Musical Approaches for Working with Time-Delayed Feedback Networks

Daniel Bisig
Institute for Computer Music
and Sound Technology
Zurich University of the Arts
daniel.bisig@zhdk.ch

Philippe Kocher
Institute for Computer Music
and Sound Technology
Zurich University of the Arts
philippe.kocher@zhdk.ch

ABSTRACT

Highly recurrent networks that exhibit feedback and delay mechanisms offer promising applications for music composition, performance, and sound installation design. This paper provides an overview and a comparison of several pieces that have been realised by various musicians in the context of a practice-led research project.

1. INTRODUCTION

Over three years, the ICST Institute for Computer Music and Sound Technology has run a research project entitled *FAUN – Feedback Audio Networks* that explored the musical potential of time-delay and feedback mechanisms within densely interconnected recurrent networks [1]. Such networks are interesting for several reasons: The changing activity of the network can be rendered audible through direct audification which abolishes the need for a potentially arbitrary sonification mapping. The manipulation of delay times provides a formalism of potential use for both sound synthesis and algorithmic composition. The networks lend themselves for generative approaches that explore the sonic potential of self-organised processes.

The *FAUN* project follows a practice-led approach to study how time-delayed feedback networks can be adopted for musical creation. This paper considers how musicians appropriate and integrate the conceptual, functional and aesthetic principles of these networks into their own creative practice. Accordingly, the paper does not provide a systematic analysis of particular network algorithms but rather highlights and discusses the diversity of individual approaches that were chosen by the musicians.

2. BACKGROUND

This section presents a brief overview of the application of feedback and delay principles in sound synthesis. It also provides information about approaches that transfer computational data and processes into experienceable representations. These approaches can inspire musicians to render sound synthesis techniques perceivable not only sonically but also through the tangible, spatial and interactive characteristics of sound installations.

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 [2]. In digital signal processing, typical applications include the design of recursive filters or the simulation of room acoustics (see e.g. [3]) In sound synthesis, several physical modelling techniques, such as digital waveguide synthesis, employ feedback and delay to simulate the propagation of acoustic waves through physical media (see e.g. [4]).

Approaches that employ feedback and delay mechanisms within highly recurrent networks are much less common. Such networks can give rise to interesting phenomena of self-organisation. The term *generative audio system* is used to designate generative approaches in computer music that do not operate on symbolic data but rather create the sonic output through direct audification [5].

There exist a few examples that employ neural networks for sound synthesis [6, 7]. Approaches that are not related to neural networks are equally relevant. The computer music environment *resNET* represents an early example [8]. It permits the realisation of networks for sound synthesis that consist of interconnected exciter and resonator units. More recently, a sound synthesis system was realised based on iterative maps whose variables are coupled via a network [9]. Recent research has been conducted on feedback networks consisting of time-varying allpass filters [5].

2.2 Exposure of Generative Systems

Due to their complex dynamics, time-delayed feedback networks can be employed as generative systems that exhibit autonomous and self-organised behaviours. This renders these networks attractive within the context of generative art [10, 11]. An ongoing debate in generative art refers to the challenge of devising an artwork in such a way that the specific characteristics of the underlying algorithms manifest themselves as principal aspects of the work. By directly exposing the algorithms in the perceivable characteristics of an artwork, the audience becomes engaged not only on an aesthetic level but can also gain through a process of experiential reverse-engineering an intellectual appreciation of the work [12]. The principle of rendering generative processes directly perceivable can serve as a compositional strategy in computer music [13, 14]. In this context, the method of mapping abstract algorithms into perceptible outcomes is important but also controversial [15]. By reducing the disjunction between algorithms and the sonic material they organise, the correspondence between formal and aesthetic principles can be made more compelling. 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 [11] or ontological alignment [15].

3. WORKS

Several musicians have been invited to realise a work. Apart from the requirement to employ time-delay and feedback mechanisms as main means for sound creation, the musicians were free in their choice of musical ideas and technical implementations. The works include compositions, improvised performances, and sound installations. All works have been shown to the public during a small festival which was organised in October 2016 at the Zurich University of the Arts. An online video trailer provides a brief impression of the festival activities [1] For each work, a representative video excerpt is available online: Roj [2] , Twin Primes [3] , Errant it is [4] , Circular [5] , Thread [6] , Stripes [7] , Sheet Music [8] , Studie 24.2 [9] , Watchers [10] .

