The Aesthetics of Musical Complex Systems

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This article introduces the history and aesthetics of feedback-based music, from early practitioners to more advanced methods and state-of-the-art works based on adaptation. Some of the most relevant techniques developed over almost six decades of investigations in the area of recursive systems for electronic music are discussed to show the variety and richness that a single specialised domain can have, providing examples of how scientific and philosophical principles can be translated into music. The historical context is key to understanding the evolution of the field: feedback-based music arose during the same years in which cybernetics, together with other disciplines, were experiencing a profound transformation. I will provide an overview of how such disciplines changed, highlighting the connections between seemingly distant areas such as philosophy, biology and engineering, and the fact that the development of feedback-based music appears to have followed somewhat closely the evolution of systems thinking. Finally, the article explores questions of musical aesthetics and music theory related to the use of complex autonomous systems in live performance through observations on the author's creative practice.

1. INTRODUCTION

Complex systems are large networks of non-linearly interacting components. These systems are characterised by dense structures of positive and negative feedback mechanisms that compete between converging and diverging behaviours to generate non-triviality and unpredictability in short-term and long-term time scales. Complex systems are emergent systems by definition, and their most important aspect is being at the *edge of chaos*, a condition where order and disorder coexist and mutually determine each other. I will refer to complex systems to describe systems that exhibit complex behaviours with or without adaptation. Recent studies suggest that the components of complex adaptive systems (CASes) are themselves adaptive agents (Holland 2014) and that the structures and organisations of the agents and the whole are affected by one another, underlining the upward and downward causation found in the emergence of autopoietic organisms (Maturana and Varela 1980). The history of CASes, discussed in the next section, shows a relevant connection from the evolution of complexity and systems thinking to the creative practice in music with electronic feedback instruments. While cybernetics was shifting towards second-order cybernetics, thus emphasising the importance of observers and environments in complex systems and their inherent self-referentiality, electronic music practitioners working with feedback explored the autonomy and ecosystemic aspects of such instruments in live performance as a means to discover new aesthetics. We can trace a significant influence from the scientific fields of cybernetics and complexity to that of electronic music that allowed composers to see the machine as an entity with the ability to generate novel forms and sounds, and studying the evolution of these fields may provide a deeper understanding of the electronic feedback music practice from the 1960s to today.

Another historical perspective on cybernetics and feedback-based music can be found in (Sanfilippo and Valle 2013). In that publication, the focus is on formalising cybernetics principles within the sound and music domain and creating a typology of music feedback systems. In this article, on the other hand, the historical perspective is key to understanding the aesthetics of music complex systems, which is the centre of the investigation of the relationship between the human and the machine. The aesthetics of musical CASes is a critical aspect to investigate as they open new paradigms in music composition and performance. Three of the most relevant points in the aesthetics of musical CASes proposed in this article are: the differences between failure and operational criticality; the machine as a self-referential entity that thoroughly explores its state variables; and the fundamental relationships that arise from the interaction between a human and a highly autonomous machine in live performance. The first point describes the operational state of these systems as substantially different from the approaches found in music based on failure and glitch aesthetics. *Far-from-equilibrium* dynamics characterise CASes, representing a high sensitivity to environmental perturbations and a strong non-linearity and unpredictability. Combined with iterative configurations and adaptation, these conditions produce emergent behaviours and radical novelty through which conventional tools for electronic music can be turned into new instruments.

The second point analyses these systems from the perspective of self-performing machines. Owing to adaptation, these machines can re-organise their

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internal configurations and the variables that define their behaviours, replacing the role that human performers have in conventional human–machine interaction performance. Particularly in the case of improvised performance, it is observed that patterns and recurrent trends may appear, for improvisation can be formalised as a recursive mechanism, and hence be a process that may follow the cybernetic principles of positive and negative feedback. The self-regulation and adaptation in CASes allow for counterbalancing mechanisms that prevent excessive redundancy or entropy, hence increasing the variety and potential complexity of the music system by exploring a broader set of combinations of parameters and configurations.

The third point proposes a new perspective on human–machine interaction performance with CASes. This view highlights and favours the development of the aesthetics of the machine, that is, a conscious decision of the performer to interfere as little as possible to achieve a compelling musical output by observing the evolution of the system. This approach raises questions concerning the need for a new conception of musicianship and virtuosity in live music performance with systems with a high degree of autonomy.

