In/Finite: a live performance system investigating complex adaptation and agency in audio networks inspired by processes of organic degradation

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Abstract*—*In/Finite **is a live performance software system implementing audio feedback networks with complex adaptation mechanisms inspired by processes found in organic composting and aerobic biodegradation. The system, implemented in the Faust programming language, originated from a commission for an autonomous sound installation as part of the Waste Kompost Radio project; later, we extended it into a more advanced system and deployed it in live performance with human-machine interaction. Drawing inspiration from the three main families of organisms in biodegradation, namely bacteria, fungi, and actinomycetes, we rendered a similar configuration in the audio domain as three groups of signal processes performing sonic decomposition: granular resampling, allpass diffusion, and filtering. Each of the three DSP families includes four interdependent adaptive agents, and the families are interconnected via a time-variant matrix through which they exchange energy and information. While nested control mechanisms ensure stability and self-oscillation, the system's overall behavior is influenced by a global energy metric. This metric, analogous to temperature in the biological model, determines the activity and survival rate of the DSP families. We believe that the system produces compelling sonorities and musical forms with or without human intervention, exhibiting complex emergent behaviors across multiple time scales.**

***Index Terms*—Music, machine listening, music information retrieval, embedded systems, complex adaptive systems, feedback systems, cybernetics, biodegradation, compost**

I. Introduction

The fields of cybernetics and complexity science have provided an essential framework for understanding phenomena where the collective behavior of a system exceeds the sum of its individual parts. This systemic approach has long found fertile ground in sonic arts, where sound itself is viewed not as a static object but as a dynamic process rooted in the relationships that give rise to it [1]. Pioneering figures of the XX century in live electronic music, such as John Cage, David Tudor, and Gordon Mumma, explored these concepts by designing distributed feedback circuits and agent networks that created emergent behaviors in their musical practice [2]. These artists pushed the compositional act towards innovative technologies, where their system's architecture became inseparable from the music itself.

In recent years, the IoMT emerged as a natural extension of the Internet of Things (IoT) into the musical domain. It is an emerging field dedicated to studying how IoT devices can be used in musical performance to extend and enable new forms of interaction between human-computer, performers and audiences, musician-musician, among others [3]. However, this field has largely focused on technical challenges, often lacking an in-depth consideration of practical implications in artistic works and musical compositions by artists who have long explored distributed, cybernetic systems in their practices, including the exploration of non-human agency and systems-based performance.

The goal of this work is to illustrate a practical case study of a complex adaptive network operating in real time, showing how it is modeled and how it processes sound in performance through distributed interactions: between human agents and the system, within the system, and between the system and the performance space.

A. Case study: from Waste Kompost Radio to the development of In/Finite

In early 2023, we received a commission for an installation from Alan Alpenfelt and Daniela Allocca, as part of their Pro Helvetia-funded project, *Waste Kompost Radio* (WKR) [4], [5]. WKR is conceived as a live "composting" radio station that operates in real time and collects "sonic waste" (audio files) from the public and processes it through an autonomous system that mimics microbial and chemical decomposition into an evolving "sonic humus." This challenge led us to extend our musical practice in design of audio autonomous complex adaptive system to the domain of the Internet of Musical Things (IoMT). Specifically, we designed a web-based complex adaptive system that allows remote users to interact with the installation through sending audio files to the online audio streams. But what does it mean to compost a sound?

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At the beginning of this commission, we began studying traditional composting processes using scientific references for industrial compost [6]. We focused on the three main groups of organisms: bacteria, fungi, and actinomycetes as the core agents in our dynamic system model. The system's design is inspired by the functional principles of microbial community succession, metabolic activity, and their ecological roles throughout the stages of composting. Key ecological mechanisms such as the sequential appearance and disappearance of microbial populations across composting phases, the exchange of energy and matter among co-existing microbial communities, and the thermophilic-to-mesophilic shifts characteristic of composting cycles, inspire algorithmic sound transformations that closely mimic the biodegradation process in compost.

Following this first phase, we extended the conceptual and technical framework into a performative-installative context, resulting in *In/Finite*. Whereas WKR emphasized networked radio streaming, *In/Finite* brings the system into physical space and introduces extensive modifications to its architecture, signal processing strategies, and agent interactions. These developments, detailed in the following sections, allow the system to respond dynamically to performers, the audience, and the acoustic environment, adapting in real time to the local spatial conditions.

