TOWARDS A TYPOLOGY OF FEEDBACK SYSTEMS

Dario Sanfilippo
Scuola di Musica Elettronica
Conservatorio di Musica San Pietro a Majella di Napoli

Andrea Valle
CIRMA - StudiUm
Università degli Studi di Torino

ABSTRACT

Feedback-based systems for audio synthesis and processing have been in use since the '60s, resulting both from the theoretical reflection on Cybernetics and System theory, and from the practical experimentation on analog circuits. The advent of computers has made possible the implementation of complex theoretical systems into audio-domain oriented applications, in some sense bridging the gap between theory and practice in the analog domain, and further increasing the range of audio/musical applications of feedback systems. In this paper, we first briefly introduce feedback systems; then, we propose a set of features to characterize them; finally we propose a typology targeted at feedback systems used in the audio/musical domain, and discuss some relevant examples.

1. INTRODUCTION: FEEDBACK PROPERTIES

The notion of feedback is widely used both as a technical feature in the design of audio and music application and as an aesthetic key in their description (see e.g. [14] [26] [9] [18], as well as the musical works based on feedback that we will discuss later). In short, many feedback based systems for audio and music production/composition exist and many sound artists/composers consider feedback as a crucial notion at the basis of their work. Rather than being a monolithic category, feedback is a complex notion that presents many different features and aspects that are grouped together because of a family resemblance. A minimal definition of feedback takes into account the configuration of a system, provided with input/output, in which some kinds of transformation are carried out, where the output is connected (fed back) to the input after a delay (namely greater than 0 seconds) [13]. In *negative* feedback the input-output relation is inverse: an increase in the output causes a decrease in the input, and vice versa. Thus, the response of the system to stimuli is that of compensation, and it will tend to be in equilibrium around a desired target. In a positive feedback configuration, the input-output relation is direct: if the output increases, the input increases; vice versa, if the output decreases, the input decreases. In this case, a deviation of the system towards a direction will produce a further shifting in the same direction, and the behavior will be that of magnifying the effects caused by the stimuli [2][19][22][21][40]. The positive and negative feedback concepts can also be generalized as *causal relations* [22]. In a system with a causal relation between two variables $A \rightarrow B$, a positive feedback occurs if an increase (decrease) in A produces an increase (decrease) in B; on the contrary, a negative feedback occurs when an increase (decrease) in A produces a decrease (increase) in B. For example, in the relation *infected people* $\rightarrow$ *viruses*, an increase in the infected people will lead to an increase in viruses, which will in turn lead to an increase in infected people (positive feedback) [22]. In the relation *rabbits* $\rightarrow$ *grass*, more rabbits eat more grass, grass decreases and so will the rabbits, but a decrease in the rabbits allows more grass to grow, eventually leading to more rabbits, and so on (negative feedback) [22]. Negative feedback is widely used in control and self-regulating systems (from thermostats to living organisms), and its major role is that of creating stability. Positive feedback, instead, has a typically unstable behavior and causes exponential variations.
A set of specific features emerges from a wide literature on the subject of feedback systems, also in the audio/musical domain. As a consequence, a specific corpus of works and practices sharing these features can be identified in electronic/electroacoustic music. Even if the corpus can be identified by means of these features, still its internal variety is very high, and a classification schema can be proposed in order to clarify in which way some systems differ from other ones. In the following we first introduce the set of features that can be recognized in feedback systems; then we propose a classification schema for the identified works.

1.1. Nonlinearity and circular causality

A system is said to be linear when its output (effects) is proportional to its input (causes). As an example, let's consider a pool ball not subject to friction forces. If the ball is hit with a force *f*, it will have a velocity *v*. When the force is twice greater, the velocity is doubled. Actually, many natural phenomena and systems in the world are intrinsically nonlinear, thus with no proportional relation between causes and effects. As a result, in a nonlinear system, causes of reduced size can have greater effects, and, on the other hand, causes of greater size can have smaller effects. A feedback system is typically nonlinear, nonlinearity being the result of a process with circular causality [19][21]. In such a configuration, effects are also causes [21], and there is a mutual relation between them. The causes are fed back to themselves through their effects, and the effects are the result of their combination with the causes, thus breaking the input-output linear proportion. Another important feature of feedback configuration and circular causality is that processes become *iterated*, leading to systems which will be capable of self-alimentation. From a musical perspective, nonlinearity clearly emerges in feedback-based systems where the change of internal variables can result in very different behaviors in the final output. A clear example is provided by the work of Japanese improviser Toshimaru Nakamura. Talking about his performance with the *No-Input Mixing Board* system (see 2.2), he states:

> You can't totally control no-input music because it's all about feedback. Things like turning the tuning knob, even by one millimeter, make a big difference to the sound. [...] It's very hard to control it. The slightest thing can change the sound. It's unpredictable and uncontrollable. Which makes it challenging. But, in a sense, it's because of the challenges that I play it. I'm not interested in playing music that has no risk. [...] [1]

It is not surprising to realize that sonic features of different kind (amplitude, pitch, sustain, spectral roughness, etc.) that can be considered unrelated in linear audio systems, are instead deeply interrelated in feedback configurations, where a modification of one of them can potentially lead to modifications in all the others.