2. THE EVOLUTION OF COMPLEXITY AND MUSIC FEEDBACK SYSTEMS

The Macy conferences, which lasted for nearly 20 years starting in the early 1940s, were a fundamental series of events attended by scholars from different disciplines sharing the perspective of cybernetics and systems thinking. Some of the most prominent figures who attended the meetings were Ross Ashby, Margaret Mead, Gregory Bateson, Heinz von Foerster and Norbert Wiener. The latter is considered the father of cybernetics as he first defined the term in his *Cybernetics or Control and Communication in the Animal and the Machine* (Wiener 1948). Modern cybernetics began as a discipline interconnecting different fields such as network theory, mechanical engineering, evolutionary biology and psychology, focusing on the study of systems with interdependent agents having non-trivial behaviours. Eventually, cyberneticians had the intuition that the process of analysing a system could itself be non-trivial, and they started to consider the issues related to the role played by the observer. In an interview from 1976 (Brand 1976), Margaret Mead and Gregory Bateson stated that classic cybernetics considered systems as elements independent from their surrounding environment or observer. Cybernetics then evolved into second-order cybernetics, which Heinz von Foerster defined as 'the cybernetics of observing systems' (von Foerster 2003).

It is possible to notice an emphasis on the system as a cognitive and self-referential entity capable of sensing its context (Etxeberria, Merelo and Moreno 1994; Barandiaran and Moreno 2006). Coherently to this theory, during the same period, the notion of radical constructivism was formulated by Ernst von Glasersfeld. To approach the concept of self, he used the metaphor of an invariant condition resulting from the counterbalancing mechanism of mutually affecting changes. He identified such a metaphor in the cybernetic domain as a self-regulating closed loop, essentially paraphrasing the notion of circular causality: what we see in a feedback loop is the past being affected by the present, which is about to be compensated by the immediate future. Hence, it is impossible to depict such a mechanism's state through a single element, for, by nature, it consists of one or more relationships, and relationships are between things rather than in things (von Glasersfeld 1979). What we experience as *self* takes place in the circular relationship between the entity and its surroundings.

The early studies on complexity are from at least the 1970s with Edgar Morin and V. Rao Vemuri (Morin 1977; Vemuri 2014), but several others were researching the same field from different directions. For example, Ilya Prigogine was investigating dissipative structures, non-equilibrium thermodynamics and the function of time in biological systems (Prigogine and Nicolis 1985); the theories on autopoiesis by Umberto Maturana and Fransisco Varela (Maturana and Varela 1980); Kauffman and his work on random Boolean networks showing the emergent evolution of their self-organisation (Kauffman 1984); and the research on artificial life by Langton (1986). In the 1970s, John H. Holland implemented a computational model of adaptation in evolutionary systems inspired by the work of Rosenblatt (1958). In 1975, Holland published his early research on genetic algorithms (Holland 1975), and he was a distinguished researcher in the field of adaptivity (Wilensky and Rand 2015). Holland also became part of the Santa Fe Institute (www.santafe.edu/about) in 1985, where some of the most prominent CASes thinkers such as Melanie Mitchell and James Crutchfield work.

CASes are now used in several fields, and they have gained substantial importance over the years. Some of their applications are to predict and understand complex real-world phenomena through computational models for economic trends or the development of technological progress (Farmer 2002; Farmer and Lafond 2016), the evolution of intelligence (Krakauer 2011), or global behaviours in societies (Lagi, Bertrand and Bar-Yam 2011). CASes are also applied in the implementation of artificially intelligent systems such as self-repairing software and intelligent anti-virus systems (Forrest, Hofmeyr and Somayaji 1997), or robotics and linguistics (Steels 1997, 2003).

