MUSICAL APPLICATIONS OF GENERALISED MULTICHANNEL DIGITAL WAVEGUIDES

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ABSTRACT

We propose different applications in which extensions of digital waveguides have been used in a compositional context.

1. INTRODUCTION

One dimensional digital waveguides are a synthesis technique widely used in the computer music community to model waves propagating along different media, such as strings and tubes.

Efficient simulations of different musical instruments, such as plucked, struck and bowed strings, woodwinds and percussions have been built using the waveguide approach. Digital waveguides combine an efficient simulation which provide a low cost realtime implementation to to a meaningful physical interpretation. The idea behind digital waveguides was first introduced in a paper by McIntyre, Schumacher and Woodhouse in the early 80s [1]. The authors discovered that different classes of musical instruments, such as a bowed string, a flute and a clarinet, can be modeled using a similar approach of a nonlinear excitation coupled to a linear resonator. Smith developed this idea and introduced the digital waveguide theory, which has been since widely used in the computer music community [2].

In this paper we propose generalized digital waveguides with different topologies with the intent of creating extended physical models. We built different waveguide structures in which traditional and not traditional excitations are fed into a network of eight independent digital waveguides. The following sections describe a description of these networks as well as different musical applications in which they were used.

2. THE EXTENDED WAVEGUIDE STRUCTURE

We started by experimenting with eight independent digital waveguides connected in parallel and excited by different excitation functions, as described below.

2.1. Nonlinear functions as excitations

We started by implementing different nonlinear excitation functions such as a velocity dependent friction curve to reproduce rubbing different hard surfaces and a pressure dependent nonlinear function to reproduce blowing different surfaces. The waveguide resonator was coupled to the nonlinear sustained excitation in a feedback loop.

2.2. Soundfiles and live inputs as excitations

Beyond excitation via mathematical functions, both soundfiles and live audio inputs can be used to drive waveguide networks. For example, we used sampled excitation functions to model rich impulsive excitations such as hit plates and bowls. The excitation was obtained by recording different objects struck at different positions and removing the main frequency components using spectral analysis and inverse filtering. The residual was fed into the waveguide resonator in a feed-forward loop.

The use of soundfiles as excitations also invokes the use of waveguide networks to simulate reverberation; however, more esoteric transformations are also possible. For instance, it is possible to compose continuous transitions between soundfile reverberation and feedback generation, through careful control of delay lengths and gain coefficients

We have also designed networks which are excited by live audio inputs. Depending upon the network topology and system gain, microphones don't even have to be plugged in to excite the network; self-noise at the ADC may be sufficient to set the process in motion. These setups, as in the John Cage realization described in section 6.2, can produce complex and interesting interactions between the activities of a live performer and the output of the network.

3. VARIATIONS ON WAVEGUIDE SECTION STRUCTURES

3.1. Peak gain control with nonlinear functions

Traditional waveguide topologies, like other signal processing elements which involve feedback (e.g., IIR filters) are explicitly designed to preserve system stability. However, it is possible to impose at least bounded amplitudes in signal processing systems which do not need traditional criteria for stability. Local peak control can be implemented via waveshaping with nonlinear functions that produce soft clipping. Charles Sullivan presented one such function in his work on physical models of the electric guitar [3]:

$$f(x) = \begin{cases} \frac{2}{3}, & x = 1 \\ x - x^3/3, & -1 < x < 1 \\ -\frac{2}{3}, & x = -1 \end{cases} \tag{1}$$

Related methods for amplitude management include peak limiting compression and the "elastic-mirrors" in Xenakis' GENDYN technique ([4, 5]).

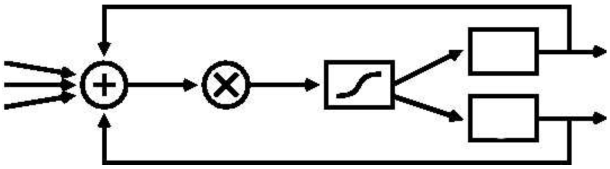

Figure 1: *Block diagram for a non-waveguide-like section of a feedback network.*

Nonlinear waveshaping functions necessarily color the sonic output of a system. This is especially apparent when nonlinearities are deployed at several different points in a network. While this timbral alteration may seem like a disadvantage, in a compositional context it can just as well be viewed as a desirable feature. After all, peak-managed feedback networks are of interest precisely because they encourage non physical designs with unusual sonic characteristics.

