Mapping, Triggering, Scoring, and Procedural Paradigms of Machine Listening Application in Live-Electronics Compositions

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Abstract. *Since the advent of real-time computer music environments, composers have increasingly incorporated DSP analysis, synthesis, and processing algorithms in their creative practices. Those processes became part of interactive systems that use real-time computational tools in musical compositions that explore diverse techniques to generate, spatialize, and process instrumental/vocal sounds. Parallel to the development of these tools and the expansion of DSP methods, new techniques focused on sound/musical information extraction became part of the tools available for music composition. In this context, this article discusses the creative use of Machine Listening and Musical Information Retrieval techniques applied in the composition of live-electronics works. By pointing out some practical applications and creative approaches, we aim to circumscribe, in a general way, the strategies for employing Machine Listening and Music Information Retrieval techniques observed in a set of live-electronics pieces, categorizing four compositional approaches, namely: mapping, triggering, scoring, and procedural paradigms of application of machine listening techniques in the context of live-electronics music compositions.*

1. Introduction

In the last two decades, the search for new approaches related to techniques aimed at Machine Listening (ML) and Music Information Retrieval (MIR) in the live-electronics repertoire has expanded considerably. The growing interest in exploring the possibilities that such tools offer to music creation resulted in artistic productions that encompass the most varied aesthetics currents, technical approaches, and compositional strategies.

In this article, we seek to outline remarkable characteristics of the compositional use of ML/MIR tools in live-electronics/interactive music combining instrumental/vocal sounds and DSP processes. By observing some compositional strategies that have been explored for composers in the context of ML/MIR and DSP techniques for the extraction of musical data, we aim to circumscribe a series of approaches by organizing them into compositional paradigms.

The article comprises two main parts. In the first one, we seek to situate ML/MIR as interdisciplinary research fields, placing in context these areas and tools both in music researches/application as well as in a broader scope. In the second part, we seek to identify approaches to the use of ML/MIR processes in creative processes involving interactive systems, outlining four distinctive compositional paradigms in the field of interactive music: (1) *mapping*; (2) *triggering*; (3) *scoring*, (4) *procedural*.

2. ML and MIR as Interdisciplinary Research Fields

As interdisciplinary research fields, ML and MIR involve several areas, comprehending computer science, electrical engineering, acoustics, psychoacoustics, music theory, among others. In general, researches and applications in these fields involve the investigation and development of algorithms and DSP models that allow for the estimation of distinctive sonic/musical attributes from audio signals/streams and the extraction of correlated quantitative data through audio descriptors (including, possibly, machine learning and statistical methods).

By employing different DSP methods and psychoacoustic models, ML/MIR techniques retrieve quantitative data that, through a correlation with some semantic characteristics of sound, may give relevant clues about qualitative and perceptual elements of sound and music. These techniques allow for data retrieving from audio signals that can be useful to outline both more traditional music concepts (pitch, tempo, key, and intensity, for instance) as well as psychoacoustic-based parameters (like harmonicity/inharmonicity, brightness, roughness, loudness, among others). To the extraction of these features, many higher-level ML/MIR algorithms rely on cognitive and psychoacoustic models, seeking to simulate organs, mechanisms, and specificities of human auditory perception [1, 2].

According to [1], most of these algorithms are based on hypothetical modeling of human auditory perception and seeks to mimic psychoacoustic phenomena. There are several research areas aimed at the study of the operation and behavior of the human auditory system. For instance, the Auditory Scene Analysis (ASA) [3] studies how our cognition and auditory perception are capable to decompose and separate overlapping sounds and, consequently, identify them as their sound sources. In this sense, recent studies in the ASA field are focused on computa-

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tional modeling of these methods [4, 5], thus giving rise to Computational Auditory Scene Analysis (CASA), a new research field with several interests, motivations, and goals in common with ML and MIR fields.

