2017.xCoAx.org

Lisbon
Computation
Communication
Aesthetics
& X

WATCHERS — AN INSTALLATIVE REPRESENTATION OF A GENERATIVE SYSTEM

DANIEL BISIG
daniel.bisig@zhdk.ch

Institute for Computer Music
and Sound Technology
Zurich University of the Arts
Zurich, Switzerland

Abstract

Watchers is an interactive sound installation that serves as an example how a generative system can be made experienceable by exposing its algorithmic properties through the installation's perceivable characteristics. The generative system is based on a simulation of recurrent networks that exhibit delay and feedback mechanisms. Through a combination of natural mapping strategies and spatial metaphors, several of the network's properties are aligned with the sonic output of the installation and become accessible for interaction through tangible affordances. This article contextualises *Watchers* with respect to direct audification approaches, principles of tangible computing, and related approaches in musical interface and installation design. The article also describes the conceptual motivation, technical developments, and interaction principles that led to the realisation of the installation. The text concludes with a discussion of those aspects of the chosen approach that seem sufficiently generalisable to inform further research and experimentation.

Keywords
Generative art
Sound installation
Mapping strategies
Audification
Tangible computing

1. INTRODUCTION

The installation *Watchers* has been realised in the context of a research project entitled *Feedback Audio Networks* (*FAUN*). The goal of this project is to explore the musical potential of generative systems which employ delay and feedback mechanisms within recurrent networks (Bisig and Kocher 2013). Such networks are interesting for several reasons. The changing activities of network nodes can be rendered audible through a direct audification approach (Kramer 1993). This abolishes the need for devising a potentially arbitrary sonification mapping. The manipulation of delays permits the creation of musical structures across different temporal scales and thereby provides a formalism that is of potential use for both sound synthesis and algorithmic composition. Feedback networks can exhibit complex dynamics and therefore lend themselves for generative approaches that explore the sonic potential of self-organised and autonomous processes. The realisation of *Watchers* is part of a research strand within the *FAUN* project that addresses the issue of rendering the algorithmic principles of a generative system experienceable not only through a sonic manifestation but also via spatial and tangible representations. These representations provide affordances for interaction and thereby allow visitors to engage through embodied actions with the generative system. *Watchers* has been developed as an example how the characteristics of a network-based generative system can be represented by an interactive sound installation.

2. BACKGROUND

2.1. Feedback and delay in sound synthesis

Feedback and delay mechanisms play a prominent role for the creation and processing of digital audio signals (Sanfilippo and Valle 2012). In digital signal processing, typical applications include the design of recursive filters or the simulation of room acoustic phenomena (for an overview, see e.g. Neukom 2013). In sound synthesis, several well established physical modelling techniques such as digital waveguide synthesis employ feedback and delay mechanisms to simulation the propagation of acoustic waves through physical media (see e.g. Bilbao 2004). Less common are approaches in computer music that employ feedback and delay mechanisms within highly recurrent networks. Such networks can give rise to phenomena of self-organization which is interesting for generative forms of sound production. Surges, Smyth, and Puckette (2015) use the term generative audio system to designate generative approaches that don't operate on symbolic data but rather create the sonic output through a direct audification mechanism. There exist some examples that employ neural networks for sound synthesis. An early investigation describes a sound synthesis method based on a recurrent neural network that consists of continuous-time and continuous-value neurons whose interconnections possess both weight and delay (Ohya 1998). A more recent example uses a neural network-based synthesis system that consists of two neurons only. These neurons exhibit mutual inhibition and lock their internal oscillations to the frequency of an input signal (Eldridge 2005).

Approaches that are not related to neural networks are equally relevant. A computer music environment named resNET permits the realisation of networks for sound synthesis that consist of interconnected exciter and resonator units

(Hamman 1994). In a more recent example, a sound synthesis system was realized based on iterative maps whose variables are coupled via a network (Battey 2004). Very recently, Surges, Smyth, and Puckette (2015) have conducted research on networks consisting of time-varying allpass filters which exhibit generative behaviours when organised within feedback networks.