3.2. Selective destabilization: waveguides without polarity inversion

Peak-management techniques like nonlinear waveshaping allow a rethinking of the elements and connections within a single waveguide. Many of the waveguides tested in our work feature continuously changing delay lengths, including dynamic delay lengths independent for each rail of a waveguide. Some sections tested even forego the notion of rails, placing delays in configurations which cannot be interpreted physically.

Similarly outside of the domain of physical interpretation, peak management makes it possible to eliminate the typical inversion of polarity as a signal passes between rails of the waveguide [6]. Waveguides which don't utilize sign changes tend to output DC. However, they can be encouraged to produce audible signals if they are perturbed, through changes to the gain coefficients, the delay lengths, or the excitation.

4. NETWORK TOPOLOGIES

4.1. Circular and "spoke" topologies

Nonlinearities and other forms of peak management facilitate a wide range of network topologies, eliminating concerns about the gain structure of a particular architecture [7]. Our experiments have focused on circular architectures (networks without a particular beginning or end), including structures with "spokes" connecting nonadjacent sections.

5. SPATIALIZATION

5.1. Spatialization of independent waveguides

Because the primary goal of physical modeling has traditionally been to recreate sounding physical bodies, techniques of waveguide synthesis have largely dealt with exteriors of bodies. One natural extension of the physically-based waveguide network is the use of independent spatial modulation of individual waveguides. By distributing the waveguides of a physically-based system around the listener the notion of "body" as perceived from an exterior orientation, and the perceptually interior notion of "space," can be modulated. Spatial modulation of the system allows for an extended notion of the objecthood of the model, and the possibility of transforming it from body into space, or from object into environment. In previous work, the authors have explored extended techniques for physical models by taking advantage of the disassociation of the synthesis and control aspects of the virtual instruments [8, 9].

Building on this work, the physical model of the Tibetan singing bowl suggested an extended approach to spatialization for waveguide networks. A bowl model was implemented allowing each of eight waveguides to be controlled independently. In order to explore the acoustic effect of moving from an exterior to an interior position of the bowl, the impulse response of the bowl was taken from different locations in and around the bowl. Microphone placed inside the center of the bowl, 30cm above the bowl, and 20cm to the side recorded the different impulse responses of the bowl. From these recorded impulse responses, we extracted the frequencies of the main resonances of the instrument, together with the corresponding damping factors, using spectral analysis. The modeling of the multichannel bowl has been discussed in depth in [10].

The resulting instrument, implemented as an extension to the Max/MSP environment, allows simultaneous independent control of the eight fundamental frequencies, eight decay times for the low-pass filters, eight bandwidth for the resonant filters, four dispersion coefficients for the allpass filters, one inlet to input an external source of energy, one excitation position (i.e. where the bowl is hit), one excitation pressure (i.e. how hard it is hit) and one excitation velocity. Eight outlets, each outlet corresponding to a mode of the resonant structure, are sent to spatial processing algorithms for diffusion through a multichannel loudspeaker configuration.

The spatial transformations of the physically-based waveguide networks described here, as in earlier work, represent a desire to explore extended techniques of physical modeling synthesis, in this case using spatial processing. In both projects the possibilities of the embodiment of the model are being broadened. The virtual body is not confined to the same limitations as the physical body, and an extended technique is explored that blurs the boundaries between resonating body and acoustic space.

It was found that multi-channel diffusion of the modes stresses the coherence of the model, perceptually pulling apart the synthesis into constituent parts as the components are treated separately in space. This technique has been identified as an example of Spatio-Operational Spectral (SOS) Synthesis, and discussed in greater detail in another paper ([11]).

5.2. Spatialization of circular network topologies

For waveguide networks composed of many discrete sections, one approach to spatialization is to output each section separately. Figure provides a simple example; eight discrete sections of the type are arranged in a circle, with the output of each section routed to its own loudspeaker.

This type of configuration essentially sonifies the propagation of sound through the network, making it possible to hear the influence of particular regions of the network on their adjacencies. While there is no panning or illusion of motion in the traditional sense, cascades of audible activity around the network can produce a variety of interesting spatialization effects.