This situated and adaptive behavior can be understood through the notion of a sonic ecosystem: In the context of live electronic music performance, we define an ecosystem as a sound-generating and processing unit that exchanges energy and information with its real environment, i.e., the physical space where sound generation occurs [7]. Since *In/Finite* software is also autonomous, its approach draws heavily on agent-based modeling. This paradigm simulates complex systems through interacting autonomous agents that follow local rules, collectively generating unpredictable, self-organized phenomena [8], [9].

The name *In/Finite* was chosen to evoke the conceptual framework of Poincaré's recurrence theorem. It intentionally plays on the ambiguity between "infinite" and "finite," suggesting that the system operates within finite constraints while exploring an effectively infinite space of sonic permutations.

II. System overview

In/Finite implements a self-oscillating large delay network with nested feedback loops, nonlinearities, and processes that operate entirely at the audio signal level, without any symbolic layers of musical representation (Fig. 1). In line with Di Scipio's notion of "sound as the interface" [10], the system treats its own output as the sole operative medium, recepting it, analyzing it, and using the resulting information to continuously regulate, adapt, and evolve internal network behavior.

Following agent-based and meta-systemic modelling paradigms, we combine three families of digital signal processors each representing a different method of sonic decomposition (Fig. 2), allowing for continuous mutual interactions between the families within both virtual and real environments.

Each family contains four agents of the same processing type. Within each family, the four agents are interconnected via a Hadamard scattering matrix with delay lines of different prime lengths, thus creating feedback loops with unique periods and maximally dense modes. The three processing techniques for sonic decomposition are diffusion, bandpass filtering, and granular resampling. In this framework, and in analogy with composting processes, the three DSP families can be understood as distinct decomposition mechanisms acting on different features of sound. The first family reorganizes sparse time- and frequency-domain energy into a dense distribution, the second family selectively isolates partials from sonic textures, and the third family rearranges the temporal and spectral composition of sonic events. Finally, the three families are interconnected via a thermal model within a larger feedback loop, with a scattering matrix determining the degree of influence of each family relative to itself and to the others. For the thermal model, we use functions inspired by classical growth models, such as those of Monod [11], Gompertz [12], and Richards [13]:

$$h(a, b, c, d, x) = a \sin^{2b}\left(\pi \cdot \min(1, x + d)^c\right) + \frac{(1 - x)}{3}$$

For the three families, we use the following parameters, resulting in the following curves (Fig. 3):

$$y_0 = h(1, 0.5, 5, 0.1, x) \quad \{0 \le x \le 1\}$$
$$y_1 = h(1, 0.5, 5, 0.24, x) \quad \{0 \le x \le 1\}$$
$$y_2 = h(1, 0.5, 5, 0.4, x) \quad \{0 \le x \le 1\}$$

In analogy with the microbial model, these processes do not correspond to a literal translation of bacteria, fungi, and actinomycetes in composting, but they fulfill comparable roles: each family selectively attacks and transforms specific sonic materials, enabling the system to sustain a continuous cycle of degradation and regeneration.

A. Adaptive infrastructure

Given the time-variant nature of the processes, and despite our control signals being inherently in the infrasonic range, we use structurally robust DSP techniques for the implementation of the agent families. Specifically, the diffusers are implemented via networks of time-variant comb allpass filters following the design by Werner [14]; the bandpass filters follow the topology-preserving transform (also known as zero-delay feedback) technique, which is known for its robust performance under audio-rate modulation of the parameters [15]; finally, the granular processing uses windowing functions with continuous higher-order derivatives to minimize distortion, and higher-order interpolation for high-quality pitch variations with maximally flat frequency response. Furthermore, the entire network runs at 192 kHz sample-rate to reduce any artifacts related to sample-rate resolution.