2.1. Elementary definitions of the feedback vocabulary

The basic definition of a feedback loop considers a system that transforms an input value or signal and outputs the result by feeding it back into the input with some delay (Heylighen and Joslyn 2001). Despite the large family of behaviours that can be modelled through a feedback network, there are only two types of feedback relationships, although by combining them in different amounts it is possible to achieve a great variety of responses in virtually any area. The two main feedback types are positive and negative feedback loops. On a system subject to stimuli, a positive feedback loop can create a response with exponential growths or decays from the system's natural equilibrium point. Often, positive feedback is seen as a chain reaction where perturbations that tend towards a certain direction will be amplified recursively by the system, resulting in further shifts towards the same direction. In positive feedback loops, then, the input–output relation is direct, and an increase (or decrease) in the input will cause an increase (or decrease) in the output (Wiener 1948; Ashby 1957; Heylighen 2001; Heylighen and Joslyn 2001; Gershenson 2007). On the other hand, negative feedback loops have a complementary behaviour to positive feedback, and they tend to oscillate around a stability point. Indeed, negative feedback systems are in dynamical equilibrium and perform a counterbalancing action on the external stimuli to maintain balance. In this case, the input–output relation is inverse, and an increase (or decrease) in the input will cause a decrease (or increase) in the output. Generally speaking, negative feedback represents convergence towards equilibrium, while positive feedback represents a divergence from equilibrium.

Despite the structural simplicity of feedback loops, such recursive mechanisms have significant consequences on the behaviours of systems or interdependent components in general. While the distinction between origin and consequence in open circuits is rigorous and linear, closed loops depict a condition where distinguishing between causes and effects is impossible. Heinz von Foerster and other scholars taking part in the Macy conferences called this particular condition circular causality. Von Foerster describes it as closed loops that, if opened, whether the causes for an effect are in the present or the past depends on the opening point (von Foerster 1952). For von Foerster, circular causality fills the gap between effective and final cause, or motive and purpose. Furthermore, von Foerster says that a closed loop decreases uncertainty as it is no longer necessary to provide the initial conditions for the system: the final conditions themselves can already provide them. Heylighen and Gershenson explain how circular causality is intrinsically related to the non-linearity of a system (Heylighen et al. 2001; Gershenson 2007). In systemic terms, the non-linear interactions between components determine a non-linear behaviour in the system. It means that negligible causes can result in significant long-term effects, whereas large causes may not result in significant effects. In other words, there is no proportionality between the input and output of a system.

Ross Ashby identified another fundamental property of feedback systems that he referred to as coupling (Ashby 1957). Essentially, a feedback connection that relates a system to itself (self-coupling) or two or more components among themselves (cross-coupling) creates a structural coupling that redefines the system as a whole. Then, a system becomes self-referential or self-affecting, while cross-coupled components determine their states by mutually affecting each other. This type of relationship defines the very concept of interaction at the structural level as a continuous and ongoing exchange of energy and possibly information, too, between the coupled parts. Synergetic phenomena and structural interactivity highly characterise feedback systems and their behaviours as higher-level wholes. The identity of a system is the result of a distributed cooperation between all interconnected parts.

Feedback loops, both within the system and between the system, environment and observer, are essential elements in second-order cybernetics that became popular in different areas, including music, due to the success of the discipline. Some of the earliest examples of feedback-based music are from the 1960s. Roland Kayn drew inspiration from cybernetics and implemented self-regulating music systems based on feedback, both as models for instrumental pieces and analogue networks for sound generation (Patteson 2012). During the same period, technologies and techniques for sound reinforcement were being investigated, favouring the studies in signal processing and acoustics for analogue audio equipment. Specifically, the phenomenon of acoustic feedback, or Larsen, named after the Danish scientist Søren Absalon Larsen who discovered it a few decades earlier, raised particular interest and was a significant concern in analogue audio and sound reinforcement. While sound engineers were researching techniques to prevent the Larsen effect (Boner and Boner 1966), some music practitioners believed that such a phenomenon might be a powerful creative means for music composition and performance.

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2.2. Historical and contemporary feedback music practice

Robert Ashley's *The Wolfman*, from 1964, is a work for tape, voice and feedback. In the same year, John Cage composed *Electronic Music for Piano*, a piece for piano and Larsen network. Steve Reich's *Pendulum Music* from 1968 also explores the Larsen effect and its modulation through the repositioning of microphones with respect to the loudspeakers. Specifically, he uses microphones as pendulums over the loudspeakers, hence investigating two fundamental aspects of Larsen itself: phase, given by the angle of incidence of sound on the microphone, and gain, given by the distance between microphone and loudspeaker. In 1969, Alvin Lucier composed *I Am Sitting in a Room*, a fascinating use of the Larsen phenomenon. Lucier's piece consisted of two tape recorders, a microphone and a loudspeaker. The microphone recorded his voice while he read a short text that lasted about 75 seconds. The recorded voice would then be played back in the room through the loudspeaker and recorded on the other tape recorder through the microphone. Thus, the two tape recorders were needed to perform the task of playing back and recording simultaneously. Today, the same process can be achieved by using a long-enough delay line. The exciting aspects of Lucier's piece are that he stretched out in time the recursive process of the Larsen effect, that is, the circular action of reproducing and capturing sounds through microphones and loudspeakers. Lucier allowed inspecting this recursive process on a different time scale, but he also demonstrated that slowing down such a systemic process would result in different emergent behaviours rather than merely slowing down the final output itself. Furthermore, Lucier consciously recognises the environment as part of the process – the room is indeed a filter that shapes the Larsen – underlining the strong ecosystemic nature of the process itself.