2.2. Experiential algorithms in generative art

Time-delayed feedback networks are interesting in the context of generative art. This is not only due to the complex dynamics that these networks exhibit but also because of their suitability for direct audification.

The topic of direct audification is related to an ongoing debate within generative art. This debate refers to the challenge of devising a generative artwork in such a way that the specific characteristics of the underlying algorithm manifest themselves as principal aspects of the work. There is some agreement, that the abstract processes which give rise to the perceivable output of a generative artwork should lie at the focus of an artist's attention (Dorin 2001). According to this opinion, to tap into the unique potential of generative art implies to focus on processes both as core aspects of artistic creation and mechanisms of exposure to an audience (Galanter 2009). By exposing algorithmic processes through the perceivable characteristics of an artwork. the audience can become engaged not only on an aesthetic but also an intellectual level (Whitelaw 2005). In this context, the principle of mapping is relevant but also controversial (Eldridge 2012). By focusing on the specificity of the relationship between algorithms and sonic material, a strong correspondence between formal and aesthetic principles can be established. In the most extreme case, there exists a full match between formal and perceptual properties of a generative system. Such a situation has been described as natural mapping (Dorin et al. 2012) or ontological alignment (Eldridge 2012). The direct audification of time-delayed feedback networks represents such a case. Interactivity can play an important role for rendering algorithmic principles accessible to sensorial experience and intuitive understanding. In the context of software art, Borevitz (2004) argues that interaction provides the visitor with the opportunity to experience through an embodied encounter the ontology of the underlying code. The relatively recent technique of model-based sonification (Hermann 2011), provides a well established framework that can inform interaction and mapping concepts in generative art and algorithmic music. This framework offers a principled approach for interaction with a sound synthesis mechanism that helps a user to gain an intuitive comprehension of the complex processes from which the data originate.

2.3. Tangible computing

The field of tangible computing can provide a useful conceptual and technical inspiration for rendering abstract generative principles accessible for interactive engagement. Tangible user interfaces establish a close relationship between the physical elements of an interface and the characteristics of a computational system. Tangible interface elements are both embodied representations of digital data and at the same time provide the means for their manipulation (Ullmer and Ishii 2000). And tangible interfaces leverage the connection of body and cognition by facilitating tangible thinking (Shaer and Hornecker 2010). Accordingly, tangible elements not only form part of the experienceable properties of a computational system but they also contribute to its legibility and learnability.

Concerning the characteristics of the correspondence between physical and digital objects, Koleva et al. (2003) propose a framework that is based on the degree of coherence between physical and digital objects. The more specific this relationship is, the stronger the resulting coherence between physical and digital objects becomes (Boriana et al. 2003). The strongest form of correlation results from aligning the mutual ontological status of digital and physical objects. This level of alignment is also known as full metaphor (Fishkin 2004) and corresponds to the previously mentioned notion of natural mapping (Dorin et al. 2012).

2.4. Tangible musical interfaces and sound installations

Notions of tangibility play an important role for the design of digital musical instruments. Here, the main emphasis lies on the establishment of interaction affordances that allow for gestural interaction and provide tangible feedback (Marshall 2008). The specificity of the relationship between interaction affordances and sound generating algorithm is less often taken into account. An interesting example concerning the latter approach is provided by Graham and Bridges (2015). In this publication, the authors investigate how embodied image schema theories (Lakoff and Johnson 2008) and the concept of Spectromorphology(Smalley 1997) can be combined to inform the development of design heuristics in musical interaction design. Another interesting concept is provided by Essl and O'Modhrain (2006) in the form of the hypothesis of weak sensori-motor integration. This hypothesis helps to define the limits of plausibility between haptic interaction and auditory output.

There exist several tangible musical interfaces that establish a specific correspondence between the physical aspects of the interface and the algorithmic properties of a sound synthesis system. One of the most famous examples is the table-based instrument named reacTable which employs tangible objects and the users' hands as physical proxies for the direct manipulation of a sound synthesis patch (Kaltenbrunner, O'Modhrain, and Costanza 2004). Gelineck and Serafin (2010) have developed a physical interface named PHYSMISM that encourages an experiential rather than analytic exploration of the sonic capabilities of physical sound synthesis models. An interface named Neurohedron has been developed to control a neural network-based sequencer (Hayes 2010). This interface in the shape of a Dodecahedron possesses faces that correspond to one node each. Pushing the faces triggers or suppresses the activity of the nodes. A particularly striking example is a mechanical interface that controls a physical model of cicadas sound production method (Smyth and Smith III 2002). The interface implements interaction affordances that are based on a mechanical analogy of this physical model.