1.2. Interaction, interdependency and synergy

A fundamental property in feedback configurations is that of *coupling* [2]. Two or more elements within a feedback loop are coupled because they operate in a condition where they mutually affect each other. From a systemic perspective the concepts of interaction, interdependency and synergy are crucial in order to understand feedback systems. A totality which is made up of different components, interconnected by specific relations, shows a certain behavior and identity thanks to the cooperation of all its parts. Any small change in the organization of the relational network can potentially change the identity of the system and radically alter its behavior. Any system of this type, thus, relies on all its components, and each of the parts has a fundamental role in the global functioning of the system. The strict interaction between the components allows for the combination of their properties, leading to new entities which are not the result of a mere summation of the properties of their parts, but, rather, result from their synergy. In most cases, interaction in performances is described as a high-level relation occurring between the human and the machine, where –typically– gestural devices let the performer define actions to be followed by reactions in the machine, without taking into account a real mutual influence. On the contrary, Di Scipio has been able to provide an interesting perspective on interaction in music by describing it as a condition that takes place in the sound domain [14]: interaction occurs among sound materials. Christopher Burns followed Di Scipio's path in his realization of *Electronic Music for Piano* by John Cage [9]. He implemented a system based on a network of eight delay lines in a bidirectional circular audio feedback configuration, where two microphones are connected to two of the eight delay lines, feeding the network with the sound from the piano, and where each node's output is connected to a loudspeaker (see Figure 1). The nodes have an independent time-varying delay, and they also contain sound transformations like resonators and ring modulators. Apart from the technical implementation, the behavior of the system provides a practical example of how sonic interactions may happen. The network acts as a Larsen effect[2] which is triggered and perturbed by the sound from the piano. Although the system design is relatively simple, a high number of loops and sub-loops are activated between microphones and loudspeakers. As a result, the output of each node is dependent from the piano and from all of the other nodes, in turn feeding back the network. It thus becomes possible to hear the sound of the single nodes together with their mutual influence.

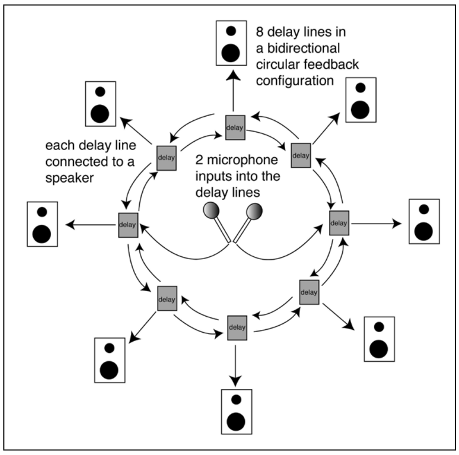

Figure 1. Burn's setup in his Cage's realization.

1.3. Self-(dis)organization, homeorhesis and homeostasis

Self-organization has received many definitions in different contexts, such as Cybernetics, Information Theory, Thermodynamics, Synergetics and others, and although the term is widely used, there is not a generally accepted meaning [20]. Here, we will describe the main features of self-organization so that it becomes possible to apply the concept to the musical domain, as a property characterizing feedback systems. Intuitively, self-organization happens when a system is capable of organizing itself au-

[1] "No-input. Sachiko M and Toshimaru Nakamura", http://www.youtube.com/watch?v=Tl8IMc-8-N8, 5'05".