In 1966 and 1967, Gordon Mumma composed, respectively, *Diastasis, as in Beer* and *Hornpipe*. Mumma realised groundbreaking works as they are arguably some of the first music pieces implementing elementary forms of CASes. In particular, Mumma implemented analogue feedback networks coupled with the environment through instruments that he used as filters or transfer functions in general. He mainly generated control signals using envelope followers to pilot some of the parameters that transformed the sounds from the instruments, resulting in self-regulating adaptive networks (Mumma 1967). Nicolas Collins realised his *Pea Soup* in 1974. Similar to the work of Mumma, Collins also implemented envelope followers to pilot the parameters of a self-regulating network. In his case, in particular, the network only consisted of one positive feedback loop and one negative feedback loop and their cooperation: the positive feedback loop was the Larsen effect given by the iterated amplification of a signal through microphones and loudspeakers; the negative feedback loop resulted from controlling a phase shift in the input signal through its envelope contour. Loud signals, which indicated the onset of Larsen, phase-shifted the signal by a higher amount. Since feedback is a function of phase, the result was that the Larsen effect would suppress itself whenever enough energy built up, giving the possibility for different tones to emerge in different areas of the spectrum. Despite the simplicity of the network, the expressiveness and articulations of the sonic output were outstanding (for a more detailed analysis of some relevant feedback-based pieces, see Sanfilippo and Valle 2013).

Today, Alice Eldridge and Agostino Di Scipio have provided some of the most important contributions to the creative practice with adaptive systems. Alice Eldridge is a composer and performer working with improvisation with a background in psychology, adaptive and evolutionary systems, and informatics. Her work focuses on ecosystemic music creation and performance with emergent evolutionary models and adaptive systems (Eldridge 2007; Eldridge, Dorin and McCormack 2008). In collaboration with Chris Kiefer, she has developed the *Feedback Cello*, a self-oscillating instrument that bridges physical tools and computational methods within the field of feedback systems. The Feedback Cello is an autonomous instrument capable of adaptation that can be implemented in human–machine interaction performances or sound installation to display complex autonomous behaviours (Eldridge and Kiefer 2017). Agostino Di Scipio has contributed significantly to the field of computer music since the early 1990s, and he is regarded as one of the most influential figures in the area of ecosystemic live electronic music. His publication 'Formal Processes of Timbre Composition Challenging the Dualistic Paradigm of Computer Music' (Di Scipio 1994) is a landmark conceptual work and distinctive formulation that proposes composition techniques capable of merging what he referred to as the dualistic paradigm of computer music. The dualism can be summarised into the two main approaches that see practitioners *composing sounds* or *composing with sounds*. This paradigm fundamentally describes the standard workflow of computer music composition, where a performer generates a set of sonic materials that are subsequently arranged into a music piece. Di Scipio proposes a *theory of sonic emergence*, a process-based composition paradigm where structures defined at a lower level for the generation of timbres would allow for the emergence of musical forms at a higher level. Di Scipio then began his exploration of emergent music systems following autopoietic metaphors and ecosystemic designs.

Another milestone in his works is '"Sound is the Interface": From Interactive to Ecosystemic Signal Processing' (Di Scipio 2003). In this work, Di Scipio describes his aesthetics of music composition that has reached a clear identification and connotation: Di Scipio's focus is on the exploration of the dynamical behaviours that emerge through the coupling of an autonomous system such as a DSP network of interdependent components with the environment that is hosting the performance. The concepts from second-order cybernetics and the structural coupling between system and environment, typical of autopoietic and living systems, are crucial. Furthermore, Di Scipio formulates a radical paradigm shift in live performance, from *interactive composing* to *composing the interactions*, questioning the basic design of interactive music (performer–controllers–DSP–sound), which is substantially linear without explicit closed loops – as is implied by the notion of interaction – and proposes a design strategy where interaction is a structural characteristic of music systems taking place in the domain of sound.