In the context of computer-music researches, the term “machine listening” was firstly used to refer to the extraction of symbolic music parameters associated with the extensive use of MIDI protocol and its employment in the design of interactive music systems [6]. Later, the evolution of MIR, as a study field, was largely related to the development methods for analyzing and extracting sound attributes directly from digital audio, [7], having as initial motivation the implementation of indexing mechanisms for digital music files; content-based music search, retrieval, and recommendation systems; and interfaces that allowed easy access to massive online collections.

In the present context of technical and creative researches on the real-time computation of music and sound, both ML and MIR refer to processes of extracting quantitative data from audio streams and/or files. Specially since the second half of the ’90s, within the spread of personal computers, and consequently with the emergence of musical computing environments — such as *Pure Data*, *Max/MSP*, and *Supercollider* —, the implementation of digital signal processing techniques was facilitated, allowing the creative exploration of real-time ML/MIR based techniques.

3. Compositional Paradigms

To understand the technical realizations, compositional approaches, and poetic conceptions that composers employ in the creative exploration of the set of tools of our interest, we propose an arbitrary organization of the different ways of thinking about its use into four groups, namely: (1) *mapping*; (2) *trigger*; (3) *scoring*; (4) *procedural*. We identified these paradigms regarding strategies of the conception of the algorithms, the organization and treatment of the extracted data, and the approximations on the creative use of these techniques to create the most diverse computational processes within the scope of live-electronic music.

We emphasize that the pieces discussed in this text are not meant to be representative of any aprioristic paradigm, which would precede them as a model, category, or aesthetic group. The identification of these paradigms is consciously arbitrary, built upon analytical interpretations. The objective, however, is not the categorization of these paradigms but to understand different poetic approaches regarding the use of specific tools in music creation. The idea is to identify poetical stances with regard to the creative application of the tools, aiming less at the segregation of particular aesthetics or compositional schools and more to comprehend how the insertion of these new tools into heterogeneous poetic practices takes place.

3.1. Mapping

We classify as *mapping paradigm* the creative applications of MIR/ML tools that rely on correlations and transformations between input parameters and the algorithms of sound transformation/generation. It is strongly related to the processes of “liaison strategies between the outputs of the gestural controller and the input controls of the sound generation”[8] units in the context of the design of New Digital Instruments, allowing for building more simplistic or more complex relationships between these values and the synthesis algorithms they control. This correlation happens through a mediation layer, which is in charge of defining the paths that the input information stream will take, and the function that they will acquire within the architecture of the synthesis processes [9]. In short, mapping operates on transferring information and converting it into parameters in order to control computational actions and processes.

Mapping is a characteristic process of digital luthiery, i.e., the design of digital/expanded instruments and digital music interfaces [8, 10, 11]. While in acoustic instruments, the interface is linked directly to the sound production mechanism — the violin strings are an integral part of both the control and the sound generator mechanisms —, in digital instruments, in general, the interface is separated from the sound production device: the relation between them needs to be defined, what is done through mapping processes[12].

In general, mapping processes are conceived through pre-defined strategies, which correlate in straightway a set of data to a series of parameters — e.g., the roughness rate extracted from a signal can control the grain size of granular synthesis. Therefore, these correlations can be divided into four categories: (1) one input data controls only one parameter (one-to-one); (2) one input data control more than one parameter simultaneously (one-to-many); (3) more than one input data controls only one parameter (many-to-one); (4) a combination of all three categories, in which more than one input data controls more than one parameters (many-to-many) [13].

A practical example of mapping application can be observed in the chamber opera, *PS. I will be home soon!* (2012), for six instruments, four voices, and live-electronics, by Anna Einarsson. The libretto was written by Maria Sundqvist and is based on the life of the Swedish sailor, Calle Pettersson covered in the book *Kung Kalle av Kurrekurreduttön* [14].