Of specific interest in the context of this article are tangible interfaces that take the spatial characteristics of a sound synthesis algorithm into account. In their installation, van Walstijn, Alcorn, and Bilbao (2005) relate the vibrational propagations across simulated membranes to acoustic propagations across a speaker array. An installation named *Sound Flinger* represents a sound spatialisation instrument that employs a simulation of a mass-spring system to generate haptic and aural feedback to user interaction (Carlson, Marschner, and McCurry 2011). Burns (2006) presents a sonification strategy that relates the acoustic distances between nodes in a network of delay lines to the physical distances among speakers. An installation named *Black Box* consists of a surround-sound speaker setup and a black box that is suspended from the apex of a dome (Michon, Borins, and Meisenholder 2013). Visitors can push the box away from its rest position and thereby affect the acoustic resonances within a simulated delay system.

3. CONCEPT

Watchers serves as example for rendering the behaviour of a time-delayed feedback network experienceable not only through acoustic rendering but also through the provision of tangible and spatial affordances. The specification of these affordances and their relationship to properties of the network combines different approaches that are inspired by the previously described concepts. An important design decisions deals with the extension of the natural mapping principle beyond a direct audification of the network. For this, the compositional approach of point source spatialisation was chosen. Each of the six loudspeakers in the installation is associated with a corresponding network node whose changing activity level is directly emitted as acoustic output by the loudspeaker. Accordingly, the loudspeakers and the network nodes possess the same ontological status as signal sources. In addition to this ontological alignment, the installation establishes a relationship between loudspeaker setup and network topology that is based on spatial metaphors. Each loudspeaker is endowed with the capability to recognise the presence of other loudspeakers as long as they are located more or less along the loudspeaker's *line of sight*. This *visibility* principle affects the connectivity among network nodes. For loudspeakers that can see other loudspeakers, a connection is established among the corresponding network nodes. And conversely, network nodes that correspond to loudspeakers that can't see each other are not connected. A third type of mapping is inspired by the hypothesis of weak sensorimotor integration. This mapping relates the rotational acceleration of a loudspeaker to a change in the delay of a recurrent connection that connects the corresponding node with itself. As result, manually rotating a loudspeaker causes an acoustic perturbation effect that becomes perceivable as changing doppler effect.

4. CONCEPT

This section provides a technical overview of *Watchers* installation. This includes a description of the sound synthesis method and the hardware and software components, all of which were specifically developed for the installation.

4.1. Sound synthesis

Sound synthesis is based on a time-delayed recurrent network consisting of nodes the pass incoming signals through a wave shaping function. This function serves as a non-linear distortion effect and as gating mechanism that silences the output of nodes whose activity lies outside of a pre-specified range. The basic functionality of each node is depicted on the left side of Figure 1. All signals arriving from incoming connections are summed and then passed through the wave shaping function before being output through one or several outgoing connections. In parallel, the signals' amplitude is calculated and compared with the lower and upper value of a threshold function. If the amplitude lies outside of this threshold, the parameters of the wave shaping function are modified to decrease its slope. The velocity of this change affects the amplitude envelope of the outgoing signal. Furthermore, each node includes a wavetable oscillator that generates a sine wave. This signal is added to the incoming signals. Connections among nodes are unidirectional and signals that travel through them are delayed. Connections can be used to create recurrent loops within the network. Apart from the delay mechanism, these connections integrate additional signal processing stages. These are depicted on the right side of Figure 1. The processing stages include: an input gain that attenuates the signal emitted by a node, a high pass filter that removes DC offset, a low pass filter that removes high frequency content that has been generated by fast changes in the wave shape function, a delay line, and an output gain that attenuates the signal before it arrives at the receiving node.