6. MUSICAL APPPLICATIONS

6.1. That which is bodiless is reflected in bodies II (Burtner)

In the musical composition, *That Which is Bodiless is Reflected in Bodies II*, SOS synthesis is used to explore the threshold between physical and non physical reality. The composition takes as its starting and ending point the physical model bowl as a true acoustic representation of the physical body. In the piece, the physical object is transformed and explored as a multidimensional space that gradually disintegrates into nonphysical reality. The compositional process in the pieces draws on a gradual disembodiment and reimbodiment of the acoustic nature of the bowl's physicality.

In order for the physical model to become a transformative emersive environment, the possibility of recreating a spatial representation of the transformational modal bowl is explored in the composition. Changes in modal properties of the bowl effectively alter the size and shape of the bowl. If the physical model bowl were a real bowl it would be seen changing dynamically in space. Extending this principle from an exteriorization of sound to an interior perspective, if the listener is positioned inside the bowl as a type of room, the room would be changing shapes around the listener.

In order for the listener to effectively experience these changes in a performance context, modal transformations of the bowl are linked with spatial propagation of the sound. To accomplish this, each mode of the multichannel bowl discussed above, was assigned to a separate, distinct audio channel. Figure 2 details the implementation of this configuration.

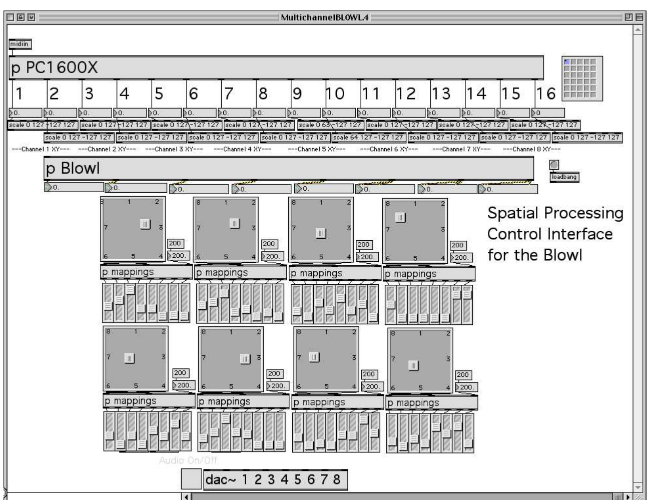

Figure 2: *Max/MSP interface for the extended bowl.*

The output of the modes are coordinated in a spatial configuration surrounding the listener. As the modes change, the spatial location of the signal changes accordingly. *That which is bodiless is reflected in bodies II* draws the listener close to and then inside the acoustics of the resonating bowl. Once inside the bowl, the modes are multiplied generationally, and the sound environment diverges from any physical representation, becoming an abstract auditory environment built from waveguide networks. *That which is bodiless is reflected in bodies II* offers an initial example of how physically-based modal waveguide synthesis can function as an extended technique in combination with spatial processing.

6.2. Cage "Electronic Music for Piano"

Our first application of a peak-managed feedback network was for a realization of John Cage's Electronic Music for Piano [12]. In keeping with the increasingly improvisatory nature of Cage's approach to music with live electronics during the 1960s, the handwritten prose score of Electronic Music for Piano is suggestive, not prescriptive. Inspired by and in appreciation of Cage and especially dedicatee David Tudor's work in the domain of feedback, we designed this version around a feedback network, implemented using Miller Puckette's Pd software [13]. The feedback network is the most prominent of several parallel signal processing chains applied improvisationally to a live performance of Cage's Music for Piano 69-84 [14]. The network represents the most extreme form of signal processing in the realization, in that the sustaining, swooping output sounds utterly unlike the piano input.

The feedback section of the instrument passes the two microphone inputs into a circular chain of delay structures, with sixteen delay lines grouped in eight sections. Although each section has two delays, these are not configured as upper and lower rails, and there is only one polarity inversion in the entire structure. Each of the delay lines has a continuously variable length. These lengths are randomly and independently generated for each delay, as are the sweep and sustain times which control the transitions between each new length.