Considering the technical and musical aspects, Anna Einarsson developed tools and procedures aiming at musical/spectral information extraction from the singing voice, mapping these parameters to control the interactive processes of the piece. According to the composer, the idea since the beginning of the compositional process was to develop mechanisms of dynamic control of the electronics, without requiring physical interfaces or sensors to be coupled to the performers [15].

In collaboration with the researcher Anders Friberg, Einarsson has implemented in *Ps. I will be home soon!* an extraction method for retrieving attributes related to the vibrato range produced by the singing voice. Such a method relies on an algorithm called CUEX (Cue-

Figure 1: Excerpt with vowel tremolos referring to bars 122 to 130 of *Da una crepa*, by Marta Gentilucci

extractor), developed by Friberg in MatLab and, posteriorly, ported for *Pure Data* [16]. The extracted information from the voice is mapped and used to control four polyphonic synthesizers, each of them containing resonant filters and oscillator banks, which are excited by the noise signals [17].

The extraction process can be divided into five steps: (1) fundamental frequency detection and signal amplitude measurement through the Yin algorithm [18]; (2) creation of a gate using a specific pitch range and an amplitude threshold (only the pitches which fall within this limit will pass to the analysis); (3) the signal is divided into two parts, the first part is filtered by a low-pass filter and the second by a medium filter with a window size equals to a vibrato cycle — considering a vibrato rate equals to 6hz; (4) the two parts are subtracted in a way that the resulting signal will be zero when there is no vibrato; (5) the average of the absolute signal value is calculated through a medium filter with the double size of a vibrato cycle (thus the signal resulting will be proportional to the extent of a vibrato given in cents) [16, 17].

In *Ps. I will be home soon!* the mapping process is related to the notion of *metaphoric mappings*, such as described by [19]. What is transferred, in this process, are not the attributes themselves, but the relationships between the source domain (origin) and the target domain (destination). According to [17], in this piece, there is a relationship of forces employed to the mapping method. The density expresses the force in the target domain, which represents a dynamic structure of grouping of pitches, and the vibrato is the expression of the force in the source domain, i.e., the singing voice. Thus, the greater the presence of vibrato, the denser the grouping of pitches resulting from the synthesis process.

Another piece that illustrates very well the employment of what we call here mapping paradigm, is *Da una crepa* (2011-2012), for choir, soprano, ensemble, and live-electronics, by Marta Gentilucci (Figure 1). Some of the central compositional aspects of *Da una crepa* arise from Gentilucci's desire to explore rhythmic structures, both at the macro-level — controlling and developing complex rhythmic structures throughout the composition — and at the micro-level — relationships between the internal temporal structures of the sound, and the possibility of using these structures as a control interface to generate and/or manipulate other sounds.

In this context, there arises the idea of correlating the rhythmic structures generated by vowel tremolos extracted from the singing voice — i.e., the repeated alternation of vowels over the same note, for example, "a-e-a-e" — to parameters that could manipulate pitches in electronic processes. In other words, the alternation of vowels would be applied to a given sound to control the amount of variation in the transposition of that same sound. In short, the composer intended to design a process that could modulate the pitch of a tenuto (sustained) sound through the rhythmic structure generated by the articulation of the voice.

Thus, the process of extracting and mapping the attributes used in *Da una crepa* is carried out in three steps. Throughout the piece, certain excerpts are recorded and saved in buffers. Then, these segments are analyzed with the help of audio descriptors (a combination of spectral deviation, odd to even second tristimulus, and total energy to extract the vowel tremolo [20]), and the resulting data of this analysis, being stored in a `[coll]` object [1]. Finally, the stored data maps the transposition of two modules of pitch shifter and a harmonizer.