The synthesis network that has been used to generate the acoustic output of the *Watchers* installation consists of six nodes, each of them corresponds to a particular loudspeakers. If all nodes are fully connected, the network consists of 726 connections (see left side of Figure 2). Since the connectivity of the network is directly related to the visibility among loudspeakers, the network is never fully connected. The connectivity that is depicted on the right side of Figure 2 corresponds to the exhibition situation that is shown as a 3D rendering on the left side of Figure 5.

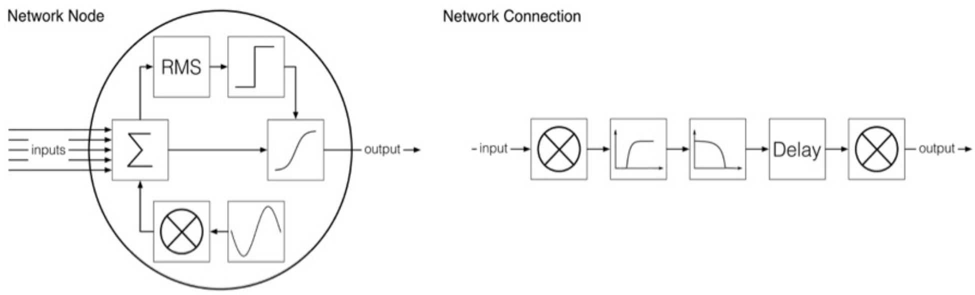

Fig. 1
Schematic Depiction of the Network-based Synthesis Mechanism. The left image shows the characteristics of the network node. The right image that of a network connection. The symbols in the node graphics are as follows (in clockwise rotation starting at the summation symbol): signal summation, root mean square deviation, threshold function, wave shaping function, wavetable oscillator, gain function. The symbols in the connection graphics are as follows (from left to right): input gain, high pass filter, low pass filter, delay line, output gain.

4.2. Installation hardware

The hardware of the installation consists of a custom designed loudspeaker housing that integrates a broad band speaker driver, a mono audio amplifier board, an infrared light detector, and infrared light emitter, a gyroscope module, and a micro controller (see Fig. 3). The infrared emitting and detecting components form the basis for the capability of the loudspeakers to detect and identify each other. The gyroscope module measures the angular acceleration of a loudspeaker. Each loudspeaker is attached to a rotational joint that also houses a slip ring. This joint is mounted on top of a speaker stand. The audio signal, I2C communication and power supply pass through the slip ring. Located at the bottom of the loudspeaker stand is a wooden box that contains a Wifi enabled micro controller and a hum suppression transformer. The wi-fi micro controller serves as interface between the cable-based I2C communication and a wireless network. A master computer is connected to a wi-fi router, an audio interface and a secondary screen. The screen is used to show to the visitors a visual representation of the sound synthesis system. A schematic representation of this setup is shown in Figure 4.

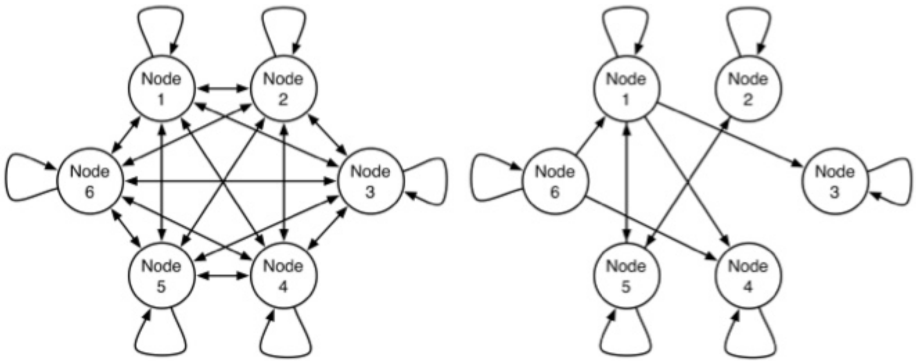

Fig. 2
Schematic Depiction of the Connectivity in a Network Consisting of Six Nodes. Shown on the left side is a fully connected network. The connectivity depicted on the ride side corresponds to the exhibition situation shown on the left side of Figure 5.

