Computational Implementation of Henry Pousseur's Harmonic Networks Applied to Live-electronic Music

*Rael Bertarelli Gimenes Toffolo
State University of Maringá (UEM)
rbgtoffolo@uem.br

Abstract: *Considering the recent discussion involving the improvisational techniques and the more speculative structural process in the creation of live electronic music, we present, in this paper, the computational implementation of Pousseur's Harmonic Network in SuperCollider computer language in order to contribute to the development of real-time music. Initially, we present a brief review of the Pousseurian Harmonic thinking and how the Belgian composer created Harmonic Networks, discussing their uses for music making. Then, we present how Pousseur's Harmonic Network was implemented in SuperCollider computer language considering the algorithmic solutions to this task. Finally, we demonstrate how Harmonic Networks can be used in live electronics compositions.*
Keywords*: Pousseur's Harmonic Network. Live-electronics. SuperCollider.*

I. Introduction

In recent years, a great number of composers have invested in producing live-electronic works, and, consequently, there has been an increase in number of both theoretical and esthetical studies approaching such musical practice ([19, 18, 11]). It is thus only natural that favorable or opposing arguments to live electronic music spring in such context, and, even among those who favor such practice, there are, at times, antagonistic esthetical positions.

Dias ([2]), in his "Quarrel of times: a study on the aesthetic divergences in electroacoustic music", touches on one of the most popular discussions aroused at the beginning of live electronic music, which is that which refers to the interpretive temporal malleability resulting from the live electronic music practices that are potentially not possible to be reached in differed time electroacoustic music. For Dias, live electronic musicians have argued that such practice respects the historical continuity, leaving it to the performer the interpretive decisions, which were considerably limited in differed time electroacoustic music. On the other hand, supporters of music on differed time state that the tools available for the creation of live electronic music do not allow for such level of speculative control in relation to the creation and manipulation of the electroacoustic materials.

*I would like to tank the Research and Sound Production Laboratory (LAPPSO) at the State University of Maringá, and the friend and Computer Scientist Flávio Schiavoni.

Both arguments are debatable, as pointed out by the author. In the first case, the temporal malleability provided by live electronic music is a compositional decision. Its presence or absence is dependent on the plan and structure as conceived by the composer, and by the manner with which he/she manages such structures, which are not necessarily conditioned to the fact that the electroacoustic processes are not live. In the second case, the tools available for recent electroacoustic music production, both for differed time and live, are basically the same. The technological differences that used to permeate the synthesis and processing of the signal for differed time and live electronic music are almost inexistent today. Software such as Max/MSP, SuperCollider, Csound, PureData, among others, are used in both cases.

Not only has the recent technological development equated the techniques in both fields, but it has also contributed to the development of new interactional patterns, which are widespread over all the different forms of art production. Visual and performing artists are now committed to the development of interactive work, using a great deal of the tools once dedicated to music production, such as PureData, SuperCollider e Max/MSP.

In the visual arts, the concept of interactivity is usually discussed within the area of performance and it involves both the relationship between the spectator and the work, and the interaction between the different artistic languages, such as visuals and the body, sound and the body, sound and visuals, among many other possible combinations. Such speculations, resulted from the many different artistic languages, have fostered a great development among the most varied types of detectors and sensors that, by its turn, have significantly broadened the possibilities of the interaction man-machine.[1]

Simon Emmerson ([4]) dedicates his book "Living electronic music" to the study of the live electronic music status amid the recent technological developments, presenting an overview about the music esthetics in such context. He starts from the idea of the reintegration of the living or of the presence of the living[2] within contemporary artistic production, strongly based on the post-Pontyan philosophy[3], considering that the reinsertion of references in concrete music marks the beginning of this position. In this sense, he approaches the issue of how information about the dimension of the living can be extracted from the sound flow. Initially, he ponders how the many sensors are used to get information from the instrumentalists. Later, he dedicates to the concept of sonification, used to describe pieces that aim at creating musical structures from data collected from non-musical sources. For the author, such strand has its origins in the work of the theoretician and composer Iannis Xenakis, who used mathematical and statistical models for the creation of music structures. Such paradigm develops in such a way as to consider data extracted from biological or social structures, among others. Finally, he considers how the body has been the focus of attention from artists and musicians as source of information for art creation.

Within this broad overview and a certain technological fetishism associated to the strong proliferation of new means of production, as stated by Menezes ([12, p.9])[4], several works have

[1] For an overview on the relationship man/machine, in the music field, check ([20, 21, 7]). For a view on the uses of technology in visual and performing arts, check Domingues ([3]).

[2] This living dimension considered by Emmerson encompasses from the electroacoustic music instrumentalist to the extraction of information from nature, populational dynamics from several species, changes in climate patterns from any biological sphere and others.

[3] The author presents a more direct relationship to philosophers following the Merleau-Ponty phenomenology in his text, such as Varela ([23]), Maturana ([10]), among others. For an overview on philosophers of such strand, check Petitot ([13]).