To facilitate the comparison between the various works, we standardise the description and depiction of the formal aspects. For each work, the algorithms are described by highlighting the characteristics of the network nodes, connections and topologies. Figures showing the internal characteristics of nodes and connections depict a single node as circle and a single outgoing connection as outlined rectangle. The depicted number of incoming and outgoing signal connections is not representative of the actual network topology. Fig. 1 shows a set of graphical symbols that represent common processing elements within a node or connection. Figures showing the network topology depict network nodes as circles and unidirectional network connections as black arrows. Arrows pointing on both sides are a graphical simplification of two unidirectional connections. Physical audio lines connecting the networks' output or input to loudspeakers and microphones, respectively, are depicted as bold black lines without arrowheads.

3.1 Concert Performances

3.1.1 Roj

The piece *Roj* by Bojan Milosevic employs network-based algorithms for creating a body of sonic material that was later manually arranged and performed as tape music. A core musical interest of the musician concerns the acoustic effects that result from continuously changing delay times and network topologies. For this purpose, the musician developed a network implementation that allows to dynamically change the connectivity among network nodes and the mapping of control values on delay times.

The node and connection characteristics are depicted in Fig. 2. Each node sums the incoming audio signals and passes the result through a gain function before sending it out to other nodes. This gain function forms part of an automated signal amplitude control mechanism. Sine oscillators or noise units can be added whose output is mapped on the delay time.

The left side of Fig. 3 shows a schematic representation of a network. While this network represents an arbitrary example, it nevertheless highlights several key elements that were used for the creation of musical material. The network possess recurrent connections that connect different nodes with each other and single nodes back on themselves. Also, the network incorporates several number generators for automating changes in delay times. The acoustic output passes through a mixing desk which permits to distribute the output spontaneously during a performance.

Figure 1. Graphical symbols used for the schematic representation of network nodes and connections. From left to right: summation, threshold function, sigmoid transfer function, gaussian transfer function, negative exponential function, gain function, root mean square (RMS), random number generator, low pass filter.

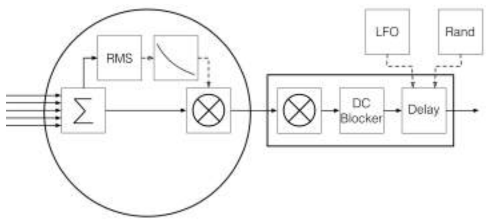

Figure 2. Node and connection characteristics for the piece *Roj*.

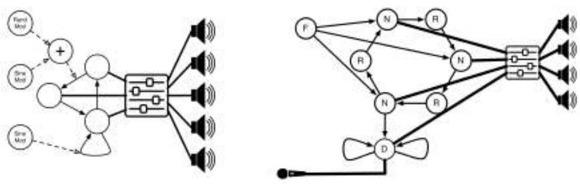

Figure 3. Network topologies for the pieces *Roj* (left) and *Errant it is* (right) . The labels stand for: F = Fourses unit, N = Izhikevich neuron, R = Karplus-Strong resonator, D = feedback and delay unit.

[1] https://vimeo.com/217825545
[2] https://vimeo.com/217974487/5fc155cb32
[3] https://vimeo.com/217974854/0ec449eac6
[4] https://vimeo.com/217974122/4ac141f4c3
[5] https://vimeo.com/217973648/30df6779f8
[6] https://vimeo.com/217851901/f8a43e9e1b
[7] https://vimeo.com/121604263
[8] https://vimeo.com/121603682
[9] https://vimeo.com/217859390/a32a315736
[10] https://vimeo.com/217893895/ad977f1a11

3.1.2 Twin Primes

The piece *Twin Primes* by Philippe Kocher combines the audio output of time-delayed feedback networks with instrumental sounds from two percussion sets. The piece establishes a relationship between musicians and network by using the acoustic output of the musicians as input material for the network. The gradual change of this relationship forms part of the musical development of the piece. Initially, the network briefly processes the percussive sounds before falling silent again, later on, the network assumes a more autonomous role and produces sustained sounds.

The node and connection characteristics are schematically depicted in Fig. 4. The node contains the same auto gain mechanism that was used in the piece *Roj*. The scaled input signal is passed through a gating element whose opening and closing is controlled by the amplitude of the microphone input: The gate opens if the RMS of the microphone signal lies above a threshold. The gate closes either after a predefined duration or when the microphone input exceeds the threshold a second time. The opening and closing of the gate is not instantaneous and its speed constitutes an additional musical control parameter. Whenever the gate closes, it triggers a randomisation of the delay values of the node's outgoing connections.

The piece uses multiple network topologies which are used either in parallel or sequentially throughout the performance (see Fig. 5). These networks receive audio input from contact microphones which are taped to various instruments of the percussion set. The acoustic output of the network nodes is routed to five speakers on stage according to a fixed matrix. The switching of networks, the control of network behaviours and parameters, and the routing of the microphone output are all predetermined as part of the compositional structure of the piece.