3.2. Triggering

The *triggering paradigm* is related to the ML/MIR employment in the conception of systems and algorithms aimed at sound/musical event detection. This strategy deals with procedures that rely on logical processes. In

[1] Max/MSP object that allows the storage, organization, editing, and retrieval of messages

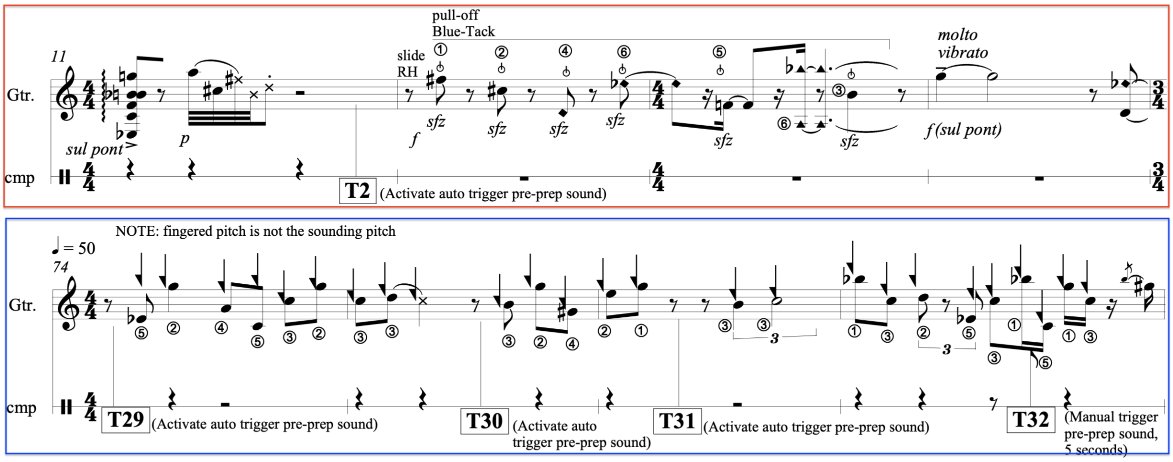

Figure 2: Bar 12 (red) and bars 74 to 76 (blue) of *Decostructing Dowland*

other words, algorithms analyze the digital signal looking for specific characteristics, which can describe certain events, such as pizzicato; dynamic variation; trills; vibrato, among others. Upon the detection of such events, the algorithm may trigger some electronic process.

The triggering paradigm is widely used within the scope of *live-electronics*, as well as in the design of *interactive musical systems* and autonomous agents [1], as a direct interaction strategy between the machine and the performer. By "listening" to the instrumentalist and detecting the presence of pre-defined events, the computer triggers processes, thus establishing a direct relationship between the instrumental gestural actions and the response of the machine to these impulses.

Decostructing Dowland (2009), for acoustic guitar and live-electronics, by Natasha Barret, illustrates in a simple and didactic way the practical application of the triggering paradigm (Figure 2). With the desire to unite ancient music with current musical practice, Barret takes, as a starting point, the three galliards for lute solo published in the first book of songs by John Dowland.

In this piece, the triggering paradigm occurs through the application of an attack detector to automatically and accurately trigger small sound samples previously conceived in the studio and saved in buffers. To realize this, Barret uses used the `[bonk~]` object, implemented by Miller Puckette [21], for *Pure Data* and *Max/MSP*.

The `[bonk~]` works in the audio signal analysis to detect attacks, through the search for sudden changes in the energy envelope, which presents specific characteristics. The detection process is applied in bar 12 and in the excerpt that goes from bar 74 to bar 76 of *Deconstructing Dowland*. In these two excerpts, the `[bonk~]` responds to Bartók pizzicatos (measure 12), and the attacks produced by the artificial harmonics (measures 74 to 76), triggering the pre-recorded sound samples. Although such excerpts have relatively simple rhythmic structures, the automatic attack detection strategy results in more precise synchrony between the action of the instrumentalist and the sample triggering. This provides an efficient amalgamation between acoustic instrument sound and the pre-recorded samples so that the triggered sounds work as a spectral extension of the acoustic guitar resonance.