[2] The Larsen effect happens when –if enough amplification is provided– the sound captured from a microphone connected to a speaker is reproduced and again captured, recursively, resulting in a positive feedback producing pitched tones from the iterated amplification of a signal [7].

tonomously, without an external entity [1] (see [3] for details). According to this definition, any automated music system might be considered as self-organizing. In order to provide a stricter definition, self-organization can be defined as the emergence of coherent patterns at a *global* level out of *local* interactions between the elements of a system [21][19]. Because of the recursive relations between the system's components, the self-organization process is *parallel* and *distributed* [21], as it takes place through the simultaneous action of all the elements, none of them playing the role of a coordinator. Self-organization, indeed, is opposed to the hypothesis of a *centralized* control: it excludes the presence of an external element regulating the system. From this perspective, music systems in which the elements are independent (with no interaction among them, as it often happens), and in which automations are high-level processes of sound organization, cannot be considered as self-organized. If a state of a system is any configuration of its variables (i.e. its overall output), hence self-organization can be thought as the shift from one state to another, including the different behaviors rising from the process of state shifting. A system can enter a stable state, in which either the behavior is statical or it shows dynamic equilibrium. An opposite situation is that of a dynamic unstable behavior, in which the system continuously shifts from one state to another. Such a distinction allows to oppose self-organization (stability or dynamic equilibrium) –leading to an increase in order (a decrease in statistical entropy [21][22])– to self-disorganization (dynamic unstability), leading to an increase in disorder. Self-organization and -disorganization are in some respect analogous to homeostasis and homeorhesis, the two terms indicating respectively a tendency towards stability and a tendency towards a certain point (an "attractor") while the system shifts through different states (following a "trajectory"). An example of work which is based on the concept of self-organization is *Ephemeron* by Phivos-Angelos Kollias. The composer describes the system metaphorically as a living organism, its cells being sonic units in the process of adapting to the surrounding audio environment. Adaptation occurs thanks to the capability of the cells to sense the loudness features from the environment [25]. The system is initially fed with the sound captured from the audience's applause to the piece performed just before *Ephemeron*. Cells' perception of the applause is used to dynamically control the signal processing inside each cell. The work emerges from this self-organization of a mass of cells interacting mutually and with the environment, and evolving through the time.

1.4. Chaos, complexity and emergence

Chaos is a widely diffused term which is often used as a synonym to "unpredictability", yet the two terms do not semantically coincide, as, although chaos implies unpredictability, the reverse relation is not always true. First, chaotic behaviors can be unpredictable even if no randomness is involved. Second, in chaos, what happens now, is the effect caused from what happened before. More generally, chaos can be thought as a highly dynamical behavior where order and disorder coexist and "compete", and where a causal connection between past, present and future is established. Feedback can be modeled as a nonlinear iterated process, a formalism usually associated to mathematical models of chaotic systems [24]. In feedback systems, chaotic behaviors can occur at two different levels. In a situation of dynamical equilibrium, while there is an overall stability, the inner activity can be highly chaotic. On the other hand, if considering homeorhesis, each of the states that the system passes through can be chaotic, exactly as the trajectories that the system follows. Complexity is yet another important concept that can be used to characterize feedback systems [24]. The paradigm of Complexity states that a mass of very simple processes can leads to achieve very complex an unexpected results. Indeed, feedback is an interesting case of a simple behavior that leads to unexpected results (due to nonlinearity) through iteration. In this sense, it can be described in the framework of Complexity. The notion of complexity is strictly related to that of emergence, the first defining the structural organization of the process, the second the quality of unexpectedness of the results. Emergence can refer to organizational levels [29], to self-organization [39], to entropy variation [41], to nonlinearity [28], or exclusively to complexity [5][6] [10] [23] or synergy [12]. Here we will focus on the description of emergence referring to the organizational levels approach, as it seems to particularly fit the musical domain, since an analogy can be traced between low-level and high-level, and, respectively, micro-structure and macro-structure. According to this approach, a phenomenon is emergent when it manifests itself at a level *L-hi* as the result of components and processes taking place at a level *L-lo* [4]. In feedback systems, the output of the system at the higher level (the overall sound output) results from the processes defined at a lower level, as the composer/performer exclusively focuses on "composing the interactions" [14]. From a qualitative and holistic point of view, emergence is the rising of global properties coming from the interactions of lower level components, where the global properties are not related to those of the components [30]. In these case, the synergy between the interacting components gives birth to an entity which is different from the sum of its parts [12]. It is more, but even less [32]. Many important works by Di Scipio, which will be further described later, are particularly relevant in relation to the features described in this subsection, as Di Scipio's approach often aims at composing dynamical and chaotic entities where homeorhesis and homeostasis are competing criteria [14], and where sound and structures emerge from the sonic interactions in the environment.

2. TOWARDS A TYPOLOGY OF MUSIC FEEDBACK SYSTEMS

The previous discussion, though very general, allows to narrow the field to feedback systems used in a wide corpus of musical projects dating back from the '60s that is still flourishing at the present day. Although bound together by the use of feedback as a common denominator, these works present a rich and complex phenomenology which requires, in order to be fully understood, a greater articulation. First of all, it is possible to propose a general schema of audio feedback systems that aims at summing up all the key features emerging in our analysis corpus. Figure 2 shows a feedback system (*System*): following the previously introduced minimal definition of feedback, *System*'s audio output (*audio*, resulting from *Out*) is re-injected into the same system input (*In*). Starting from Figure 2, it is possible to propose five main features to classify feedback-based audio/music systems. These features can be organized into couple of oppositions, defining six categories. The other elements represented in Figure 2 will be introduced while discussing the categories.