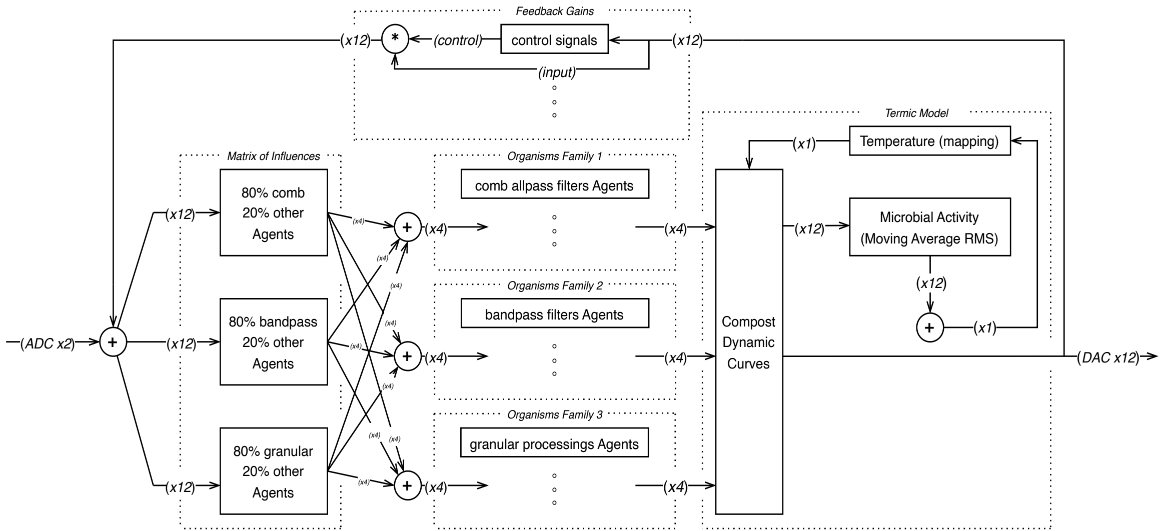

Fig. 1. System overview of *In/Finite*.

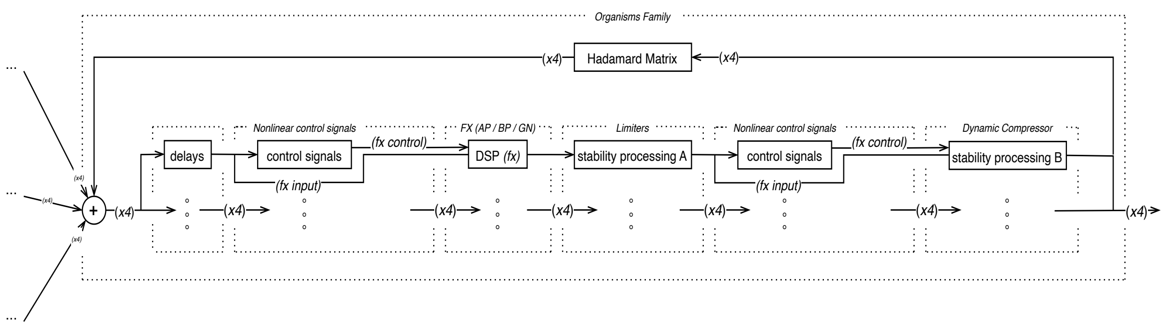

Fig. 2. Overview of the agent families within *In/Finite*.

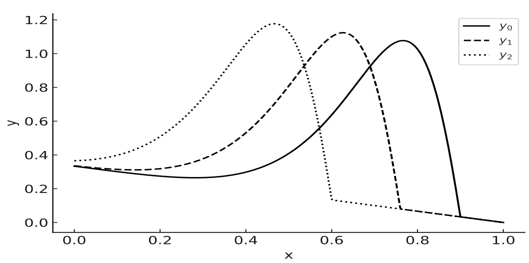

Fig. 3. Growth curves generated by the thermal model functions for the three DSP families.

At its heart, the control signal processing (CSP) algorithm deploys normalized polarity tendency to nonlinearly drive low-frequency oscillators (LFOs), which subsequently are shaped via sample-and-hold mechanisms.

Consider the sliding average of a signal over a time frame p, $\zeta = E_p(X)$, where X is an input signal stream. Then, consider the RMS of the same input signal computed over a time frame $r \gg p$: $\rho = \sqrt{E_r(XX)}$, with $\rho > 0$. Our normalized polarity metric is $\eta = \frac{\zeta}{\rho}$.