3.3. Scoring

The *scoring paradigm* is a way of thinking and conceiving the creative use of ML/MIR tools that broadly encompasses procedures, technical solutions, and compositional approaches aimed at the implementation of score following systems — i.e., methods aimed at tracking the musical performance (audio stream) and its synchronization to a score. Score-following processes rely on symbolic representation of the musical events (score) and on musical data extracted by ML/MIR algorithms. The score and the ML data are compared, with different strategies, allowing for the estimation of the probability that the instrumentalist is performing a specific section or musical event.

The first implementations of score following methods depended on the retrieval of symbolic information, strongly dependent on the extensive use of MIDI-based instruments in interactive music systems. Since the emergence of real-time DSP-based ML/MIR algorithms, score-following systems have started to get to recognize musical events of musical scores by analyzing audio streams. These new algorithms explore psychoacoustic, stochastic, and machine learning models and methods, relying on probabilistic heuristic methods and on diverse descriptor-based ML/MIR processes. These tools allow for the prediction of the performer's tempo, yielding a variable metric variable related to the instrumentalist's agogic – such as happens with *Antescofo* [2] [22].

By enabling the possibility of determining and prescribing with some degree of precision the actions that should be performed by a computer, synchronized to a live musician, the conception of morphologies resulting from computational processes begins to operate in the same domain as the instrumental writing process. Since musical notation has a symbolic and abstract character, it al-

[2] *Antescofo* is a modular score following system developed by Arshia Cont, which combines machine listening and machine learning methods

lows a musical gesture to be graphically represented and recorded on media — in this case, the score. Similarly, score-following-based processes bring close together live-electronics composition approaches and practices traditionally explored in compositions for acoustic instruments and fixed electronic media. By using score-based tools in live-electronics, composers may conceptualize sound morphologies that arise from the interaction between instrumental sounds and the computational processes [23].

One of the first pieces to creatively explore this set of strategies that we classify here as the *scoring paradigm* is *Jupiter* (1987), for flute and live-electronics, by Philippe Manoury. This is the first piece in a cycle called *Sonus ex Machina* composed in collaboration with Miller Puckette between 1987 and 1991, and stands out in the live-electronics repertoire, as it established new paradigms regarding the use of ML and interactive music systems — particularly, the synchronization and interaction strategies between electronic processes and instrumental performance [24, p. 147].

The score following mechanism implemented in *Jupiter* uses the `[scofo~]` object, capable of reading the MIDI pitches prescribed from a text file (accompaniment score) and comparing them with those extracted from the flute signal. For each note contained in the accompaniment score `[scofo~]` assigns a "theory". The theory is responsible for describing the strength of the evidence that the most recent pitch played by the flute matches the most recent pitch read from the accompaniment score. If they match, the `[scofo~]` returns the number of the event linked to it.

If the pitch extracted from the live flute matches the pitch prescribed in the accompaniment score — which may or may not is linked to an event —, a control message contained in `[qlist]` footnote*Pure Data* object that reads text files containing time-stamped messages, which can be sequenced automatically or manually is sent to the transformation and synthesis modules, and a process is triggered. If there is no event linked to that note, the system will only receive the pitch and continue following the flow of data extracted from the flute. One of the main consequences of the use of *score following* in *Jupiter* reflects on the choice of the composer to represent the structures and sound/musical morphologies emerging from the flute-computer interaction through musical notation (representation of pitches, durations, and dynamics). Since the parameters of computational processes are precisely prescribed in `[qlist]` it is possible to predict the approximate behavior they will present when triggered, enabling the representation of these parameters using traditional notation.