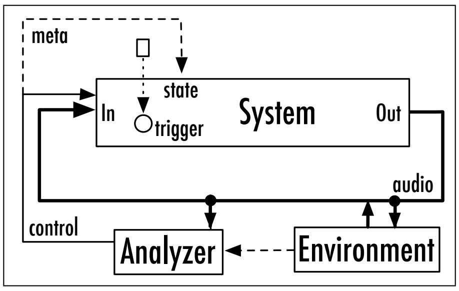

Figure 2. A general schema for feedback-based audio/music systems.

2.1. Information encoding: analog/digital

As an overall schema of feedback-based audio systems, Figure 2 is abstract from the way in which information is encoded into *System*. Thus, a first distinction that can be taken into account is between systems that encode information analogically vs. digitally, although some systems can also make use of both types. An example of purely analog feedback system is that of the Japanese improviser Toshimaru Nakamura[3]. Nakamura, with his No-Input Mixing Board project, creates music just by plugging the outputs of a mixer into its inputs, in this way turning a mixer into a bank of oscillators. The only tools on which he relies are amplification/attenuation of signals and equalization, although the result can be surprisingly complex and interesting. An example of purely digital feedback system is *Fantasia on a Single Number* by Stelios Manousakis[4], where a single number recirculating in the feedback loops sets the system into motion and generates sounds and structures. Other examples of digital feedback systems are the LIES project, a work for human-computer interaction performance, and the SD/OS installations series by Dario Sanfilippo[5] (even if in some versions of these works analog devices like microphones are also in use). These systems are implemented by means of audio feedback networks of non-random and non-automated DSP modules like reverb, ring modulation, frequency shifting and waveshaping, a design explicitly thought as technically incapable of unpredictability and dynamism, yet resulting in an organic and evolving sonic entity with chaotic behaviors and emergent properties. The work by the Australian sound artist Malcolm Riddoch[6], instead, is an example where both digital and analog devices are used. His approach is based on improvisation, with an important focus on environmental factors, soundscape transformations, and indeterminacy. Riddoch implements hybrid feedback systems using different types of input/output transducers (microphones, electric bass/guitar), and analog/digital modules for sound manipulation, even using the computer to turn sound into control signals. In this way, the artist creates feedback chains aimed at exploring the spaces where the performance takes place.

2.2. Information rate: audio/control

The output of an audio feedback system is an audio stream. Audio information rate can be described in turn in relation to perception (e.g. in terms of temporal resolution of hearing [31]) or to technology (e.g. in terms of sampling rate in a digital system). Feedback can indeed take place in the audio domain, as it happens in Larsen tones, where acoustic information from a loudspeaker is captured by a microphone, diffused again through the loudspeaker and so on. But the rate of the signal fed back into *System*'s input can be sub-audio, i.e. occurring in the control domain, when, for example, information is extracted from sound and is used to drive processes of sound transformation. In Figure 2 the thick line (*audio*) represents the audio flow re-injected into *System* in case of audio feedback. Rather, in the case of control feedback, an analysis component (*Analyzer*) is required in order to perform the extraction of information from audio and to generate a control flow (*control*). The latter feeds back *System* (note that dots represent derivations from sources of information).
Riddoch's system represents a situation of control feedback, and so does the |. (bar dot) project, a performance setup by Dario Sanfilippo (GenES, a DSP digital system) and Andrea Valle (Objectarium, an electro-mechanical, computer-controlled ensemble) focusing on the exploration of feedback systems in improvisation [36]. The systems are coupled in feedback. Namely, GenES output will be analyzed by Objectarium and will pilot the sequencing of events for the electro-mechanical ensemble, while the sound from Objectarium will be fed back to GenES and will perturb its behavior. To put it in Di Scipio's words, each system will listen to itself through the other self [16]. Another example of this type comes from the work by Roberto Garretón[7], who, in his projects *Study on Feedback I and II*, implements feedback systems capable of extracting features from sound (what he calls the "senses")