Di Scipio and I started collaborating in 2013 after we had decided to combine our independent practices in the field of autonomous music to explore the possibility of a meta-system by combining our systems and performance approaches. Between 2013 and 2014, we realised a series of studio performances and recordings to which we gave the name *Machine Milieu*. Our project explores the hybridisation of autonomous machines, with or without human intervention, and the formulation of a set of performance modalities in which the human and the machine are structurally interacting agents in a higher-level system made of systems (Sanfilippo and Di Scipio 2017; Di Scipio and Sanfilippo 2019). Finally, the author mentions two of his recent works based on his investigations on *distributed adaptation*, *Order from Noise* (2016–19) and *Constructing Realities* (2019–20). Distributed adaptation is related to the notion of evolvability in biology and genetic algorithms, and it has significantly increased the complexity and long-term variety of music systems during autonomous evolutions. This technique extends adaptation across higher levels and allows the system to re-organise the relationships among its agents and their structure circularly while interpreting and constructing its context (Sanfilippo 2018, 2020, 2021a).

3. THE AESTHETICS OF MUSICAL COMPLEX SYSTEMS

3.1. From failure to *extreme functioning*

Technology's role and influence in creative sonic practice have progressively become a central question for composers, sound artists, philosophers and critics. Several practitioners have refuted the concept of technological determinism, where technology serves as a neutral tool for ideas and eventually final results (Rognoni 1966; Di Scipio 1997, 1998, 2000; Feenberg 1992; Hamman 2002). Ideas themselves change and evolve during the creation process concerning the technology and techniques adopted. Meanwhile, the technologies and techniques used can, in turn, be affected according to the evolving ideas and results. The design process of the systems involved in sound creation and the techniques formulated and implemented in such a practice are indeed a fundamental stage whose outcome will significantly determine the final results. This section will explore feedback and complexity to deploy technologies and techniques in a state of *extreme functioning*, which will be vital in achieving novel outcomes.

Composers can use pre-existing technologies and techniques to create works reflecting their ideas and purposes, yet they will operate in a creative domain where traces of an aesthetics intrinsically sculpted in the pre-existing devices, software and techniques are present. To some extent, this can homogenise the work of the artist, for a common root will be shared between all the works using a particular technology or technique. Today, the power and accessibility of computers and sophisticated digital audio software allow composers to design their tools and systems from scratch. However, even if such software makes it possible to operate at a lower level, technology and techniques still seem to have a noticeable influence on the final result. Even though environments such as SuperCollider or Pure Data are powerful and flexible, some of their building blocks are more high level and can still be rather characteristic. On the other hand, specific sound synthesis and processing techniques can have very peculiar and recognisable features, even if implemented with very low-level programming languages.

Several composers and sound artists have deliberately altered technologies and techniques to achieve new sonic results. For instance, there are compositions based on scores where the details and required performing skills are intentionally conceived to challenge the capabilities of the performers. This strategy allows us to achieve indeterminacy and musically interesting awkwardness due to mistakes and inaccuracies, hence operating at the edge of what is physically achievable for an instrument player. Examples are *Cheat Sheet* (2007) by Michael Edwards, for solo guitar, ensemble, and computer, and *Unity Capsule* (1975–6) by Brian Ferneyhough, a hyper virtuosic work for solo flute. Cage's prepared piano has shown how changing the instrument's mechanisms and conventional performing techniques can lead to new domains of sonic materials, sometimes profoundly different from the original ones. While experimenting with turntables, Pierre Schaeffer altered the internal mechanism of such a device so that he could change the rotation of the turntable, from clockwise to counterclockwise, achieving the reverse effect by playing the recordings backwards. Other examples come from the hardware hacking and circuit bending practitioners that initially appeared in the 1960s and 1970s, where people such as Gordon Mumma, Nicolas Collins and Reed Ghazala (to name a few) realised practically brand-new sound generators by manipulating the electric circuits of everyday devices or existing synthesisers. Recently, we can see the same approach in the digital domain where devices and software are pushed towards conditions where failure takes place – what has been referred to as *the aesthetics of failure* (Cascone 2000). Artists have explored this practice in various ways: by drawing on the rear side of CDs and eventually producing irregular patterns and clicks when playing them on a CD player (Oval); by letting a digital sampler crash through a particular configuration of the parameters to create unexpected sounds (Fennesz) (Bridda 2004); or by pushing the computational capabilities of computers so that CPU overloads result in unwanted yet interesting sonic behaviours (Galarreta) (private conversation). While operating in different domains and with different approaches, what is common to all these practices is the possibility to achieve new outcomes out of tools not explicitly designed for the resulting materials and behaviours. This can be a crucial aspect of sound creation and, in general, strongly characterising the originality of a work.

