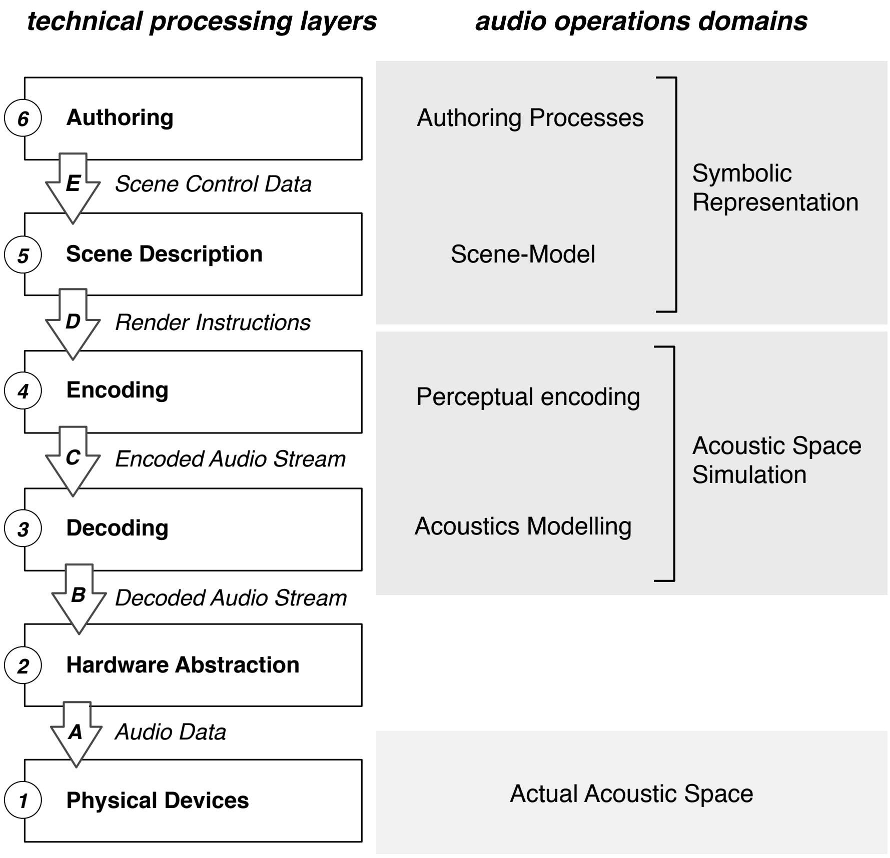

Figure 1: Spatial audio processing layers and compositional operation domains.