We use η to pilot the frequency of a sinusoidal oscillator, trying to favor mid- and long-term formal developments; hence, we shape η using the function

$$f(c,k,x) = c\cdot\tanh(x)\cdot\text{abs}(c\cdot\tanh(x))^k, k \in \mathbb{N}, 0.8 \leq c \leq 1.$$

The effect of the nonlinear shaping, typically with high ks, is to preserve the sign of the signal while pushing it towards zero. As a consequence, the oscillator is mostly still, but it will occasionally drift from its current position. Finally, we sample-and-hold the sinusoidal output when the magnitude of its slope is below a sufficiently small threshold and nonlinearly map it to several parameters.

The adaptation infrastructure extends throughout all layers in the meta-system, and it follows two main criteria. The first is based on statistical metrics extracted from the raw sample streams; the second includes low-level feature extractions for musically-informed self-control [16]. Nonlinear mapping and one-to-many mapping strategies are deployed to connect the control signals to several DSP parameters, thus creating a network of competing positive and negative feedback relationships. Self-control of the state variables within each agent includes the gain and delay values in the diffusers, the center frequency in the bandpass filters, and the pitch and window size in the granular processing. Outside of the agents and within each family, self-regulation is applied to the response times of the peak levellers (see below). In the outer layer, self-control is applied to the feedback gain of each feedback loop.

B. Stability Processing

For a system with multiple digital feedback loops and non-linear processes, analytically formulating the stability thresholds would not only require considerable effort but also fail to guarantee stability under self-oscillating conditions due to potential numerical errors. We therefore consider an analytical approach to system stability to be inadequate in this case. Instead, we deploy a combination of lookahead limiters and peak levellers, providing an effective solution to the problem that is superior to simply deploying saturators. Not only do saturators tend towards homogeneous and dense spectral outputs, but they are also unable to provide the emergent dynamics that we achieved via the slow response times of the limiters and levellers [17], [18].

III. Aesthetic Outcomes

The aesthetic proposition of *In/Finite* is grounded in a systemic and relational understanding of sound as a processual phenomenon [19]. Rather than producing predefined musical objects or stylistic artifacts, the system renders audible the conditions of its own emergence. It generates sonic forms that are the dynamic outcome of recursive interactions between minimally cognitive agents [20], human performers, and the acoustic environment.

This perspective aligns with Agostino Di Scipio's notion of interaction as the fundamental basis for emergent systems in music [10]. Here, 'interaction' itself is understood as the byproduct of interdependencies among system components. Di Scipio emphasizes the shift from producing predefined sounds through interactive means to composing networks of interactions whose emergent sonic behavior constitutes the composition itself. Such systems exhibit adaptive dynamics to external conditions and become self-observing, maintaining internal states that evolve through their relationship with the environment, the performer, and themselves.

In these pieces, every variable—such as the acoustic behavior of the space and its frequency response, the reverberation time, the presence of the audience, and the overall electroacoustic chain—is not merely a constraining condition of the performance; instead, it becomes a compositional resource that reveals morphogenetic tendencies [21]. By "morphogenetic" we mean here the capacity of the system to generate higher-order sonic structures from interactions among lower-level sonic events. This concept, transposed into the musical domain, describes how patterns, textures, and forms emerge gradually from the system's iteration through its agents, performers, and internal and external environment.

A. Emergent Forms

At a microstructural level, the *In/Finite* system reflects the principles of extraction and transformation inherent to biodegradation and composting processes. It processes incoming audio by isolating and transforming spectral segments, clusters, and transients of the input signal, generating sonic residues, fragments, and textures resulting from the decomposition and recombination of the source material. Recurring traces, such as the echoes of transients, spectral imprints, and recognizable fragments, re-emerge over extended timescales, altered and recontextualized. The result of these operations is a layered acoustic material: sound as a sedimented, reworked byproduct of interaction. Rather than forming fixed or repetitive patterns, these textures remain in flux, shaped by accumulation, decay, and recurrence, mirroring the continuous, nonlinear breakdown of organic matter.

Here, these micro-level sonic events, propagate through the network, recombining, interfering, and layering over larger timescales. These distributed processes generate musical structures where the system's long-term behavior reveals emergent forms shaped by global energies and internal dynamics. Such tendencies induce slow, profound transformations that traverse states of high density, saturation, homeostasis, and eventual silence before entering regenerative phases. This cyclic behavior, moving between phases of accumulation, saturation, and renewal, mirrors the thermophilic and mesophilic stages of composting, where periods of intense transformation are followed by intervals of relative rest and re-stabilization.