Technology and techniques can be altered and shaped into something original. After this process, they operate in a meta-state whose behaviour may differ from the one they were designed for. As a result, exploring methods that lead to such a meta-state corresponds to exploring potential new creative practices and aesthetics. There are different ways to achieve this. In the case of Cage's prepared piano or hardware hacking, the kind of action required is manipulating the structure of the tools themselves. On the other hand, when discussing this approach in the digital domain, we have seen that the tendency is to push digital systems towards failure and malfunctioning. Instead, a conceptually and technically different approach deploys feedback mechanisms (Sanfilippo 2013). Through feedback, it is possible to turn elementary tools into what Heinz von Foerster called a non-trivial machine: a system that is self-related, autonomous, unpredictable and analytically non-determinable (von Foerster 2003). Feedback is also ubiquitous in the discussions regarding complex and emergent systems (Gershenson and Heylighen 2005; Kitto 2006; Morin 2007), and emergence is indeed a key aspect of this approach for the alteration of technology.

Emergent systems are different from the sum of their parts because of synergetic relationships between their components (Corning 2002), and this particular characteristic allows such systems to operate in that meta-state that leads to an alteration. With feedback, it is possible to radically alter the behaviour of analogue and digital devices, or synthesis and processing techniques, so that hidden characteristics can be unfolded. Different materials and forms, two aspects that with such an approach become inseparable (Di Scipio 1994), can then be discovered. Microphones, loudspeakers, mixing boards and audio manipulation techniques within the feedback loops are no longer sound capturers, reproducers or transforming units: they become sonic generators with their identity and systemic role in the emergent whole. Feedback systems, unlike the examples previously discussed, are not cases of manumission or malfunctioning. Instead, the state characterising feedback systems could be referred to as *extreme functioning*: a condition where the operational level coincides with the limits of the machines themselves, where equilibrium and instability coexist. Feedback systems push technologies and techniques towards their extremities, up to the threshold where the original identity of such technologies and techniques is replaced with an emergent one.

3.2. The objectivity of the machine

The concept of *objectivity of the machine* is helpful to understand the importance of autonomous systems – specifically CASes – in the practice of music composition and performance. The idea has been informed by several years of experience as an electronic music composer and performer, particularly after realising the difficulties related to predictability in improvised music and redundant procedures in using electronic instruments by looking backwards at my practice as a musician. The objectivity of the machine describes the ability of complex systems to explore a richer and more varied parameter space in musical instruments through non-trivial developments. Owing to complex unpredictability, the resulting state transitions and evolutions are fundamental to reaching unexplored formal solutions in live performance and music creation.

Radical improvisation is by definition the approach that offers the highest degree of freedom in the live act of music performing, although it is by no means an approach that guarantees an acceptable degree of variety and complexity. Formally, radical improvisation can be described as a feedback loop coupling a

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human performer and a sound-generating device, which we generally refer to as *a machine* (Pressing 1984). The human and the machine constitute a hybrid higher-level system where the input is the human's auditory system, and the output is the set of actions performed by the human through the sonic results generated by the machine. We are assuming the basic case in which the machine is not autonomous. Similarly, the practice of electronic music composition in the studio also resembles a feedback configuration, although the process takes place in a non-real-time domain. Namely, the composer working in the studio and following a standard workflow, for example, using software to generate and process sounds that are eventually arranged into pieces through editors and digital audio workstations, cycles through two main phases: *modification* and *result-checking*. The iterative process is repeated until the piece is complete, that is, when it does not require further modifications.