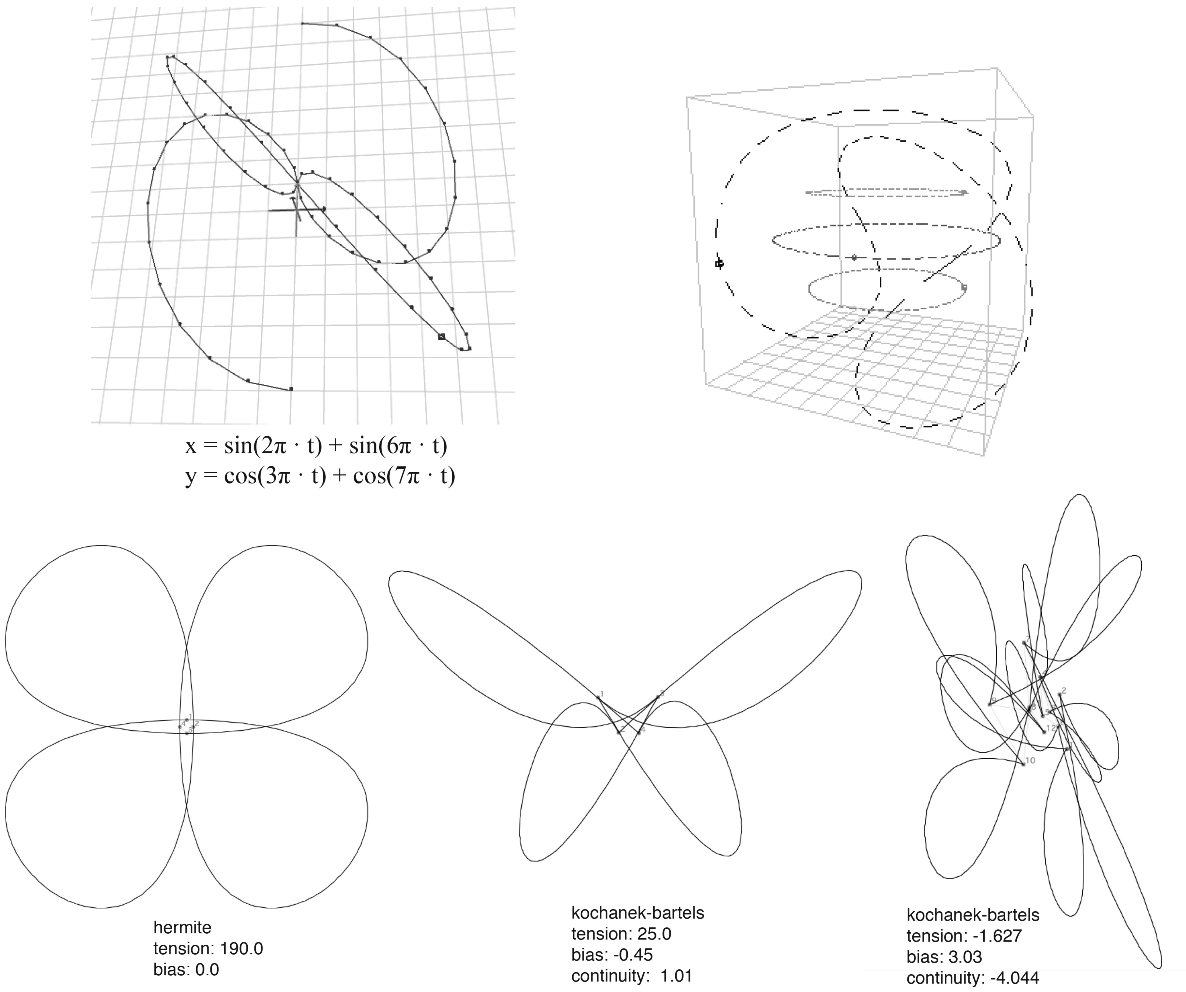

Figure 2: Visualisation and formulas of the 'Turenas' *insect* lissajous trajectory in a three dimensional view (top left). Wishart's cyclical cloverleaf, butterfly and irregular oscillating motions (bottom row). A three dimensional view of three circular paths, and a closed cyclical path made of Bézier-curve segments (top right).

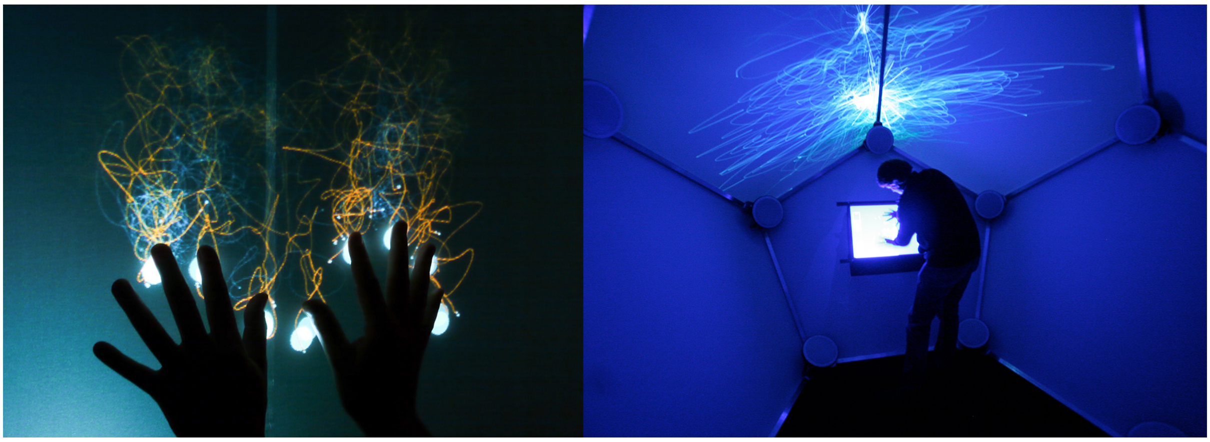

Figure 3: Touch-based interactions with three hierarchically linked flocks in ‘Impacts’ in the interactive generative installation ‘Flowspace’ (2009–2010). In this piece visual and sonic outputs originate from the flocking simulation, which generates musical structure by analysing agent behaviour and by triggering and spatially positioning sound events in a dodecahedral 20-channel speaker array (Photographs by Jan Schacher (c) 2010)

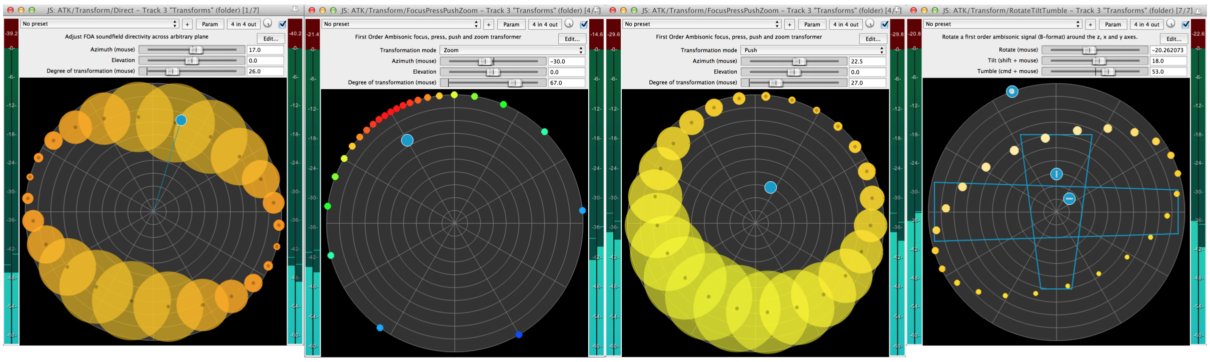

Figure 4: Four views of Ambisonic Sound-field transformation implemented by the ATK in the Reaper plugins by Lossius and Anderson (2014). The processes change the directivity, and zoom, push, or rotate the sound-field. (Screenshots used by permission)