[3] http://www.japanimprov.com/tnakamura/
[4] http://modularbrains.net/
[5] http://dariosanfilippo.tumblr.com/
[6] http://malcolmriddoch.com/
[7] http://www.robertogarreton.com/

such as amplitude, spectral flatness, spectral centroid and pitch tracking which are processed in a control DSP engine (what he calls the "brain"), and finally used to pilot sound transformations like pitch shifting, granulation and spectrum smoothing. An example of a work based on audio feedback is the classic *I Am Sitting in a Room* by Alvin Lucier (1969). Technically, the process adopted by Lucier, that of iteratively recording his voice after the latter is acoustically shaped by the room, is nothing but a Larsen phenomenon (in this case triggered the voice itself) stretched in time [15]. The room itself acts like a filter, and what is to be expected after a very high number of iterations is to hear the resonance frequency of the room, after all other frequencies have been attenuated (see also [27] for an in-depth phenomenological analysis). An example of exclusively control feedback is the *Rumentario Autoedule* sound installation by Andrea Valle[8]. The work features two main components, a computer for sound analysis and scheduling of events, and an electro-mechanical orchestra made of 24 acoustic generators (the "rumentario", [38]). The analysis extracts onset, pitch and loudness from the environment, to be used to drive the orchestra. At each detected onset, the recognized pitch, quantized to quarter tone pitch classes, selects the next mechanical sound generator that will play, while the loudness is proportional to the current used to drive motors/actuators. As the environment coincides with the orchestra itself scattered over a surface, the system reacts to itself. Considering that the orchestra is highly percussive, the pitch detection is intrinsically very noisy, resulting in a dynamical and ever-changing system.

2.3. Environment openness: closed/open

A crucial aspect in feedback system lies in their relation with the surrounding environment, represented in Figure 2 by *Environment*. Here we define *Environment* as all the audio information that is external to *System*, i.e. not generated neither controlled by *System*. Indeed, sources of audio information can be of very different kind, e.g. the surrounding soundscape captured by microphones but also an audio stream resulting from playing back audio files and provided as input to *System*. A third descriptive category thus deals with the openness to environment. Closed systems do not exchange energy/information with the environment, while open ones are coupled in an external feedback loop with the environment. Nakamura's work is an example of closed feedback system, and so is the work on feedback by David Tudor [11], implemented by interconnecting everyday analog pedal effects and handmade electronic analog circuits[9]. The composer called his systems "friends", as they had the possibility to express themselves, the role of Tudor being that of putting into evidence what was already inside the systems [33]. Riddoch's work, instead, is clearly oriented towards open systems, just like the previously described *I Am Sitting in a Room* by Lucier or his *Bird and Person Dyning*, in which the American composer explores the Larsen phenomenon through ear-microphones and loudspeakers, walking through the concert hall and directing his ears. Another interesting example of open system comes from Mark Trayle's *Phantom Rooms* [37]. In 2010, Trayle has been invited to create and perform a piece which would somehow interconnect two different locations 200 kilometers away (in Turin and Cuneo, Italy). Two electro-acoustic ensembles in two different locations, and the spaces themselves, where linked through a bidirectional, very fast internet connection. The performers could share not only data but also audio streams in real time coming from the microphones placed in each location. They were also provided with impulse responses of their environment which would have been used to filter the sound. The name of the project was *Phantom Rooms*, as in some sense each location was appearing acoustically in the other one. To put it in Trayle's words, "it is like being invited to someone's house and bring your own room there" [37]. Hybrid systems in this category are common, as it is easy to establish/break feedback with the environment through, for example, microphones and loudspeakers. Yet, the crucial point for open systems is that some kind of interaction has to take place between the system and the environment, and the sole physical connection may not be enough.

2.4. Trigger modality: internal/external

In positive feedback systems, the initial conditions are particularly relevant, as some energy is required in order to trigger the amplifying feedback loop. As shown in Figure 2, this initialization step (*trigger*, to speak with computing parlance) can result from the internal activity of the system itself or be operated by some external agent. In relation to the first case, an analog system always has residual noise in its components, that can be used as the only source of alimentation. In the digital domain, it may be possible to have numerical garbage within the software that can be used in a similar way. Otherwise, the system can e.g. be excited with an impulse and then let run with no external sources. Another possibility is that the system features some kind of external perturbation as an element to alter its spontaneous behavior. This situation could also be considered as a particular hybrid case for the audio/control category, as the external audio is used to alter the behavior of the system, which can have effects in short or long terms. Nakamura and Tudor are also examples of no-input feedback systems, and so are the LIES and SD/OS projects. Lucier's *Bird and Person Dining*, instead, is an example for the opposite feature. The mechanical bird taking part into the performance acts as a perturbation agent, triggering Larsen tones in the audio setup with its twittering.