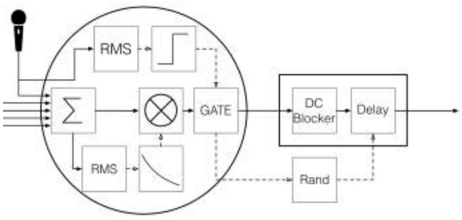

Figure 4. Node and connection characteristics for the piece *Twin Primes*.

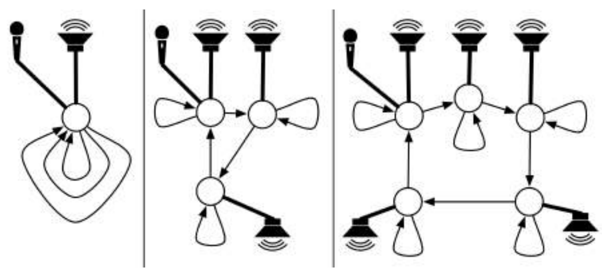

Figure 5. Example network topologies and audio routings for the piece *Twin Primes*.

3.1.3 Errant it is

The piece *Errant it is* by Volker Böhm combines a computational model of spiking neurons with several audio signal processing elements. This approach integrates the hardly predictable dynamics of a biologically inspired model network with more familiar and easily controllable elements from digital signal processing. The resulting heterogenous network serves as an improvisation tools for live performance. This network integrates the following elements: nodes that implement the *Izhikevich* spiking neuron model [16], *Karplus-Strong* string resonators, a time-delay and feedback network, and a so-called *Fourses* unit. This unit creates audio signals by confining multiple sawtooth waves within each others' amplitude envelope. [11] During the performance, various network parameters are modified in realtime using a Midi controller. Initially, the musical output is created solely from the acoustic output of the model neurons. Later on, the output of the *Fourses* unit is used to create rhythmic patterns. Towards the end, the musical output is generated by the feedback and delay network which receives its audio input from a microphone.

A graph representation of the differential equation set that describes the behaviour of the *Izhikevich* neurons is shown in Fig. 6. The characteristics of the nodes and connections that were used in the feedback and delay network is shown in Fig. 7. The nodes pass the summed input signal into an output connection. The connection contains a DC blocker, a pitch shifter, an equaliser, and a delay unit. The RMS of the node's audio signal can be used to automatically control the delay time. The topology of the heterogenous network that was used during the performance is shown on the right side of Fig. 3. The network is divided into two subnetworks. One subnetwork consist of three *Izhikevich* model neurons and three *Karplus Strong* string resonators which are connected to each other in a circular arrangement. The other subnetwork consists of a single node that possesses two recurrent delay connections to itself. A single *Fourses* unit is connected to all *Izhikevich* model neurons and serves as an external signal generator. The acoustic output of the *Izhikevich* model neurons and the time-delay feedback network node are mixed and then routed to four loudspeakers.

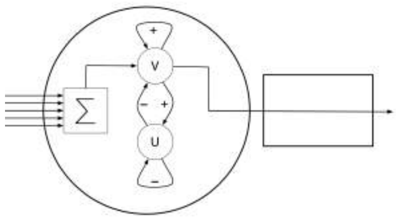

Figure 6. Node and connection characteristics of *Izhikevich* neuron models for the piece *Errant it is*.

3.1.4 Circular

The piece *Circular* is different from the other pieces in that it employs a physical feedback mechanism. The main

[11] http://vboehm.net/2014/12/fourses/ (accessed 2017-02-26)

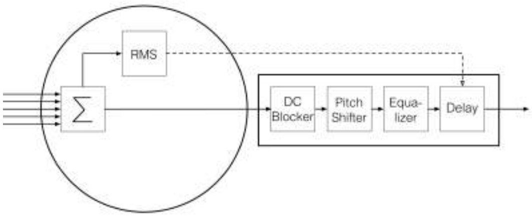

Figure 7. Node and connection characteristics of a feedback and delay network for the Piece *Errant it is*.

role of the performer is to control the feedback effects through the manipulation of a hand drum. This drum interferes with the acoustic transmission between a loudspeaker and a microphone and serves as acoustic filter and trigger. Fig. 8 shows a diagram of the stage setup on the left side and a photograph of the performance on the right side. The audio signal that is picked up by the microphone is routed into a simple signal processing patch. This patch passes the incoming audio signal through a multi band compressor and a gain unit, the latter of which can be controlled with a Midi foot pedal.

Figure 8. Diagram of the stage setup for the piece *Circular* (left) and a photograph of the performance (right). From left to right, the graphical elements represents a foot pedal and a hand drum.