4.3. Installation software

The sound synthesis system has been implemented in the Processing programming[1] environment and makes use of the Beads library[2]. The software also creates a graphical representation of the synthesis system which is shown on screen to the visitors. Another software that has also been implemented in the Processing programming environment manages the communication between the sound synthesis software and the micro controllers. This software handles the automated registration of the network addresses of the micro controllers at the startup of the installation, it also coordinates the sequential emission of the infrared signal via a round robin scheme in order to avoid interference, and it controls the acquisition and temporary storage of the acceleration and infrared visibility data which are subsequently sent to the master computer.

1
https://processing.org

2
http://www.beads project.net

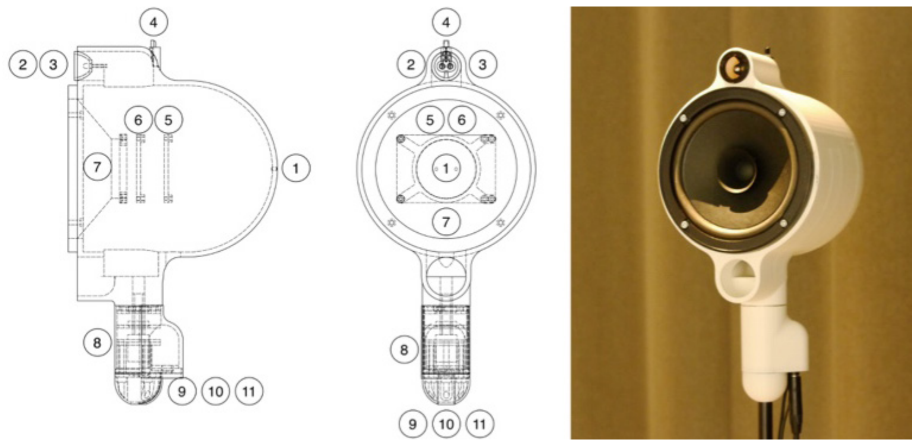

Fig. 3
Loudspeaker Housing. A schematic representation is shown on the left side, a photograph on the right side. The schematic depiction indicates the hardware components that have been integrated into the housing. The numbered labels correspond to the following components: 1: status leds, 2: white light emitting led, 3: infrared light emitting led, 4: infrared light receiver, 5: micro controller board, 6: audio amplifier board, 7: speaker driver, 8: slip ring, 9: audio connector, 10: I2C connector, 11: power connector.

5. CONCEPT

The *Watchers* installation has been exhibited in 2015 at the Zurich University of the Arts as part of a small festival that showcased several artistic and musical works that had been realised in the context of the *FAUN* project. For this exhibition, the installation consisted of six loudspeakers that were arranged in a circular setup with a diameter of about three meters. A 3D rendering of the exhibition situation is shown on the left side of Figure 5. A photograph taken during the opening of the exhibition is shown on the right side of Figure 5. Video recordings taken during the exhibition are available online[3,4,5,6]. The following aspects were given particular attention during the preparation and setup of the installation for the exhibition: a configuration of the sound synthesis system that produces very pronounced acoustic results from interactive manipulations, the striking of a balance between self-organised installation behaviours and fast and reproducible

3,4,5,6
https://vimeo.com/210686756
(non-interactive situation)

https://vimeo.com/210686050
(interactive situation)

https://vimeo.com/210686722
(interactive situation)

https://vimeo.com/210686633
(exhibition opening)

reactions to interactive manipulation, the provision of different types of visitor engagements through tangible and spatial forms of interaction.