2.5. Adaptivity: adaptive/non-adaptive

System can be able to transform itself, i.e. to change its internal state (*state*), as a function of its input. This is

[8] https://vimeo.com/37148011

[9] https://sites.google.com/site/futureecircuits/david-tudor-electronics

typically the case when *System* is coupled with *Environment*. In this case, it may be capable of extracting information from *Environment* (see the dashed *meta* path in Figure 2) in order to adapt its state to changing environmental conditions. This extraction is performed by analysis algorithms at the control level (*Analyzer*) but, as it determines a change to a different state of the system and not only a variation in its actual state, is placed at a higher level (hence the name *meta*). An example of adaptive system is the *Audible Ecosystems* project, a remarkable set of works by Agostino Di Scipio[10]. The systems that belong to the project are based on a structural coupling with the environment, with microphones and loudspeakers being terminals through which the system exchanges energy and information with the environment. The sound is analyzed with a feature extraction algorithm: the control signal thus obtained is used to drive digital processes of sound transformation based on psychoacoustic criteria. The resulting audio is reintroduced in the environment, thus captured and analyzed again, recursively. A fundamental condition for the system to "survive" (i.e. remain active) is to be coupled with the environment (see Figure 3).

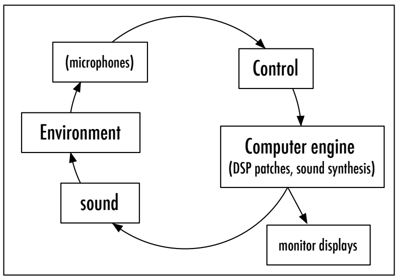

Figure 3. Overall conceptual design of the *Audible Ecosystems* project.

Two further considerations are possible. First, adaptation is independent from environment coupling. A system, although coupled with the environment, may not have the capability of changing its internal state as a reply to a changing environment. Second, while environmental coupling is indeed the classic case for adaptation, a (closed) system can adapt to itself, that is, change its state as a result of its output. An interesting example comes form DSP software. Volta software by MOTU is a virtual instrument plug-in that turns the sound card into a voltage control interface[11]. Volta generates and sends DC signals via the sound card to voltage-controlled analog synths, thus allowing the user to reach a digital control over analog hardware. In turn, the audio signal output by the analog device can be connected in a feedback loop to the sound card input and received by Volta. Through this feedback loop, Volta is capable of autocalibration on analog synths. By the way, Volta is also a "hybrid control system" [34] that couples an analog and a digital component.

[10] http://xoomer.virgilio.it/adiscipi/
[11] http://www.motu.com/products/software/volta/

2.6. Human-Computer Interaction: absent/present

A final category, this time exclusively musical, concerns the presence/absence of a human performer interacting with the systems, and entering the feedback loop. Being structurally sensitive to minimal variations in their input, feedback systems tend to prompt an opposite performing situation. In the first case, the performer is absent, and the system is entirely machine-based. In the second case, the performer is present: as s/he is forced to dynamically interact with the dynamical machine system, in the design of the performance an improvisational mood is often preferred to a fixed set of instructions. Also, as improvisation is a process where actions are causally related to listening, an aural feedback loop is established between the machine and the performer, the latter becoming an integral part of the overall system. As feedback systems, and more generally electro-acoustic and computational devices, can operate without external control or actions by the performer, the latter, while improvising, is in front of an entity that can be autonomous, where the human-machine relation is not necessarily based on subordination, but rather on a not-hierarchical exchange between two entities with their own aesthetics [17] [35] [8]. The performer is not explicitly represented in the general schema of Figure 2 because s/he can play different functional roles. S/he can trigger the system (acting like *trigger*); contribute to perturb the environment by producing/modifying sounds (that is, becoming a part of *Environment*); extract information from audio (like *Analyzer*) in order to vary system parameters (as in the *control* signal flow) or to make the system change its state (like the *meta* flow). As the performer is theoretically a black box, the analytical treatment of her/his behavior with respect to the other components of the feedback configuration may result very complex and lead to ambiguous findings.

3. CLASSIFICATION AND TYPES

Starting from the categories discussed above, it is possible to describe feedback systems by encoding the values that each system assumes for each category. In a relevant number of cases it is not easy to define the value for the categories. On one side, the system may appear ambiguous to the observer because of its complexity or of the lack of information on its internal processes. On the other side, hybrid configurations are indeed possible, that do not clearly allow to place the system with respect to the category (the typical case being that of mixed analog/digital configurations). In order to classify feedback systems, each category can receive a value in the range $[0, 1, 2]$ where 0 and 2 represents the opposed features, and 1 the case of unassigned, hybrid systems for that category. In short, each feedback system can be represented by a ternary string encoding its properties. Table 1 shows a comparison of the previously discussed examples. Columns represent categories, rows shows values for each example. As there are six categories to be taken into account, each one with three possible values, the total number of combinations is very

