Emergent Behavior from Idiosyncratic Feedback Networks

Christopher Burns

Center for Computer Research in Music and Acoustics (CCRMA), Stanford University
email: cburns@ccrma.stanford.edu

Abstract

Traditional waveguide networks are designed for stability and predictability. However, idiosyncratic variations to feedback network structures become possible when peak gain is controlled throughout the network by nonlinear waveshaping functions. These functions facilitate destabilizing changes to the network gain structure and topology, producing unpredictable behavior with interesting applications in composition and improvisation. These applications suggest further extensions to the waveguide network model, including nonstandard excitation functions, control parameters, and spatialization techniques.

1 Feedback networks and stability

Traditional signal processing architectures which utilize feedback are constructed to ensure their stability and predictability. For instance, there are canonic limitations on the coefficients of IIR filters, and waveguide sections are explicitly designed to preserve system stability.

However, it is possible to impose at least bounded amplitudes in signal processing systems which do not meed traditional criteria for stability. For instance, Xenakis' GENDYN software uses "elastic-mirrors" to ensure that amplitudes generated by random walks will not exceed appropriate boundaries (Xenakis 1992, Hoffmann 2000). Peak-limiting compression algorithms are another method for achieving this result. A third, easily implemented technique for peak control is waveshaping with nonlinear functions that produce soft clipping. Charles Sullivan presented one such function in his work on physical models of the electric guitar (1990):

$$f(\mathrm{x}) = \begin{cases} 2/3; & \mathrm{x} \bullet 1 \\ \mathrm{x} - \mathrm{x}^3 / 3; & -1 < \mathrm{x} < 1 \\ -2/3; & \mathrm{x} \bullet -1 \end{cases}$$

Figure 1 presents a plot of this function over the range $-1 \bullet x \bullet 1$. Relatives of this function (of the form $x - x^n / n$, for odd $n \bullet 3$) can also be used to produce different varieties of soft clipping.

Nonlinear functions manage peak gain because they are inherently lossy. They also change the harmonic structure of their input, coloring the system output. (The effect will be particularly pronounced when nonlinearities are deployed at several different points in a system). 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, destabilized feedback networks are likely to be of interest precisely because of their unusual sonic characteristics.

2 Beyond standard architectures

When the peak gain of a feedback network is controlled through nonlinear waveshaping or other limiting techniques, then a variety of extensions and modifications to traditional waveguide designs become possible. Variations tested include unusual excitation methods, network topologies, spatialization techniques, and control parameters. In general these extensions cannot be readily interpreted as models of physical or acoustic phenomena. Indeed, some of the network topologies demonstrated are so distant from traditional architectures that they no longer can properly be described as waveguides; hence the more general term "feedback network" used throughout this paper.

2.1 Excitation functions

In feedback networks with peak gain controlled by nonlinearities, it is not necessary to discriminate between impulsive and continuous excitations, or to match the energy of the excitation to the lossiness of the network. Practically any excitation can be used to drive any network.

For instance, soundfiles can be used as excitations. With careful control of delay lengths and gain coefficients, it is possible to compose continuous transitions between soundfile reverberation and feedback generation.

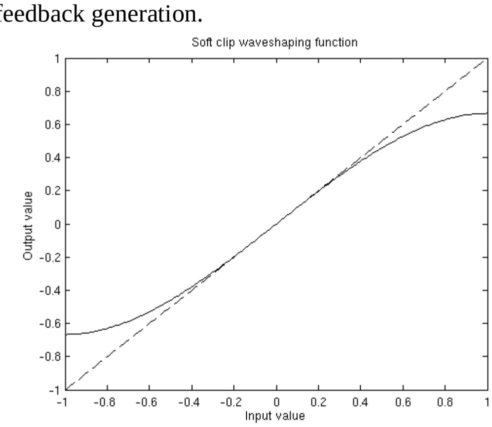

Figure 1: soft clipping function (Sullivan 1990)

Other networks tested employ live microphones for their excitation. (Depending upon the system gain, the microphones don't even have to be plugged in; self-noise at the ADC may be sufficient to excite the network). These setups can produce complex and interesting interactions between the activities of a live performer and the output of the network.

2.2 Network topologies

As with excitation functions, nonlinearities facilitate a wide range of network topologies, eliminating concerns about the gain structure of a particular architecture (Essl and Cook 2002). Our experiments have focussed on circular architectures (networks without a particular beginning or end), including structures with "spokes" connecting nonadjacent sections.