3.1.5 *Thread*

The piece *Thread* employs four steel wires that serve as unconventional loudspeakers. These wires are 8 meters long and attached to two hand-rails of a car ramp. The output of multiple different feedback and delay networks which are interactively controlled by the performer is routed through transducers onto the wires. The realisation of the piece is motivated by the following musical interests: The combination of the network-based sonic material with the highly idiosyncratic acoustic properties of steel wires. A musical improvisation based on the real-time exploration of different acoustic phenomena within subregions of a large network. The performance alternates between musically minimalistic phases during which the performer hardly interferes with the network's behaviour and more musically diverse passages during which the network is subject to more frequent manual control.

The characteristics of the network nodes and connections is depicted in Fig. 9. Each node passes the sum of the input signals through a gating element before exiting through outgoing connections. This gating mechanism operates in a similar manner as has been described for the piece *Twin Primes*.

Fig. 10 shows a diagram of two example network topologies that were used during different stages of the performance. In these two networks, the node in the top left corner of each network deserves special mentioning. This node functions as compositional element in that its activity and the time delays of its outgoing connections are sequentially modified according to a predefined list of values.

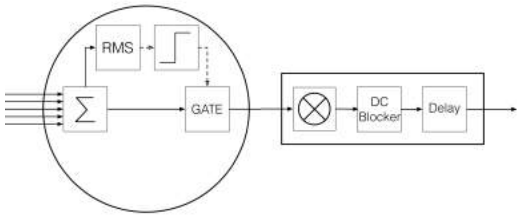

Figure 9. Node and connection characteristics for the piece *Thread*.

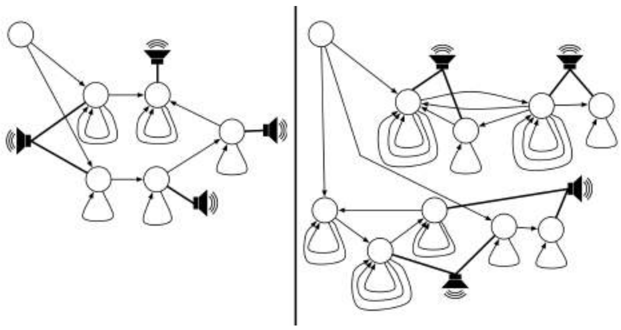

Figure 10. Example network topologies and audio routings for the piece *Thread*.

3.2 Installations

Several musicians have realised sound installations. In these installations, the acoustic output and certain aspects of the physical and/or spatial setup are set into correspondence to properties of the network algorithms. The installations presented in this section were realised by members of the ICST.

3.2.1 *Stripes*

The sonic output of the installation *Stripes* is generated by a non-standard form of waveguide synthesis that consists of a feedback system with four delay lines. Unlike regular waveguide synthesis, the delay times vary over time and they do so independently from one another. This approach permits the creation of constantly changing timbres and rhythmic gestures. The installation routes the output of each network connection to a corresponding loudspeaker. As a result, signal propagation through network connections becomes audible as a spatial propagation of sonic changes across the loudspeaker arrangement.

The characteristics of the network nodes and connections is depicted in Fig. 11. Each node employs the same auto gain mechanism that was used in the pieces *Roj* and *Twin*

Primes. The output connection contains a delay unit whose time is constantly changed by linearly interpolating between random values. The network topology is shown on the left side of Fig. 12. The network consists of a single node and four recurrent connections that connect the node with itself. The installation setup consists of four piezoelectric speaker films, each of them 1.8 metres long, that hang from the ceiling (see right side of Fig. 12).

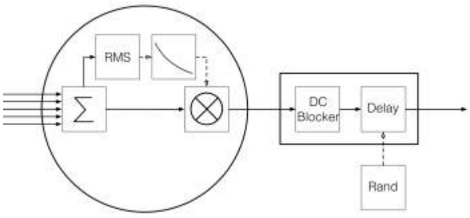

Figure 11. Node and connection characteristics for the installation *Stripes*.

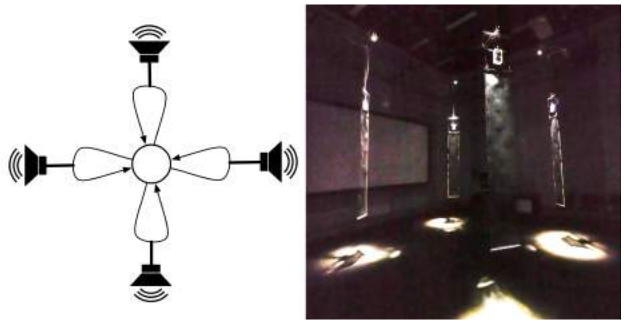

Figure 12. Network topology and audio routing for the installation *Stripes* (left) and a photograph of four piezoelectric loudspeakers (right).