5.1. Acoustic configuration

The sound synthesis system was configured in such a way that the effect of interaction on the behaviour of the generative system results in very clear acoustic consequences. For this purpose, the sound synthesis parameters associated which each node and its own recurrent connection were assigned very different values. As a result, any loudspeaker that does not see any other loudspeaker, emits its own distinct acoustic signature. This signature helps to highlight the algorithmic consequences of interaction. The delay changes in a node's recurrent connection that result from manually rotating the corresponding loudspeakers causes a quick, localised and clearly audible perturbation of the loudspeaker's acoustic signature. In addition, whenever the re-orientation of a loudspeaker allows it to see other loudspeakers, the resulting establishment of new network connections causes the formerly isolated acoustic signature to propagate through the network. As a consequence, other loudspeakers start to blend their own acoustic signature with that of the propagating sound material. This effect is particularly well perceivable when the propagating sounds are being affected by a doppler effect that partially supersedes the more static sonic characteristics of the receiving node. And it is also particularly well perceivable when the propagating signal bounces back and forth via recurrent connections and thereby eventually leads to a full harmonisation of the sonic output of all loudspeakers involved. Rotating a loudspeaker into an orientation in which it can no longer *see* other loudspeakers will cause its sonic output to gradually return to its original signature characteristics.

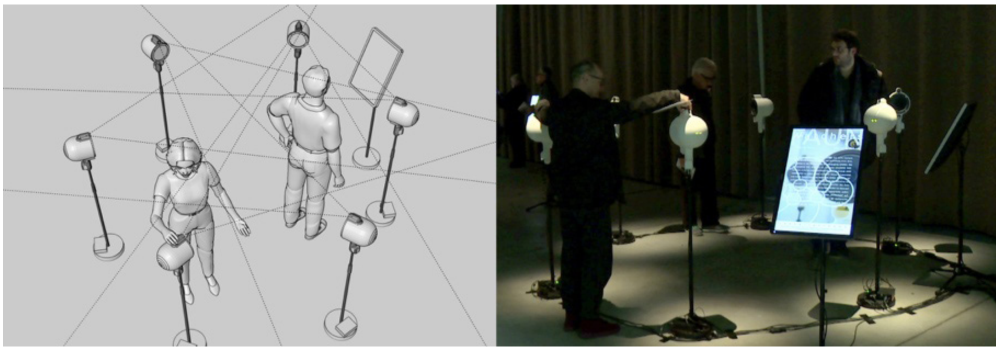

Fig. 5
Exhibition Situation. Shown on the left side is a 3D rendering of the installation setup including two visitors. The right side shows as photograph of the installation in an exhibition situation. In the rendering, the dashed lines emanating from the loudspeakers indicate visibility cones within which a loudspeaker can *perceive* other loudspeakers. The network connectivity that corresponds to this exhibition situation is shown on the right side of Figure 2.

5.2. Behavioural configuration

The ring configuration of the speaker setup has a strong effect on the behaviour of the network. In this arrangement, none of the loudspeakers can be oriented in such a way that they *see* more than two other loudspeakers. Accordingly, the corresponding network connectivity is always sparse and often contains multiple isolated groups, each consisting of only a few or no interconnected nodes. The acoustic consequence of this modularisation of the network is the appearance of sonic islands whose local dynamics is less complex than for networks that are connected[7]. This reduces the level of self-organisation and autonomy of the sound producing network in favour of a more prominent role of interactivity. On the other hand, it is not impossible but difficult to align all loudspeakers in such

7
In graph theory, the term *connected* describes a network topology in which all nodes are connected to each other either directly or indirectly.

a way that the sound synthesis network becomes *connected*. The possibility to interactively configure the installation in such a way that its behaviour gives rise to a high level of sonic complexity becomes a rewarding goal for those visitors, who have started to grasp the principle of the synthesis method and its relationship to the tangible properties of the installation.

5.3. Interaction configuration

The ring configuration of the loudspeaker setup creates interaction situations that differ with respect to the type of engagement that they enable. Visitors can decide to interact while standing either inside or outside of the loudspeaker ring. From an outside position, a visitor is able to carefully align through tangible manipulation the orientation of individual loudspeakers and then observe from this external listening perspective the resulting changes in the sonic output. If, on the other hand, a visitor enters the installation, his or her mode of interaction is different and much more disruptive with respect to the behaviour of the installation. In this situation, tangible interaction has a less pronounced influence on the musical outcome compared to the occluding effects of the visitor's spatial body position on the visibility between loudspeakers.