The low-level elements of a waveguide network can also be rethought in this context. Many of the networks tested feature continuously changing delay lengths, in many instances changing delay lengths independently for each rail of a waveguide. It even becomes possible to remove the change of polarity as a signal passes between rails of the waveguide (Smith 1987). Networks which don't utilize sign changes (or don't utilize them consistently) tend to output DC. However, they can be encouraged to produce audible signals if they are perturbed in some way. Changes to the gain coefficients, the delay lengths, or the excitation will temporarily divert the network from its tendency towards DC. Figure 2 presents a block diagram for one section of a feedback network whose component sections do not correspond to waveguide structures; the notion of upper and lower rails is eliminated in favor of a more generalized use of delay, multiplication, addition, and waveshaping.

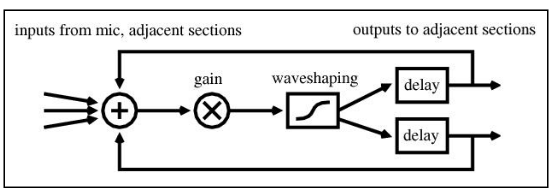

Figure 2: block diagram for a non-waveguide-like section of a feedback network

2.3 Spatialization

An obvious extension to non-physical-model feedback networks composed of many discrete sections is to spatialize the output of each section separately. Figure 3 provides a simple example; eight discrete sections of the type described in Figure 2 are arranged in a circle, with the output of each section routed to its own loudspeaker.

This type of configuration essentially sonifies the 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 in the traditional sense, the cascade of audible activity around the network can produce a variety of interesting spatialization effects.

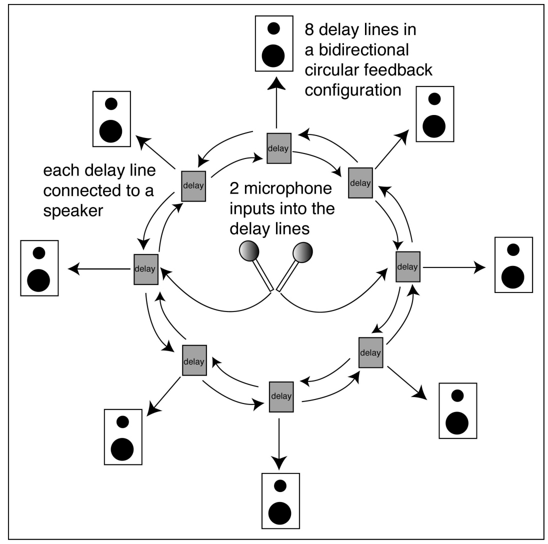

Figure 3: eight network sections from Figure 2 are arranged in a circular configuration and spatialized separately. Note that each "delay" in the graphic represents two independent delay lines.

2.4 Parameterization and control

As with physical models, the parameters for feedback networks tend to be somewhat abstracted from their sonic characteristics. These networks produce articulate, continuously-varying, and even seemingly phrased sonic materials, but they are not directly controllable in musical terms.

However, musical intuitions do apply to the parameters of such a network. Delay lengths do not always correspond to single pitches, but they certainly can be used to specify the presence of a particular harmonic series. Similarly, the gain coefficients of the network are closely linked to both the amount of sonic activity and the spectral content of the resulting sounds.

3 Instability and Improvisation

Our first application of a feedback network like the ones described here was for a realization of John Cage's *Electronic Music for Piano* (1968). 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. As a result there was an extraordinary amount of latitude available for the design of the realization.

Cage's notations include the phrases "feedback" and "for David Tudor." During the 1960s and 70s, Tudor gradually reoriented his career from the performance of avant-garde works for piano to the creation of live electronic music, with electronic feedback systems as the defining component of his work (Adams 1997, Chadabe 1997). Inspired by and in appreciation of Cage and Tudor's work in the domain of feedback, we designed this realization around a feedback network, implemented using

Miller Puckette's Pd software (1996). 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* (1960). 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 (identical to those in Figures 2 and 3). Each of the sixteen delay lines (grouped in eight nodes) is given 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. The delay lengths are chosen from within the frequency range available on the piano keyboard, an idea suggested by the presence of blank staves and ledger lines indicating the piano's complete range in Cage's score. The automatically generated sweep and sustain times are selected from a range between fifteen and fifty seconds.