This process of notation of electroacoustic events in the musical score converges with the notion of *Solfège of models*. This concept consists of knowledge, intellectual and cognitive skills acquired by the composer when designing certain processes, allowing to control and master the musical structures resulting from generative models and to associate graphic/textual representations of certain *software* and musical systems and the final musical result [25]. The use of *score following* linked to the idea of *Solfège of models* allowed the composer, from previous knowledge of the nature and parameters of the processes of sound transformation/generation involved in the piece, to glimpse their behavior when integrated with the flute gestures. This leads us to believe that an important step in the compositional process of *Jupiter* — and that seems to be one of the most present characteristics in musical writing of Manoury — concerns, precisely, the conception of the electronic part in an approximate way of the instrumental composition — ie, imagining musical structures and morphologies resulting from the amalgamation of computational processes and instrumental gestures, and reducing their sonic complexity to a symbolic abstraction that could be represented by traditional notation. The figure 3 shows the beginning of the section **ID**, of *Jupiter*, which shows the representation of the morphology resulting from the interaction between the flute (lower stave) and four modules of transposition of heights associated with a reverb (upper staves).

The desire to bring the concept of live-electronics computational processes closer to the notational dimension of instrumental writing seems to us to be a central issue that permeates the compositional processes that explore the scoring paradigm, as shown by some aspects of the compositional process of *Jupiter*. This becomes even more accentuated when we observe some compositional thoughts used in pieces that explore the use of the *Antescofo* as a tool that acts in the integration between these two environments.

An example of a compositional strategy that employs the *Antescofo* can be seen in *Dispersion de trajectoires* (2014), for baritone saxophone and live-electronics, by José Miguel Fernández. In this piece, *Antescofo* plays a central role in the process chain, as it is responsible for connecting, monitoring, and coordinating processes in different devices and computing environments. Like happens in *Jupiter*, there is in *Dispersion de trajeroires* a compositional thought that to some extent implies the use of some a media or technological apparatus aimed at the conception and registration of sound events in parallel with the instrumental score — again in an attempt to centralize the conception of computational/interactive processes and bring them into the realm of instrumental writing. This is evidenced by the architecture of the technical set created by the composer, which gives the *Antescofo* a leading role in coordinating processes throughout the piece.

As a technical strategy to work with instrumental writing and the conception of interactive processes in a centralized way, Fernández developed a library called *Antescollider*. This library integrates the *Antescofo* with the *SuperCollider*, allowing the conception of a centralized electronic score. The audio processing information is distributed to the SuperCollider servers using the Open Sound Control (OSC) protocol under the supervision and coordination of a score/script conceived in the *Antescofo* language. With *Antescollider* the audio processing can

Figure 3: The beginning of section ID of *Jupiter*

be distributed across multiple SuperCollider servers, thus maximizing CPU efficiency [26]

According to Fernández, the centralized score is relevant to the execution of the performance, since this model of employment of the *Antescofo* and the *Antescollider* creates support that makes it possible to explicitly write instrument-computer interactions. This setup also favors a dynamic approach to managing audio processing and synthesis — audio chains in SuperCollider can be easily created and destroyed dynamically, in direct response to the actions of the *Antescofo*.

3.4. Procedural

We classify as *procedural paradigm* every process that makes use of ML/MIR techniques to design algorithmic and compositional procedures implemented to operate in real-time. These procedures can be defined as a finite sequence of rules, reasoning, or operations that, once applied step-by-step to a data set, are capable of engendering structures as a final product.

Observing through the prism of the practice of Western instrumental and vocal writing, it can be seen that the notion of algorithm is already present in compositional procedures beyond the insertion of the computer in creative practice. The rules and formulae that guide contrapuntal writing or even the composition of dodecaphonic series, for example, are very close to concepts behind the definition of *algorithm*.

This set of compositional rules presupposes a particular formalization, in other words, a process of identifying a problem and choosing a solution. This formalization does not exempt the composer from searching for individualized solutions aimed at achieving specific aesthetic results. Although the need for non-rational thought coexists, such procedures aim at solving musical impasses through a set of logical steps, which demand the implementation of a congruent and well-formalized conception.

Therefore, the approximation between algorithms and compositional procedures is valid when they predict a symbolic and quantitative representation of music, and this is submitted to logical operations. That is, the procedures are defined by a formalization that demands the elaboration and definition of mathematical representations and automated operations on these representations. [27].