[4] Menezes' words: "And so it was, for today young composers have much more access to spectral manipulations that will enable him to relate to the new technologies than the corporate and highly bureaucratic that are the basis to orchestral music. [. . .] Such fact is, however, an unquestionable confirmation: even (and above all) institutional recognition of the supremacy of the electroacoustic music is needed. However, full awareness of the technical and aesthetical potentialities of the new music compositional tools is fundamental, watching constantly to the risks of an unreasonable fetishism in

emerged, giving origin to a new quarrel, not really related to music in differed or real-time, but rather related to the opposition between improvised versus pre-elaborated music, with a higher or lower structural degree.

Philippe Manoury, one of the pioneers of real-time electroacoustic composition, shares his impressions on the abundance of both improvised and performed works:

> I'm forced to observe that musicians who come close to real-time music in a decisive way, it is not within my close esthetical family— that of composers—that I have found a more committed engagement, but in an esthetical trend that lies way far from my artistic orientation: that of improvised music and 'performers'. Such curious situation has driven me to isolation for quite a long time, for such overlap of esthetical and technological orientations that I considered my own, was only rarely shared by others. ([9, p. 6])[5]

We can then realize that improvisation is strongly present in real-time electroacoustic music ([5, 6, 22, 1]). In this context, a new compositional strand has been developed, the so called live-coding ([8]), which consists of the creation of programming codes in a collective form and in real-time.

Alongside this situation, it seems that the quantity of interconnections between the several dimensions of the artistic trade, occurred amid the exchange of information obtained by sensors of all kinds, have made space for a considerably broad universe of creative possibilities, pointing to new issues such as: how to create a relationship between data obtained by sensors, which are placed in a specific symbolic field, and the computational codes that will generate a piece of audio, a graphic animation, or will control one of the parameters of an audio processing coming from an instrumentalist?

It is within this context that this research is placed. How to foster the creation of works built in real-time, one that benefit from the temporal and interpretive malleability that real-time music allows for, keeping in mind the special attention to the speculation of structures and materials?[6]

It is for this reason that this work is out to benefit from the harmonic speculations coming from the Belgian composer Henri Pousseur and apply them to real-time music. As we will see along the lines in this text, Pousseur's harmonic networks are characterized as an interesting relationship tool between several harmonic systems from different historical periods. In this sense, Pousseur's harmonic network technique arises as an interesting field of study for contemporary art.

II. Pousseur in context

> How to "rhyme" a citation of Gluck or Monteverdi with one of Webern in a single composition (two grammatical domains that have so far seemed the exact opposite and incompatible); how to "conjugate" them, find common functions, and, to start, establish among them a series of intermediate types capable of convincing the musical ear that they once pertained to a more general common domain? ([15, p. 194])

relation to the technological means, trend which is constantly trying to be established in the capitalist cultural industry in a nefarious way."

[5] "Force m'est de constater que, parmi tous les musiciens qui se sont approchés du temps réel de façon décisive, ce n'est pas dans ma famille esthétique proche – celle des compositeurs – que j'ai trouvé l'engagement le plus conséquent, mais dans un courant esthétique beaucoup plus éloigné de mes orientations artistiques : celui des musiques improvisées et des 'performers´". Cette curieuse situation m'a laissé assez isolé pendant longtemps, car cette union d'orientations esthétique et technologique qui était la mienne, n'était que rarement partagée par d'autres. This and the next translations were made by the present author.

[6] Our proposition does not aspire to criticize or invalidate the improvisational procedures but only aim to demonstrate other process to creating live-electronic music.

Let's consider the intention expressed by Pousseur, in his "Rameau's apotheosis – an essay on the harmonic question", briefly, but not superficially, and the developments of the Pousseurian theory as it sets out to reach a meta-grammar capable of making "rhymes" from both universes, or more precisely, harmonic spaces — as he will later denominate.

It is worth mentioning that there is no naive rescue of the tonal functions in the composer's proposition, ignoring all the musical development reached by the post-Weberian generation, of which, by the way, Pousseur himself is part, mainly when expressing the will to reconsider the Monteverdian universe within the current composition. As he alerts:

> In effect, having in mind the high degree of elaboration and the extreme hegemony that this dimension exercises in tonal music, as well as the considerable cultural weigh present in the harmonic perception to Occidental ears, it is in such frame that there seems to lie the greatest dangers of a purely reactionary evolution, of a throwback that we evidently cannot admit. ([15, p. 192]).