Despite the emphasis on the algorithmic generation of low-level parameters, there is a role for an electronics operator to improvise and intervene during the performance. The operator has access to global scaling factors for each of three delay parameters (delay length, sweep time, sustain time). These scaling factors allow the operator to compress or expand the parameter ranges available to the algorithms. There is also a single parameter controlling all the (identical) gain coefficients of the network. This is certainly the operator's single most influential parameter over the behavior of the network. Finally, the operator has eight selectable output volume presets, each of which independently modifies the output gain stages associated with the eight different loudspeakers, as well as the ability to mute individual loudspeakers. Each preset has its own spatial distribution and weighting of different segments of the feedback network.

The electronics operator, through the parameters mentioned above, and the pianist, via the microphone inputs, can influence the feedback network. However, they do not command it. The network performs in unpredictable ways, sometimes imitating onsets and pitches played at the piano very precisely, sometimes remaining quiet during busy passages, sometimes bursting into noise in the middle of a long silence. Because there is only one polarity inversion in the network, it tends towards the inaudible output of DC. The pianist can perturb the system into audibility by providing an excitation; the electronics operator can encourage the system to sound by raising the gain coefficients near unity, or by seeking a new configuration of delay lengths. The operator can also reliably squelch the feedback network output by turning the gain coefficients down to zero, or by muting the loudspeakers.

The unpredictable behavior of the destabilized feedback network, enhanced by the algorithmic generation of many of its parameters, is the primary feature of the Electronic Music for Piano realization. There is a symbiosis of piano, pianist, electronics, and operator; in performance the situation is one of improvising with the electronics, rather than using the electronics to improvise. The electronics are designed to guide the operator's musical choices just as the operator guides the electronics. The emergent aspects of the electronics' behavior help foster intense listening and communication between pianist and electronics operator in performance.

6.3. " Hero and Leander" (Burns)

Following the Cage realization, more recent applied work with generalized waveguide networks utilizing peak management has focussed on the composition of multichannel tape music. In the more fixed environment of tape composition, the indeterminate aspects of the Cage realization's feedback network are less desirable, and so we have implemented a new and more pliable version of the network in Bill Schottstaedt's Common Lisp Music environment [15].

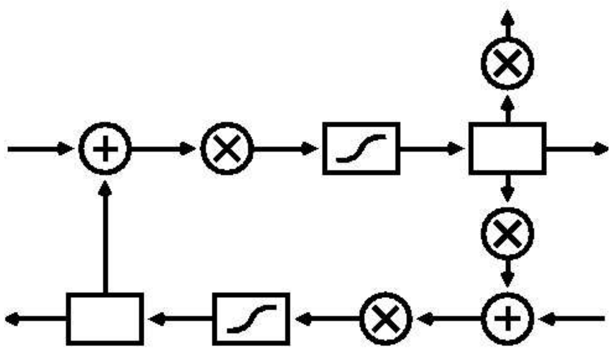

Figure 3: *Block diagram for a waveguide-like section of a feedback network including nonlinear waveshaping, used in "Hero and Leander".*

Like the Cage realization, the new design is built from a circular arrangement of eight sections. However, each section is much more closely modelled on a traditional waveguide, and therefore more stable and less likely to output DC, than in the Cage realization. The designs include upper and lower rails, and four of the eight sections include a polarity inversion. (If all eight sections included the sign change, the results would be more like a conventional physical model, and less like characteristic feedback sound of the Cage realization).

Figure 3 demonstrates the structure of one the sections which includes the polarity change. Compared to the operator's control over the Cage realization, the control parameters for this network are numerous and low-level. The excitation function is an arbitrary multichannel soundfile. The network provides time-varying envelopes for each of the sixteen delay lines, plus one time-varying envelope which controls all the gain coefficients.

If complex envelopes are used, there can be a large amount of information to specify. However, this parameterization provides for a wide variety of results, with a substantial amount of control over the sonic details of the network's output. Articulation characteristics and other sonic details are not exposed directly to the composer as parameters, but are accessible through the influence of delay lengths and gain coefficients.

7. CONCLUSIONS - WAVEGUIDES BEYOND PHYSICAL MODELING

The flexibility of waveguide synthesis allow to create different virtual instruments that are interesting from a musical prospective. This paper described various approaches of composition using digital waveguides, which will be played during the oral presentation.

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