	Encoding	**Rate**	**Openness**	**Trigger**	**Adaptivity**	**Interaction**
	Analog/Digital	*Audio/Control*	*Closed/Open*	*Internal/External*	*Adaptive/Non-adaptive*	*Absent/Present*
|.	1	1	1	1	0	2
Burns	1	1	2	2	0	2
Di Scipio	1	1	2	2	2	1
Garretón	1	1	2	2	2	1
Kollias	1	1	2	2	0	0
Lucier (1-2)	0/0	0/0	2/2	2/2	0/0	0/2
Manousakis	2	0	0	0	0	2
Nakamura	0	0	0	0	0	2
Riddoch	1	1	2	2	0	2
Sanfilippo (1-2)	1/1	0/0	1/2	1/2	0/0	0/2
Trayle	1	0	1	2	0	2
Tudor	0	0	0	0	0	2
Valle	1	2	2	2	0	0

Table 1. A comparison of feedback systems (categories and values).

high, resulting in $3^6 = 729$ types of feedback system. As a consequence, such an analytical, even if minimal, framework allows to include many different works, sharing a common reference to feedback but coming from different traditions and practices, and to specify their mutual relations.

4. CONCLUSIONS

The use of feedback clearly identifies a specific group of works that, starting from the '60s, have explored, with a various degree of awareness, a tightly related set of notions, such as nonlinearity, circular causality, interdependency, self-organization, complexity and emergence. Even if the external boundaries that define this corpus of works are, if not clear-cut, anyhow sufficiently evident, still feedback-based musical systems show a wide internal variety, that must be tackled in order to shed light on their richness. The discussed typology, resulting from the set of six, general categories, is intended to provide an analytical tool that would allow description and comparison among feedback based audio/music works. The categories can be further expanded. As an example, interaction includes many different performing modalities that can lead to other subcategories. On the other side, there is indeed a trade-off between analytical detail and overall manageability. Our future work will focus on expanding the corpus of examples in order to test the typological device and eventually modify the schema and/or redefine/refine the categories.

5. REFERENCES

[1] W. R. Ashby, "Principles of the self-organizing dynamic system," *Journal of General Psychology*, no. 37, pp. 125–128, 1947.

[2] ——, *An Introduction to Cybernetics*. London: Chapman and Hall, 1956.

[3] ——, *Principles of Self-Organization*. Pergamon, 1962, ch. Principles of the self-organizing dynamic system, pp. 225–278.

[4] E. Bonabeau and J.-L. Dessalles, "Detection and emergence," *Intellectica*, no. 25, pp. 85–94, 1997.

[5] E. Bonabeau et al, "Characterizing emergent phenomena (1) : A critical review." *Rev. Int. Syst.*, no. 9, pp. 327–346, 1995.

[6] ——, "Characterizing emergent phenomena (2) : A conceptual framework." *Rev. Int. Syst.*, no. 9, pp. 347–369, 1995.

[7] C. R. Boner, C. Paul; Boner, "Behavior of sound system response immediately below feedback," *J. Audio Eng. Soc*, vol. 14, no. 3, pp. 200–203, 1966. [Online]. Available: http://www.aes.org/e-lib/browse.cfm?elib=1149

[8] J. Bowers, "Improvising Machines. Ethnographically Informed Design For Improvised Electro-Acoustic Music," Master's thesis, KTH, Stockholm, 2002.

[9] C. Burns, "Designing for Emergent Behavior: a John Cage Realization," in *Proceedings, International Computer Music Conference 2004.*, Stanford, 2003, pp. 193–196.

[10] P. Cariani, "Adaptivity and emergence in organisms and devices," *World Futures*, no. 31, pp. 49–70, 1991.

[11] N. Collins, "Composers Inside Electronics: Music after David Tudor," *Leonardo Electronic Almanac*, vol. 14, 2004.

[12] P. Corning, "The re-emergence of emergence: a venerable concept in search of a theory," *Complexity*, vol. 7, no. 6, pp. 18–30, 2002.

[13] J. de Rosnay. (1997) Feedback. principia cybernetica web. [Online]. Available: http://pespmc1.vub.ac.be/FEEDBACK.html

[14] A. Di Scipio, "Sound is the interface': from interactive to ecosystemic signal processing," *Organised Sound*, vol. 8, no. 3, pp. 269—277, 2003.

[15] ——, "Per una crisi dell'elettronica dal vivo (analisi del brano di lucier)," *Rivista di Analisi e Teoria Musicale*, vol. XI, no. 2, pp. 111—134, 2005.