Accordingly, walking through the installation causes frequent and massive changes in the connectivity of the network and results in equally frequent and massive modifications of the acoustic output.

6. DISCUSSION AND CONCLUSION

Based on the expertise gathered throughout the conception, implementation and exhibition of the *Watchers* installation, it seems worthwhile to identify and discuss those aspects of the chosen approach that are sufficiently generalisable to inform further research and artistic experimentation. The realisation of this installation was motivated by the desire to identify and test strategies for rendering a complex generative system experienceable by directly exposing its algorithmic properties in the perceivable characteristics of the installation. Time-delayed feedback networks constitute a particularly promising candidate for this approach since their behaviour can easily be made audible through direct audification. But in order to render the generative system accessible not only to aesthetic appreciation but also to intellectual engagement, it was deemed necessary to integrate interactivity as a central element of the system's experiential exposure. Interactivity provides an excellent opportunity for visitors to gain through active exploration a first hand experience and understanding of the internal algorithmic principles that underlie the appearance and dynamics of a generative artwork. The development of strategies for establishing interactive relationships with a generative system can greatly benefit from concepts and techniques in tangible computing and musical interface and installation design. The development of *Watchers* is based on the following design heuristics: the combination of natural and metaphorical mappings between algorithmic and perceptual properties, the generation of a musical output that conveys not only aspects of the self-organised characteristics of the generative system but also provides immediate and direct acoustic feedback to interaction, the provision of an exhibition setting that equally enables and rewards playful, explorative and goal-oriented forms of engagement with the installation. These design heuristics led to the following implementations. Natural mapping is realised through a direct audification of the network node activities and by choosing a point source spatialisation approach that relates the acoustic output of each loudspeaker to the activity of a corresponding node. Metaphorical mapping is based on the spatial principle of line of sight among loudspeakers and its relation to the connectivity of the generative network. The generative and reactive aspects of the installation were balanced by integrating a doppler-like acoustic feedback as immediate response to the manual rotation of a loudspeaker and by choosing a loudspeaker setup that facilitates the formation of small subnetworks that exhibit simpler self-organised dynamics.

Playful forms of engagement benefit from the installation's fast and pronounced behavioural and sonic responses to embodied interaction. This includes not only the doppler-like response to tangible interaction but also the quick and massive changes in the connectivity of the network that result from occlusion effects by the visitor's body. Explorative forms of engagement are facilitated by interacting from a position outside of the loudspeaker ring. By experimenting with different loudspeaker orientations and observing the resulting acoustic development, the visitor can gain an understanding for the algorithmic principles underlying the relationship between the physical properties of the installation and the sounding output. Once a visitor has grasped this principle, he or she might try to create a *connected* network graph by rotating the loudspeakers into specific orientations. Since a *connected* network exhibits a more interesting self-organised dynamics than multiple isolated sub-networks, the achievement of a higher level of musical complexity can be considered to be the reward for this type of goal-directed engagement. In conclusion, it is clear that the application of complex systems for sound synthesis and algorithmic composition offers exciting opportunities to discover new sonic possibilities and to experiment with autonomous musical systems. But the abstract algorithmic principles of such systems can be hard to grasp, both for musicians who plan to integrate these principles into their sound design and / or compositional procedures and for lay people who encounter such systems in the form of a generative artwork. A direct audification approach can prove to be very useful for transferring the specific characteristics of generative algorithms into a compelling experience. And concepts and techniques from tangible interaction and musical interface design can inspire strategies for rendering the generative algorithms accessible for intuitive forms of interaction and comprehension. It is hoped that the realisation of the *Watchers* installation serves as an example as to how such an approach can be implemented.

REFERENCES

Battey, Bret. 'Musical Pattern Generation with Variable-Coupled Iterated Map Networks.' *Organised Sound* 9 (2): 137–150, 2004.

Bilbao, Stefan. 'Wave and Scattering Methods for Numerical Simulation.' Chichester: John Wiley & Sons, 2004.

Bisig, Daniel, and Philippe Kocher. 'Early Investigations into Musical Applications of Time-Delayed Recurrent Networks.' *Proceedings of the Generative Art Conference*, Milano, 2013.