B. Co-Agency

The aesthetic logic within this performative context is not reducible to either full machine autonomy or singular performative authorship. Instead, *In/Finite* establishes a model of co-agency in which the human performer is one component of an emergent system, intervening within limits rather than exercising total control. The machine is not a passive tool but a minimally cognitive partner, capable of reacting and responding to behaviors across temporal scales. This reflects a broader post-digital critique of instrumental thinking in performance, aligning with a meta-systemic view where intelligence is distributed across human and non-human components.

The system ultimately invites a speculative mode of listening that foregrounds temporality, emergence, and contingency. The sonic experience is not only aesthetic but also epistemic: it is a mode of inquiry into how the system evolves via positive and negative feedback loops. The audience is thus drawn not into a fixed composition but into a shared, evolving ecosystem of sound, in which perception, action, and material transformation are inseparable.

C. Performance Modalities

The performance unfolds as a live interaction between two performers, each operating an instance of the described system on separate personal computers. These systems form a coupled network where all inputs and outputs potentially affect all other elements in the network, including the decisions of the performers themselves. This configuration can be interpreted as a fully-connected network, where both human and machine nodes influence each other in real time.

The two systems are interconnected acoustically within the performance space through loudspeakers and microphones. These audio signals pass through a mixing console that allows both performers to intervene in the network by adjusting routing, EQ, gain, dynamics, and other signal-processing parameters. The mixer becomes an active component of the electroacoustic system's feedback structure, shaping the signal flows and mediating interactions. Each system may also be controlled via a graphical user interface (GUI), eventually linked to external physical controllers. These allow performers to manipulate internal parameters that affect the behavior of the *In/Finite* system, such as controlling the temporal evolution of the feedback delay network (FDN), adjusting positive or negative feedback gains and matrix configurations, and modifying other internal parameters.

The modalities of the performance are chosen in response to the system's behavior—specifically, its feedback dynamics. For instance, if one system produces long, continuous sounds, the other performer may react by introducing positive feedback into their own system, possibly using the homeostatic state of the other system as a resource. These interactions rely on feedback strategies that are either converging (negative feedback) or diverging (positive feedback), shaping the direction and evolution of the musical structure. Performers must constantly negotiate between reinforcing and destabilizing these tendencies, deciding whether to intervene or not to maintain a complex formal development. For a detailed discussion of such performance modalities and the formalization of adaptive human-machine interactions, see [22].

IV. Conclusion

We introduced *In/Finite*, a novel live performance system that innovatively translates the intricate processes of organic biodegradation and composting into dynamic audio feedback networks. The system is built upon three families of adaptive digital signal processing (DSP) agents: granular resampling, allpass diffusion, and filtering, each contributing to the continuous sonic decomposition of the input material. This structure, also guided by global energy metrics analogous to temperature in composting, enables the system to exhibit complex emergent behaviors across multiple timescales.

A central contribution of *In/Finite* lies in its distinctive approach to integrating models of natural processes into the domain of live electronic performance. Rather than a literal simulation, the system draws inspiration from microbial succession and metabolic activity, using them as heuristics for structuring interdependent signal processes within a complex adaptive audio network. In this way, the work extends traditional practices in audio feedback systems by embedding ecological dynamics as generative principles of sonic transformation.

Future research will focus on expanding the system's adaptive capabilities by incorporating more feature extraction techniques and sophisticated compost models that are more complex and faithful to real physical ones. This will potentially allow the system to better learn the external environment and environmental conditions, and manifest more complex behaviors.

References

[1] T. Magnusson, "Of Epistemic Tools: Musical Instruments as Cognitive Extensions," *Organised Sound*, vol. 14, no. 2, pp. 168–176, Jun. 2009. doi: 10.1017/S1355771809000272.

[2] D. Sanfilippo and A. Valle, "Feedback Systems: An Analytical Framework," Computer Music Journal, vol. 37, no. 2, pp. 12–27, 2013.

[3] L. Turchet, C. Fischione, G. Essl, D. Keller, and M. Barthet, "Internet of Musical Things: Vision and Challenges," *IEEE Access*, vol. 6, pp. 61994–62017, 2018.