Feedback loops can result in behaviours that tend towards steady-state outputs, called *attractors*, or outputs that oscillate through a limited number of states, called *periodic oscillations* (Gleick 2011). The hypothesis is that the principles of feedback systems and chaos theory may also apply to feedback configurations involving individuals, such as the practices of improvised electronic music and electronic music composition in the studio, as explained earlier. For example, Pierre Boulez claimed that improvised music is often confined within a process where *excitement* and *relaxation* alternate (Bowers 2002). Paraphrasing Boulez's statement, improvised music can sometimes be reduced to a process where musical tension progressively builds up and finally breaks down after it has reached a peak so that the process can start again. This kind of behaviour resembles a typical response of positive feedback configurations (Heylighen and Joslyn 2001), which intrinsically limits the variety of an improvised live performance as global development becomes redundant. Of course, experienced improvisers can avoid these behaviours and ensure that redundancy is diminished as much as possible. Though, the tendency towards redundancy intrinsic to some feedback configurations should be considered as it may still play a role in the unfolding of an improvised music piece. Empirically, what I could also observe in my practice as an improviser, besides a tendency towards alternating tension and relaxation, is a tendency towards retracing a limited set of configurations in the software parameters to recall familiar or otherwise known sonic environments, which, ultimately, also resulted in a large-structure redundancy.

Composers and performers have developed techniques to avoid recurring patterns in improvised music. Structured improvisation (hence non-radical) is an example. In this case, a reduced tendency towards a global redundant behaviour is achieved at the expense of the freedom of the performer, especially considering that the structures may be unrelated to the specific sonic context. Other techniques are the definitions of sound-related constraints or rules. In this case, the improvising performer has the potential freedom of exploring any number of sonic environments, although the limitations will arise from the specific sonic environment, which can be different each time the piece is executed. See, for example, *Duet I* (1960) by Christian Wolff (for background on other works following a similar approach, see Dahlstedt, Nilsson and Robair 2015; Sanfilippo 2022).

The implementation of CASes in live performance and improvised music is yet another technique that can be used to enhance the variety in the development of music performance and limit the tendencies towards redundancy of some improvised music. CASes are structurally coupled with their context, which becomes an essential element for their very existence, and exhibit a non-linear and non-trivial behaviour that is always a function of the surrounding sonic environment. This allows musical CASes to explore their parameters objectively, making it possible to have a variety of combinations that are virtually only limited by the data type representing the system's state variable. The adaptive behaviour of such systems can then explore a theoretically much larger number of sonic environments, which in turn result in a much larger number of developing curves so that the redundancy of both timbres and forms can be contrasted.

3.3. Losing control to gain complexity

The matter concerning the degree of control delegated to the machine, particularly in the case of autonomous machines, is a complicated topic that raises philosophical questions of ontological nature and more practical and empirical ones about the work of electronic music composers and performers. It may appear that the electronic musician has no aesthetic or musical ability whatsoever and that the machine is the sole entity responsible for the musical results. After several years of working in the field of electronic music, it also seems to be relatively common to consider the work of a machine as intrinsically less valuable than the work of a human. The music generated by machines is sometimes subject to an *a posteriori* judgement: despite the result initially seeming objectively convincing for the listener, knowing that a machine has generated the work may penalise it and, in some cases, negatively affect the overall experience. Furthermore, human agents may not be actively involved during the performance, especially when this happens for extended periods, which undermines the overall work's liveness. Even though the machine operates entirely in real-time and in real-space, which is a live approach by definition, it may be considered non-performative due to a lack of direct involvement from the human agent. The approach mentioned previously also establishes a rigorous separation between the human and the machine in producing a music piece: the composer is now concerned with composing a machine that composes sounds and music.

The fact that machine-generated music may be considered less valuable by non-practitioners is not a relevant issue. Unfortunately, though, the same misconception is often found in professional environments of electronic music. There is still the misunderstanding that music technologies and devices are means that solely serve composers' ideas without affecting the aesthetic content of the musical outcome. As stated by Di Scipio (2003), even human–machine interaction performances follow a linear workflow, which establishes an implicit hierarchy where the machine is subordinated to the performer. Mutuality and reciprocal alteration are implicit and fundamental features in the notion of *interaction*. These conditions are achievable when both the human and the machine can perform independent actions while simultaneously reacting to external stimuli to adjust their actions accordingly. In other words, both entities should be capable of generating autonomous behaviours and non-linear dynamics.

It is indispensable to distinguish between autonomous and automated behaviours. Autonomous is sometimes considered a synonym for automated, although the implications of an autonomous design are substantially different from standard automated systems. In several computer music workflows, the formal development and scheduling of sound events are driven by stochastic processes, that is, pseudo-randomness generators or other algorithmic rules that determine the unfolding of the piece through a predefined path. The formal domain, or *high level*, is independent of the domain where music develops, that is, the domain of sound itself or the *low level*.