Borevitz, Brad. 'Super-Abstract: Software Art and a Redefinition of Abstraction.' read_me: *Software Art & Cultures*. Arhus, Denmark, University of Aarhus, pp. 298–312, 2004.

Burns, Christopher. 'Compositional Strategies for Point-Source Spatialization.' *eContact!* 8, no. 3, 2006.

Carlson, Chris, Eli Marschner, and Hunter McCurry. 'The Sound Flinger: A Haptic Spatializer.' NIME. 138–139, 2011.

Dorin, Alan. 'Generative processes and the electronic arts.' *Organised Sound 6* (01): 47–53, 2001.

Dorin, Alan, Jonathan McCabe, Jon McCormack, Gordon Monro, and Mitchell Whitelaw. 'A Framework for Understanding Generative Art.' *Digital Creativity* 23 (3–4): 239–259, 2012.

Eldridge, Alice. 'Neural Oscillator Synthesis: Generating Adaptive Signals with a Continuous-Time Neural Model.' *Proc. of the International Computer Music Conference*. Barcelona, 2005.

Eldridge, Alice. 2012. 'The Poietic Power of Generative Sound Art for an Information Society.' *The Sciences* 2 (7): 18, 2012.

Essl, Georg, and Sile O'modhrain. 'An enactive approach to the design of new tangible musical instruments.' *Organised Sound* 11 (03): 285–296, 2006.

Fishkin, Kenneth P. 'A taxonomy for and analysis of tangible interfaces.' *Personal and Ubiquitous Computing* 8 (5): 347–358, 2004.

Galanter, Philip. 'Truth to process–Evolutionary art and the aesthetics of dynamism.' International Conference on Generative Art, 2009.

Gelineck, Steven, and Stefania Serafin. 'A practical approach towards an exploratory framework for physical modeling.' *Computer Music Journal* 34 (2): 51–65, 2010.

Graham, Richard, and Brian Bridges. 'Managing musical complexity with embodied metaphors.' *Proceedings of the International Conference on New Interfaces for Musical Expression* (NIME). Louisiana State University, 2015.

Hamman, Michael. 'Dynamically Configurable Feedback / Delay Networks: A Virtual Instrument Composition Model.' *Proc. of the International Computer Music Conference*. Aarhus, 394–397, 1994.

Hayes, Ted. 'Neurohedron: A Nonlinear Sequencer Interface.' NIME. 23–25, 2010.

Hermann, Thomas. 'Model-Based Sonification.' *The Sonification Handbook*, edited by Thomas Herman, Andy Hunt, and Neuhoff John G, 399–427. Logos Publishing House, Berlin, Germany, 2011.

Kaltenbrunner, Martin, Sile O'Modhrain, and Enrico Costanza. 'Object design considerations for tangible musical interfaces', 2004.

Kramer, Gregory. 'Auditory display: Sonification, audification, and auditory interfaces.' Perseus Publishing, 1993.

Lakoff, George, and Mark Johnson. 'Metaphors we live by.' University of Chicago press, 2008.

Marshall, Paul, Yvonne Rogers, and Eva Hornecker. 'Are tangible interfaces really any better than other kinds of interfaces?' 2007.

Michon, Romain, Myles Borins, and David Meisenholder. 'The Black Box.' NIME. 464–465, 2013.

Neukom, Martin. 'Signals, Systems and Sound Synthesis.' Peter Lang International Academic Publishers, 2013.

Ohya, Kenichi. 'Sound Variations by Recurrent Neural Network Synthesis.' *Proc. of the International Computer Music Conference*. Ann Arbor, 280–283, 1998.

Sanfilippo, Dario, and A Valle. 'Towards a typology of feedback systems.' *Proceedings of the International Computer Music Conference.* 30–37, 2012.

Shaer, Orit, and Eva Hornecker. 'Tangible user interfaces: past, present, and future directions.' *Foundations and Trends in Human-Computer Interaction* 3 (1–2): 1–137, 2010.

Smalley, Denis. 'Spectromorphology: explaining sound-shapes.' *Organised sound* 2 (02): 107–126, 1997.