[16] ——, "Listening to yourself through the otherself: On background noise study and other works," *Organised Sound*, vol. 16, no. 2, pp. 97—108, 2011.

[17] G. E. Garnett, "The aesthetics of interactive computer music," *Computer Music Journal*, vol. 25, no. 1, pp. 21–33, 2001.

[18] R. Garretón, "Autonomous systems," Master's thesis, Institute of Sonology, The Hague, 2007.

[19] C. Gershenson, "Design and control of self-organizing systems," Ph.D. dissertation, Faculteit Wetenschappen and Center Leo Apostel for Interdisciplinary Studies, University of Brussels, Brussels, 2007.

[20] C. Gershenson, F. Heylighen, and C. L. Apostel, "When can we call a system self-organizing," in *In Advances in Artificial Life, 7th European Conference, ECAL 2003 LNAI 2801*. Springer-Verlag, 2003, pp. 606–614.

[21] F. Heylighen, *The Encyclopedia of Life Support Systems*. Oxford: EOLSS, 2003, ch. The science of self-organization and adaptivity.

[22] F. Heylighen and C. Joslyn, *Encyclopedia of Physical Science and Technology*. New York: Academic Press, 2001, ch. Cybernetics and Second-Order Cybernetics, pp. 155–170.

[23] G. Kampis, *Self-Modifying Systems in Biology and Cognitive Science*. New York: Pergamon, 1991.

[24] S. H. Kellert, *Borrowed Knowledge: Chaos Theory and the Challenge of Learning across Disciplines*. Chicago: University Of Chicago Press, 2008.

[25] P. A. Kollias, "Ephemeron: Control Over Self-Organised Music," in *Proceedings of the 5th Sound and Music Computing Conference*, Paris, 2008, pp. 138–146.

[26] ——, "Music and Systems Thinking: Xenakis, Di Scipio and a Systemic Model of Symbolic Music," in *Proceedings of the 5th EMS Conference*, Paris, 2008, pp. –.

[27] B. LaBelle, *Background noise: perspectives on sound art*. New York–London: Continuum, 2006.

[28] C. G. Langton, "Computation at the edge of chaos: phase transitions and emergent computation," *Phys. D*, vol. 42, pp. 12–37, June 1990. [Online]. Available: http://dl.acm.org/citation.cfm?id=87506.87520

[29] G. H. Lewes, *Dictionnaire de la langue philosophique*. Foulquié, 1874, ch. Problems of Life and Mind.

[30] M. Mitchell, "Complex systems: Network thinking," *Artificial Intelligence*, vol. 170, pp. 1194–1212, 2006.

[31] B. C. Moore, *An introduction to the psychology of hearing*, 5th ed. Bingley: Emerald, 2008.

[32] E. Morin, "Restricted complexity, general complexity," in *Intelligence de la complexité : Épistèmologie et pragmatique*, Cerisy-La-Salle, 2005.

[33] B. C. O'Connell, "Electronic friends: David tudor and live electronic music," Master's thesis, Wesleyan University, 2008. [Online]. Available: http://wesscholar.wesleyan.edu/etd_hon_theses/124

[34] C. Roads, *The Computer Music Tutorial*. Cambridge, MA, USA: MIT Press, 1996.

[35] R. Rowe, "The aesthetics of interactive music systems," *Contemporary Music Review*, vol. 18, no. 3, pp. 83–87, 1999.

[36] D. Sanfilippo and A. Valle, "Heterogeneously-coupled feedback systems. the —. (bar dot) project," in *Proceedings of International Computer Music Conference 2012*, Ljubljana, 2012.

[37] M. Trayle, "Remote Utopias/Phantom Room," in *Prossime distanze. Atti del XVIII CIM - Colloquio di Informatica Musicale*, A. Valle and S. Bassanese, Eds., AIMI - Associazione Informatica Musicale Italiana. Venezia: DADI - Dip. Arti e Design Industriale. Università IUAV di Venezia, 2011, pp. 11–14.

[38] A. Valle, "The rumentarium project," in *Proceedings of the international conference on Multimedia*, ser. MM '10. New York, NY, USA: ACM, 2010, pp. 1413–1416. [Online]. Available: http://doi.acm.org/10.1145/1873951.1874232

[39] R. E. Varela F., Thompson E., *The Embodied Mind*. Cambridge (Mass.) and London: The MIT Press, 1991.

[40] N. Wiener, *Cybernetics or control and communication in the animal and the machine*. New York: Wiley, 1948.

[41] W. H. Zureck, Ed., *Complexity, Entropy and the Physics of Information*. London: Addison-Wesley, 1990, ch. Requirements for evolvability in complex systems : Orderly dynamics and frozen components.