This emphasis on the algorithmic generation of low-level parameters is carried throughout the other parts of the realization. However, there is a role for an electronics operator to improvise and intervene in high-level ways 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 given above. 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. The gain presets and mutes are triggered via keystrokes on a QWERTY keyboard, with the presets ordered roughly from softest to loudest. 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 are no changes of polarity at any point 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 reliably squelch the feedback network output by turning the gain coefficients down to zero, or by muting the loudspeakers.

The sonic character of the feedback network is varied and idiosyncratic. Complex, swooping pitch contours with continuous micro-alterations of timbre are typical, while the continuously varying delay lengths produce shifting, inharmonic pitch relations. Depending on the gain settings, punctuating noisy explosions may also be frequent. Because the network disregards some of the traditional tuning techniques for physical models (especially polarity inversion), it is likely to enter marginal and turbulent states. The system's behavior is emergent; the output is musical, articulate, and often surprising.

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.

4 Control and Composition

Our applied work with these techniques has more recently 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 (1994).

The new design is built from a circular arrangement of eight sections. Each section is more "waveguide-like", and therefore more stable and less likely to output DC, than the sections used in the Cage realization. In particular, 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 4 demonstrates the structure of one the sections which includes the polarity change (at the right side of the graphic).

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 of any duration. 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. As with the

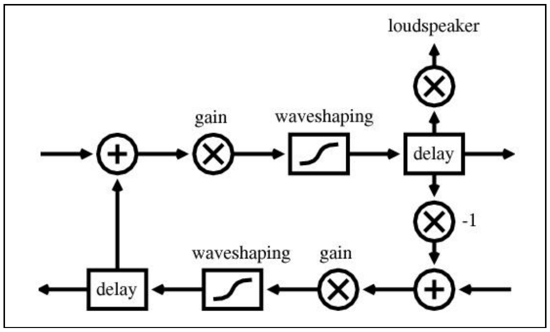

Figure 4: block diagram for a feedback network section more closely related to waveguide structures

Cage realization and our many example networks, articulation characteristics and other sonic details remain emergent, influenced by the delay lengths and gain coefficients, but not directly accessible to the composer.

5 Conclusions

Waveshaping and related peak-limiting methods make possible a new variety of network topologies and other extensions to traditional waveguide configurations. These feedback networks adapt the physical modeling notion that acoustic simulation leads to lively sonic behavior. While the new systems do not employ physical analogies, they retain many of the positive properties of waveguide networks: complex and emergent sounding behaviors with articulate and musical features. Accordingly, they represent an avenue of possibility for experimentally-minded composers looking to explore the regions beyond physical models oriented towards the accurate simulation of musical instruments.

6 Acknowledgments

Thanks to Christopher Jones for his collaboration in the development of the *Electronic Music for Piano* realization and in its performances, and to Tamara Smyth for assistance with waveguide theory and practice. Matthew Burtner created the illustration for Figure 3.

References

Adams, J. D. S. 1997. “Giant oscillations: the birth of Toneburst.” *Musicworks* 69: 14-17.

Cage, J. 1960. *Music for Piano 69-84*. New York: C.F. Peters.

Cage, J. 1968. *Electronic Music for Piano*. New York: C.F. Peters.

Chadabe, J. 1997. *Electric Sound*. Saddle River, N.J.: Prentice-Hall.

Essl, G. and P. Cook. 2002. “Banded Waveguides on Circular Topologies and of Beating Modes: Tibetan Singing Bowls and Glass Harmonicas.” *Proceedings of the International Computer Music Conference*. International Computer Music Association, pp. 49-52.

Hoffmann, P. 2000. “The New GENDYN Program.” *Computer Music Journal* 24(2): 31-38.

Puckette, M. 1996. “Pure Data.” *Proceedings of the International Computer Music Conference*. International Computer Music Association, pp. 269-272.

Schottstaedt, B. 1994. “CLM – Music V Meets Common Lisp.” *Computer Music Journal* 18(2): 30-37.

Smith, J.O. 1987. “Waveguide Filter Tutorial.” *Proceedings of the International Computer Music Conference*. International Computer Music Association, pp. 9-16.

Sullivan, C. 1990. “Extending the Karplus-Strong Algorithm to Synthesize Electric Guitar Timbres with Distortion and Feedback.” *Computer Music Journal* 14(3): 26-37.

Xenakis, I. 1992. *Formalized Music*, rev. ed. Stuyvesant, New York: Pendragon Press.