3.2.2 Sheet Music

The installation *Sheet Music* employs a network algorithm that resembles the functioning of a switch board. Whenever a node's signal amplitude exceeds a threshold, the node's output is connected to another node. In combination with a one-to-one correspondence between node activity and acoustic output via a corresponding loudspeaker, the switching behaviour gives rise to pointillistic sonic patterns that propagate through space. In addition, the installation establishes a relationship between delay times and spatial distances among loudspeakers. The delay time between nodes is proportional to the spatial distance between the corresponding loudspeakers. This allows to exploit the spatial constraints of an exhibition situation in order to create a unique and site specific network configuration.

The characteristics of the network nodes and connections is depicted in Fig. 13. Each node passes the summed input signals through a limiter and a routing mechanism that switches in a round robin manner to its next setting whenever the node's signal amplitude exceeds a threshold. The network topology is shown on the left side of Fig. 14.

The installation setup consists of eight piezoelectric speaker films, each of them an A4 sheet in size, sitting on top of a note stand (see right side of Fig. 14). Once the installation is set up, the distances among the loudspeakers are manually measured and stored in a configuration file to be read upon initialisation of the network. A more thorough description of the installation is available in [17].

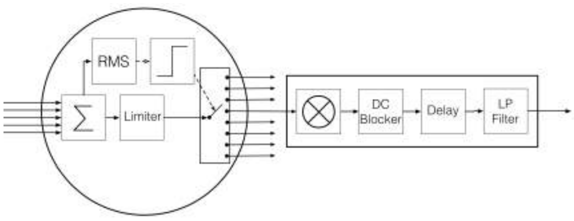

Figure 13. Node and connection characteristics for the installation *Sheet Music*.

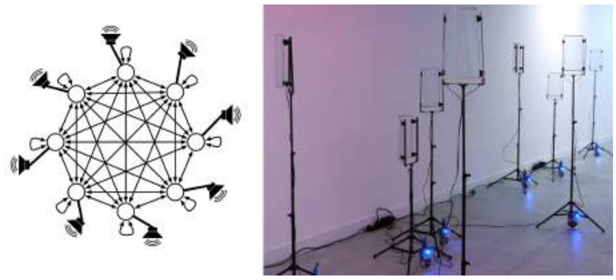

Figure 14. Network topology and audio routing for the installation *Sheet Music* (left) and a photograph of the piezoelectric loudspeakers (right).

3.2.3 Studie 24.2

For the realisation of the piece *Studie 24.2* the existing setup of the installation *Dodecahedron* was used. This setup possesses the shape of a platonic body and places twenty loudspeakers at equal distances from each other on the surface of a sphere. The piece appropriates the given geometric setup as compositional constraint in that it relates the physical loudspeakers and the metallic struts to nodes and connections in a feedback and delay-network. By modifying the probabilities of signal propagation across different network connections, temporary subnetworks are formed.

The node and connection characteristics are shown in Fig. 15. Here, the RMS of the signal amplitude is passed through a nonlinear gain function that boosts middle amplitudes while eliminating low and high amplitudes. In addition, a global amplitude control mechanism uses the RMS of all network signals to adjust the output gain of network connections. The gain and delay values are continuously randomised, which serves to create gradually changing timbres and helps to avoid the appearance of resonances.

Fig. 16 shows a schematic representation of the network topology on the left side and a photograph of the *Deodecahedron* installation on the right side. According to the direct correspondence between installation scaffold and network topology, each node is connected to three neighbouring nodes. Signals propagate in a branching manner, i.e.

a signal that arrives at a particular node from one of its neighbouring nodes can only be propagated to the other two neighbouring nodes. The probability and scaling of this branching propagation are randomly changed. This propagation principle leads to the appearance of local sonic movement trajectories.

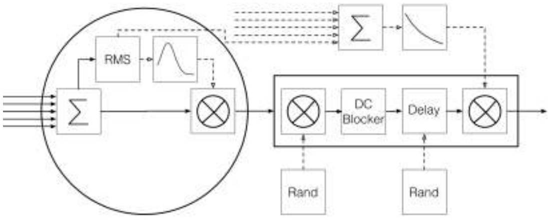

Figure 15. Node and connection characteristics for the piece *Studie 24.2*.