Before the integration of these techniques into musical thinking, compositional procedures — such as structural manipulations; rhythmic; melodic, and harmonic, as well as those aimed at organizing and transforming the sound material from the perspective of timbre and spectral behavior — took place outside the time of the performance, requiring prior elaboration and calculation to be able to materialize. With the advent of live-electronics, and above all, with the instantaneity and interactivity brought by ML/MIR tools, such procedures became part of the musical performance itself [28], being able to adapt to the most different musical situations, to bring the transformation/sound synthesis mechanisms closer to autonomous agents.

We can illustrate the use of the procedural paradigm through *Tensio* (2010), for string quartet and live-electronics, by Philippe Manoury (Figure 4). The *procedural paradigm* can be identified, in this piece, through the conception of an algorithm that acts just like a compositional procedure, engendering harmonic and melodic structures. The procedure relies on an additive synthesis process developed by Miller Puckette in 2006, called *3F synthesis* [29]. The *3F synthesis*, clearly influenced by the parallel frequency bands generated by modulatory processes such as FM synthesis and ring modulation, calculates a series of frequencies to be used in additive processes by manipulating input frequency values detected in real-time by ML processes/objects. Each of these three frequencies is subjected to all the possibilities of adding and subtracting each other so that it results in a wide range of frequencies. The generated values are then organized according to a probability index, which drives a stochastic filter of these generated parameters.

In a spectrum composed mainly of eight partials, if the probability index is equal to 1, the algorithm will select in ascending order the first eight calculated frequencies. If, on the other hand, the probability index decreases, the algorithm will select frequencies randomly farther apart from each other — which would, potentially, have more complex harmonic ratios. Thus, a proportional relationship between probability index and degree of harmonicity is established.

In *Tensio*, another compositional process that implies the employment of the *procedural paradigm* is the retrieval of musical information related to instrumental per-

Figure 4: Excerpt from Tensio that shows the interaction between the string quartet (lower staves) and the 3F synthesis (upper stave)

formance to create melodic structures driven by a Markov chain. Manoury uses pitches and durations values retrieved by real-time analysis algorithms to create a transition matrix capable of generating a sequence of pitches and durations based on the probability of appearance of each one of them after each other. In this case, this succession of pitches generated by the Markovian process is mapped to the first of the three frequencies used in the calculation of *3F synthesis* procedure, which will ultimately engender melodic structures.

The algorithm responsible for carrying out the Markovian process has some control parameters that influence the characteristics that the resulting melodic structures will present: (1) tempo of the melodic lines; (2) interval contractions and expansions; (3) pitch duration control (the higher the value, the greater the uniformity of durations); (4) transposition control; (5) minimum and maximum amplitude range; (6) interval multiplier that allows overlapping streams.

4. Conclusions

In two decades of development, ML/MIR have been growing exponentially as research fields, not only in the academic sphere but also in the industrial/commercial scenario. However, despite research in these fields is in constant expansion, transforming the possibilities placed to musical practices to boost research with very diversified creative biases, there is still a lack of works concerned with carrying out reflections on the compositional exploration of these tools.

We aim to contribute with understanding the creative exploration of these tools in contemporary creative practices, outlining and scrutinizing how composers have been applying these resources in musical creation in the context of the composition of pieces that combine instrumental/vocal and sound processing in real-time. By identifying the previously listed paradigms, it was possible to glimpse not only a series of technical frameworks but also to point out compositional approaches used by composers as strategies to solving technical-musical issues that aim to achieve certain poetic conceptions and aesthetic results.

As already highlighted, the generalization of these application strategies does not aim to exhaust or to rigidly categorize all possibilities of explorations of MIR/ML methods in the context of live-electronics/interactive music composition. As stated, the objective is to circumscribe in a general way, ways of thinking and conceiving the creative use of ML/MIR, seeking to offer a broader view of the use of these resources that can prove to be useful in analytical, creative, and pedagogical contexts.

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