On the other hand, the autonomous behaviour of CASes is a consequence of the interrelatedness between sound self-generation and formal self-organisation, that is, the tight bond between low level and high level in a network of non-linear interactions that result in complex evolutions and emergent behaviours. CASes are then particularly well suited for applications of human–machine interaction performance and autonomous music systems, and the notion of *aesthetics of the machine* is central within this framework. In the music domain, specifically, the ideas of complexity, non-triviality and emergence refer to sonic evolutions with short-term and long-term variety, with a non-linear interplay between sonic patterns and chaotic perturbations and mutations. Time scales and auditory thresholds, together with the notion of an observer, are key elements for the definition of complexity in the music domain; these are discussed extensively in Sanfilippo (2021b). The implementation of non-linear feedback delay networks and recursive loops is a widespread methodology not only in areas of acoustic physical modelling (Karplus and Strong 1983; Cook 1992; Rocchesso and Smith 1997) but also in biocybernetics and complexity for the design of artificial intelligent behaviours and artificial life (Heylighen and Joslyn 2001; Maturana and Varela 1980). 'Being and existence are emergent from all processes containing feed-back loops' (Morin 1977: 210–16). The emergent nature of CASes is a key element for creating radically new aesthetics that can challenge and enhance the creative output of composers and performers. While musical CASes are designed to produce a sonic output that is structurally complex concerning the time scales and thresholds of human perception, the particular articulations and evolutions are unique features of each system or, of each performance, more precisely, that determine the personality and musicality of the artificial entity.

The action of deliberately losing control, the action of *not doing*, hence the conscious choice as a composer/performer to discover the hidden aesthetics of an autonomous machine such as a CAS, is a process that carries a critical potential. The creative practice of musical CASes is a shift from the synthesis of sound to the synthesis of formal evolutions and artificial expressiveness. The role of the composer becomes primarily concerned with composing music systems that compose music rather than assembling sonic materials into a music piece. The aesthetics of the machine becomes vital for the exploration of new music through the cooperation of the human and the artificial.

4. CONCLUSION

I have discussed the development of systems thinking from the early cyberneticians to the modern theories and techniques in complex systems. In the 1940s, the interaction and exchange between groups of scholars from different disciplines set the beginning of the formalised study of cybernetics and systems science that greatly contributed to today's growth of the field. The application of these studies to a large number of domains ranging from psychology and sociology to engineering and biology underlined their highly transdisciplinary nature and connection to several real-life phenomena.

The early investigations in cybernetics mainly concerned understanding the behaviours of systems regardless of their interactions with the environment or observers. In the 1960s, scholars investigated the possible connections between non-trivial systems and their surroundings, including the environment and the observers. The study of cybernetics shifted towards considering non-trivial systems as tightly interrelated with their environment and observers or considering such systems as larger systems encapsulating the environment and the observers as components that contribute to global behaviours. This new conception was crucial in second-order cybernetics, which Heinz von Foerster defined as 'the cybernetics of observing systems'. Systems as system-environment couples were then regarded as self-referential entities following metaphors of self-awareness. In philosophy, von Glasersfeld was investigating the idea of radical constructivism and the notion of *self*, which he later described through concepts of second-order cybernetics, particularly circular causality. According to his idea, the experience of self takes place as retroactive relationships between the entity and its surroundings. We can see that these disciplines contributed to each other's growth.

The development of feedback-based music was also significantly influenced by this way of thinking, and it closely followed the evolution of these fields. Feedback-based music was initially based on rather simple mechanisms while it expanded over the 1960s and 1970s into more articulated techniques where the environment and self-regulation had a central role. Today, we have seen highly advanced music systems implementing large networks of adaptations through which complex musical structures emerge, allowing music technology to be explored in unconventional ways. The aesthetics of the machine has become of major relevance, and it underlines the importance of agency in music systems. The composer is now concerned with implementing autonomous systems that expand their creative potential: the control of the performer over the machine is an obsolete concept that can only limit the complexity of their synergy. Novel formalised performance modalities based on this idea become vital, and the machine can be seen as an extension of human aesthetics in a synergetic relationship that is key to achieving maximal musical expressiveness.

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