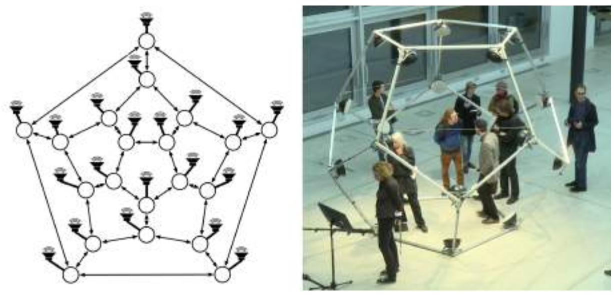

Figure 16. Network topology and audio routing for the piece *Studie 24.2* (left) and a photograph of an exhibition setup (right)

3.2.4 Watchers

The installation *Watchers* allows visitors to manually alter the horizontal orientation of loudspeakers and thereby affect the topology of the network-based synthesis system. Each loudspeaker renders the activity of a particular network node audible. Loudspeakers possess a line of sight which controls the existence of network connections. Depending on a loudspeaker's orientation, different neighbouring loudspeakers fall into its line of sight. Network connections are created between nodes that correspond to loudspeaker that can "see" each other. Whenever the establishment of a connection leads to the propagation of activity among network nodes, the sonic characteristics of the corresponding loudspeakers become gradually intermixed.

The characteristics of the network nodes and connections is depicted in Fig. 17. A node contains an internal sine oscillator whose output is combined with the sum of the incoming signals. This combined signal is passed through a sigmoid wave shaping function that serves as audio distortion and gating mechanism. The shape of the wave shaping function changes based on whether the RMS of the input signal lies within or outside a lower and upper threshold.

Fig. 18 shows a schematic representation of the network topology and audio routing. Each loudspeaker is attached to a rotational joint. Also, each loudspeaker possesses a unique identifier that is communicated to other loudspeakers vie an infrared sender mounted at the front of their casing. This signal is received by other loudspeakers via an infrared receiver that sits at the back of their casing. Each loudspeaker then transmits the list of received identifiers via Wifi to a computer which updates the topology of the sound synthesis network accordingly. A more thorough description of this installation is provided in [18].

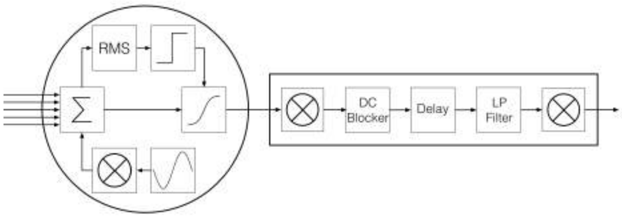

Figure 17. Node and connection characteristics for the piece *Watchers*.

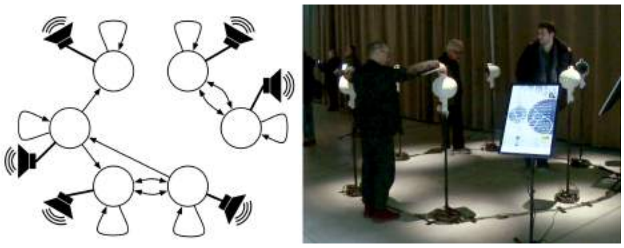

Figure 18. Network topology and audio routing for the installation *Watchers* (left) and a photograph of the exhibition situation (right)

4. DISCUSSION

This section provides a comparison and discussion of the musical approaches for the previously described pieces.

4.1 Algorithm Design

On a basic level, the design of sound synthesis network algorithms can either be informed by techniques from digital signal processing or from the appropriation of algorithms from non-musical domains. The former approach is familiar to most musicians whereas the latter results in non-standard techniques whose musical usefulness is more difficult to assess. In *FAUN*, most musicians chose a digital signal processing approach in their network implementation. Only the piece *Errant it is* implements a neural network. However, this implementation is complemented with more conventional signal processing algorithms.

4.1.1 Feedback Stabilisation

One of the challenges when working with feedback systems concerns the avoidance of instabilities caused by positive feedback. Most of the pieces employ an ad hoc approach for the automated stabilisation of feedback. The corresponding mechanisms either directly control local or global signal gain or employ a gate that closes whenever the signal exceeds a threshold. Only in two pieces for live improvisation (*Errant it is*, *Circular*), the task of feedback stabilisation is delegated to manual intervention.

Unique approaches for feedback stabilisation are employed by the following pieces: *Sheet Music* implements a connection switching mechanism that cuts of the propagation of signals that exceed an amplitude threshold, *Studie 24.2* uses a global signal attenuation mechanism and also boosts signals with average amplitude that serves to maintain a fairly constant signal amplitude throughout the piece, *Watchers* uses a wave shaping function to control signal amplitude.