[4] Waste Kompost Radio, "Waste Kompost Radio – a constant radio flow of composting sound," [Online]. Available: https://www.wastekompostradio.com/ [Accessed: Jul. 13, 2025].

[5] WKRadio, "GitHub – WKRadio/Waste_Kompost_Radio," [Online]. Available: https://github.com/WKRadio/Waste_Kompost_Radio [Accessed: Jul. 13, 2025].

[6] L. F. Diaz, M. de Bertoldi, W. Bidlingmaier, and E. Stentiford, *Compost Science and Technology*, vol. 8, Waste Management Series. Amsterdam: Elsevier Science, 2007, 380 pp. ISBN 978-0-08-043960-0.

[7] A. Di Scipio and D. Sanfilippo, "Defining Ecosystemic Agency in Live Performance: The Machine Milieu Project as Practice-Based Research," in Proceedings of the International Conference on Live Interfaces, 2019. doi: https://doi.org/10.25370/array.v2019.1.

[8] D. Sanfilippo, "Complex Adaptation in Audio Feedback Networks for the Synthesis of Music and Sounds," *Computer Music Journal*, vol. 45, no. 1, pp. 6–23, 2021.

[9] J. H. Holland, *Complexity: A Very Short Introduction*. Oxford, UK: Oxford University Press, 2014.

[10] A. Di Scipio, "Sound is the Interface," Organised Sound, vol. 7, no. 1, pp. 43–54, 2003.

[11] J. Monod, "The growth of bacterial cultures," *Annual Review of Microbiology*, vol. 3, pp. 371–394, 1949. doi:10.1146/annurev.mi.03.100149.002103.

[12] B. Gompertz, "On the nature of the function expressive of the law of human mortality, and on a new mode of determining the value of life contingencies," *Philosophical Transactions of the Royal Society of London*, vol. 115, pp. 513–583, 1825.

[13] F. J. Richards, "A flexible growth function for empirical use," *Journal of Experimental Botany*, vol. 10, no. 29, pp. 290–300, 1959.

[14] K. J. Werner, "Energy-Preserving Time-Varying Schroeder Allpass Filters," in *Proceedings of the 23rd International Conference on Digital Audio Effects (DAFx-20)*, Vienna, Austria, Sept. 2020.

[15] V. Zavalishin, *The Art of VA Filter Design*, version 1.1.1. [Online]. Available: https://www.native-instruments.com/fileadmin/ni_media/downloads/pdf/VAFilterDesign_1.1.1.pdf [Accessed: Jul. 13, 2025].

[16] D. Sanfilippo, "Time-domain adaptive algorithms for low- and high-level audio information processing," *Computer Music Journal*, vol. 45, no. 1, pp. 24–38, 2021.

[17] D. Sanfilippo, "Time-variant infrastructures and dynamical adaptivity for higher degrees of complexity in autonomous music feedback systems: the Order from noise (2017) project," *Musica/Tecnologia*, vol. 12, pp. 119–129, 2017.

[18] D. Sanfilippo, "Envelope following via cascaded exponential smoothers for low-distortion peak limiting and maximisation," in *Proceedings of the 3rd International Faust Conference*, Saint-Étienne, France, 2022. [Online]. Available: https://zenodo.org/records/6769570/files/i3.pdf?download=1 [Accessed: Jul. 13, 2025].

[19] D. Sanfilippo, "The Aesthetics of Musical Complex Systems," *Organised Sound*, vol. 28, no. 3, pp. 381–391, Aug. 2023. doi: 10.1017/S1355771823000523.

[20] A. Etxeberria, J. J. Merelo, and A. Moreno, "Studying organisms with basic cognitive capacities in artificial worlds," *Cognitiva*, vol. 3, no. 2, pp. 203–218, 1994.

[21] M. Solomos, "Emergence in Sound: On Agostino Di Scipio's Granular Approach," in *Contemporary Music Review*, vol. 24, no. 3, pp. 295–312, 2005. doi:10.1080/07494460500191212.

[22] D. Sanfilippo, "Towards the formalisation of structurally-coupling performance modalities and interfaces in human-machine interaction," *ECHO, a journal of music, thought and technology*, vol. 3, Jan. 2022. doi: 10.47041/WRST7328.