4.1.2 Network Topologies

While all networks described in this paper contain recurrent connections, the characteristics and topologies of the networks are quite diverse. In all pieces with the exception of *Studie 24.2*, many or all recurrent connections connect a node back to itself. While this is obvious for networks that consist of one node only, local recurrent connections are important in larger networks as well since they allow to maintain the activity of a node for extended periods of time. In many of the networks that consist of a few nodes only (3 to 5), the recurrent connections across different nodes serve to establish circular propagation patterns. In networks containing larger number of nodes (6 to 20), circular recurrent patterns appear as well but they do not span all neurons and thereby create subnetworks. The usage of subnetworks within larger networks plays an important role in that it renders the complex feedback dynamics more manageable than in networks that are fully connected. Also, subnetworks permit to maintain concurrent sonically distinct network activities while allowing the occasional exchange of sonic material among the various subnetworks. None of the pieces makes use of a larger network in which the nodes are fully connected.

With the exception of *Errant it is*, all pieces use networks in which nodes and connections all possess the same characteristics. This is an indication that parametrical and topological variations in homogenous networks allow for the creation of sufficiently diverse sonic material so that the added complexity of heterogenous networks is not considered worthwhile by the musicians. On the other hand, many musicians employ several different network topologies, either in parallel or successively throughout the piece.

Some of the pieces use multiple networks with fixed topology (*Errant it is*, *Twin Primes*, *Thread*). By switching between these networks or by scaling the contribution of individual networks to the overall sonic result, the pieces can progress in a predictable manner through different musical sections. Other pieces use only a single network but continuously (*Watchers*, *Sheet Music*) or occasionally (*Roj*) modify its topology. This approach leads to less predictable results since the musical result depends both on the new topology and the former activity patterns that still persist after a topological change. On the other hand, the persistence of network activity helps to create a sonic continuity throughout the development of a piece.

4.2 Compositional Approaches

The use of feedback and delay principles implies that all sonic aspects of a musical piece (pitch, timbre, rhythm, etc.) become mutually interrelated. Accordingly, a musician cannot freely decide to modify each of these aspects individually. The specification of the velocity of the gating mechanism in *Twin Primes* and *Thread* results not only in spectral but also in rhythmical effects. The changing wave shapes in *Watchers* and the connection switching mechanisms of *Sheet Music* serve a similar purpose. In *Thread*, the rhythmic structure is largely predefined by the specification of delay times in connections that pass an initial activation trigger to network nodes. *Errant it is* uses an external mechanism for controlling rhythmicity: a *Fourses* ramp generator occasionally controls periodic changes in the membrane potential of the *Izhikevich* model neurons. The piece *Roj* represents a peculiar case. By manually arranging pre-recorded material, external rhythmic and formal elements are imposed on the music that are unrelated to the characteristics of a network mechanism. This approach offers the largest compositional freedom, but this comes at the cost of sacrificing some of the potential of the networks to operate as autonomous generative systems. Most musicians tried to strike a balance between compositional freedom and generative autonomy.

An interesting relationship between human performer and generative system develops in *Thread* and *Circular*. In both pieces, the musician's behaviour consists mostly of spontaneous reactions to the complex behaviour of the network. Accordingly, both the musician and the network possess agency and it is the mutual interplay between the two that shapes the development of the piece.

4.3 Experienceable Relationships

This section addresses the establishment of relationships between network algorithms and experienceable results that go beyond purely sonic considerations.

4.3.1 Spatialisation

In all pieces, the output of the network is spatialised by a multichannel speaker setup, but two different approaches are employed. Either the output of the network is routed through a mixing desk before being distributed across the loudspeaker setup, or the sonic output of each network node is directly connected to an individual loudspeaker. Only two pieces (*Roj* and *Errant it is*) follow the first approach. In a one-to-one routing of node output to loudspeaker, the spatialisation of the sonic output is predetermined to a large extend by the network's topology. Accordingly, this approach treats acoustic spatialisation as a property that is correlated with other musical aspects through the behaviour of the network. While this second approach constrains compositional freedom, it offers the opportunity to expose the network's dynamics as spatial trajectories of sonic material.

4.3.2 Physical Correspondences

The one-to-one routing of node output to loudspeaker can be understood as an ontological form of mapping between algorithmic properties and physical objects. That is, the individual nodes in a network manifest both as acoustic point sources and tangible objects. Accordingly, the speaker setup conveys information about the structure of the network that might otherwise be hidden from the audience. This mutual object correspondence is emphasised in *Stripes*, *Sheet Music*, *Studie 24.2*, and *Watchers*.

Apart from establishing a correspondence between network nodes and loudspeakers, some of the pieces also experiment with the exposure of the network's topology through physical or spatial metaphors. *Studie 24.2* uses the given physical structure of an installation as guiding principle for the network topology: each metallic strut between two loudspeakers corresponds to a connection between two network nodes. Another approach is chosen for *Sheet Music*, where the distances among loudspeaker are mapped onto delay times. This correspondence between spatial properties of physical space and temporal properties of a sound synthesis system allows the physical space to partially imprint itself on the musical characteristics.

In *Watchers*, relationships among loudspeakers are based on the principle of line of sight. Since visitors can affect the "visibility" among loudspeakers either by manually changing the loudspeakers' orientations or by blocking the infrared signals with their bodies, this principle of correspondence can be exploited as an interaction affordance.

5. CONCLUSION

This publication provides a comparison of different musical approaches for working with time-delay and feedback networks. We believe that the pieces realised in the context of this project are sufficiently diverse to inform a general evaluation of the creative potential of such networks. Nevertheless, it is clear that the chosen approaches hardly represent the full breadth of possibilities. Some of the pieces do not follow fundamentally different approaches but belong to one of several families of similar works that have emerged during the project. Furthermore, two different approaches are underrepresented in this body of works: first, network-based forms of sound synthesis that incorporate algorithms from outside the musical domain in order to experiment with non-standard forms of sound synthesis, and second, installations in which musical strategies for establishing correspondences between musical algorithms and physical properties are exploited as affordances for interactive engagement. In a future continuation of this project, we hope to be able to offer calls for work that specifically focus on these topics.

6. REFERENCES

[1] D. Bisig and P. Kocher, "Early investigations into musical applications of time-delayed recurrent networks," in *Proc. of the Generative Art Conference*, Milan, 2013.

[2] D. Sanfilippo and A. Valle, "Towards a typology of feedback systems," in *Proc. of the Int. Computer Music Conference*, 2012, pp. 30–37.

[3] D. Rocchesso and J. O. Smith, "Circulant and elliptic feedback delay networks for artificial reverberation," *IEEE Transactions on Speech and Audio Processing*, vol. 5, no. 1, pp. 51–63, 1997.

[4] S. Bilbao, *Wave and Scattering Methods for Numerical Simulation*. Chichester: John Wiley & Sons, 2004.

[5] G. Surges, T. Smyth, and M. Puckette, "Generative feedback networks using time-varying allpass filters," in *Proc. of the Int. Computer Music Conference*, 2015.

[6] K. Ohya, "Sound Variations by Recurrent Neural Network Synthesis," in *Proc. of the Int. Computer Music Conference*, Ann Arbor, 1998, pp. 280–283.

[7] A. Eldridge, "Neural Oscillator Synthesis: Generating Adaptive Signals with a Continuous-Time Neural Model," in *Proc. of the Int. Computer Music Conference*, Barcelona, 2005.

[8] M. Hamman, "Dynamically Configurable Feedback/Delay Networks: A Virtual Instrument Composition Model," in *Proc. of the Int. Computer Music Conference*, Aarhus, 1994, pp. 394–397.

[9] B. Battey, "Musical Pattern Generation with Variable-Coupled Iterated Map Networks," *Organised Sound*, vol. 9, no. 2, pp. 137–150, 2004.

[10] P. Galanter, "What is Generative Art? Complexity Theory as a Context for Art Theory," in *Proc. of the Generative Art Conference*, Milan, 2003.

[11] A. Dorin, J. McCabe, J. McCormack, G. Monro, and M. Whitelaw, "A Framework for Understanding Generative Art," *Digital Creativity*, vol. 23, pp. 239–259, 2012.

[12] M. Whitelaw, *Readme 100: Temporary Software Art Factory*. Norderstedt: Books on Demand, 2005, pp. 135–154.

[13] T. Davis, "Complexity as Process: Complexity-Inspired Approaches to Composition," *Organised Sound*, vol. 15, no. 02, pp. 137–146, 2010.

[14] S. Kim-Cohen, *In the blink of an ear: Toward a non-cochlear sonic art*. A&C Black, 2009.

[15] A. Eldridge, "The poietic power of generative sound art for an information society," *the sciences*, vol. 2, no. 7, p. 18, 2012.

[16] E. M. Izhikevich, "Simple model of spiking neurons," *IEEE Transactions on neural networks*, vol. 14, no. 6, pp. 1569–1572, 2003.

[17] P. Kocher and D. Bisig, "The sound installation 'sheet music'," in *Proc. of the Generative Art Conference, Rome*, 2013.

[18] D. Bisig, "Watchers an installative representation of a generative system," in *Proc. of the 5th Conference on Computation, Communication, Aesthetics & X, Lisboa*, 2017.