Back to Pousseur's central issue, the one in question here: the ways of making rhymes from the tonal universe expressed symbolically by Monteverdi's music and Webern's multi-polar universe. Such desire emerges from a deep analysis of the music of his time, in special, Integral Serialism. For the author, serialism, which provided for such a rich development of the compositional practice, needed a deep review, mainly permeated by considering perceptual and even structural issues. Besides, as we will be able to confirm later, Pousseur sought different ways to redeem functional, formal, and perceptual aspects that seemed to have been neglected by strict serialism. He was obviously not the only one to make efforts in this sense, and even the Concept of Groups, back at the beginning of the Integral Serialism, had aimed at redeeming certain perceptual logics not considered by the pointillist serialism of the first phase, as he states:

> This evolution started very carefully, and, if we can recognize its first symptoms at the beginning of the so called "group techniques" (from Le Marteau sans Maître by Boulez, for example), if we can find more established demonstrations in works of the final 50s, as in Gruppen by Stockhausen or in Circles by Berio, it is quite evident that it is about the harmonic plan that major concerns were demonstrated ([15, p. 191]).

For Pousseur, serialism was lacking in its structural affiliation, reductionist in a way, to the pitch parameter as the primary element. Such abstraction process raised questions about certain perceptual properties, so dear to the composer, demonstrating a strong affiliation of his to a phenomenology of listening.

In this sense, all the typical structure processes present in integral serialism are set up in a set of rules that promote a certain paralysis or perceptual homogenization, which function as to stop properties or characteristics of music from the past from emerging, more specifically, the tonal function. If, on the one hand, this process was extremely positive in providing for a whole new universe of possibilities, it led, on the other hand, to a homogenization to be viewed as worrying for Pousseur. As he states:

> The most evident consequence of this partially voluntary paralysis is the extraordinary distance (. . .) between the level of constructive intentions and the perceptive results. The structural work, from which traditional serial techniques are the most notable example (permutation, etc), is produced on an extremely abstract plan, on which relationships to a very high intellect coefficient are made, at the same time that the perceptive result is situated, on the contrary, on the most concrete plan possible, on which pitch is nothing more than one aspect, of many, of timbre, of the more immediate

> materiality of sound. The connection between these two plans is deliberately lacking in intermediate solid support, which could be, nonetheless, provided by both a realistic as well as a logical reflection ([15, p. 173]).

From then on, Pousseur starts to investigate the parameter of pitch as an attempt to redeem certain aspects that seem to have been abandoned amidst the high degree of abstraction of the serial engendering. For Pousseur, such rescue will demonstrate that the perception of the frequencies will enable several levels of meaning, pre-musical at times, on which new musical constructions can emerge, considering its uses as color (that could generate musical meaning due to its metaphorical or symbolic properties), melody (that result from the perception of scalar relations between pitch in a temporal stream), harmony (considering its parental, proportion, attraction, and repulsion relationships), and combinatorial (considering the more abstract uses originated from permutations and inversions).

Alongside his worries on the pitch functions, Pousseur also was highly fascinated for the game of literary citations developed by the writer Michel Butor, his partner in his *Votre Faust*, who would feel more accomplished in terms of his compositions doing something similar in music. He thus aimed at finding an organic way to bring together several citations from music history within his compositional language. The key to the process would be making such set of citations "rhyme" in a way to incorporate to Pousseur's musical discourse, not as "strange bodies", as collages, but in such a way to accommodate his language so that the citations would fall into place "naturally".

> [. . .] I thought I would only be satisfied with my musical language the day I feel I'm able to insert old elements in it in such an organic way as Bach would integrate the Protestant chorale ([15, p. 193]).

Therefore, Pousseur was not interested in including only citations by other composers or historical periods, but to put together different ways to characterize the harmonic spaces in which such musical contexts would develop, and, once such "background structures" were detected, find a musical meta-grammar that relate them:

> An initial possibility would consist in taking an example from music history and find the first elements of a "grammatical scale", of an integral harmonic space in the evolution that conducted tonality to atonality (especially in Viennese music), with the gradual logics known to us. [. . .] It was then necessary to find an organizational system at the same time ample and coherent enough to fit all historical cases in one place, in a way that they would finally seem to have been engendered exactly by this system ([15, p. 194]).

In this sense, we notice that, in Pousseur's thoughts, there is a deep complementarity between the search for the organic use of citations and harmonic speculations that are, on their turn, a result from his revisionist criticism to serialism. Such complementarity is expressed by the composer first when considering the harmonic aspects that instigated him:

> (. . .) I was not convinced that I had lost "deepness" definitely that only the harmonic functions – tonal (or post-tonal) or modal, occidental or extra-European, known or only sensed – seemed to be able to offer, and that I saw it as one of the most precious riches, one of the central values of music as a whole, susceptible to qualify it in its irreducible specificity [. . .] ([15, p. 192]).

Still on the same text, when considering the historical referencing that encompasses both a citational and a functional level, the author states that when he "heard a symphony by Monteverdi or a Lied by Schumann, a Hindi Raga or a symphonic work by Debussy, he could not help it but to think, with certain nostalgia, that we voluntarily deprived ourselves of something irreplaceable, and that I would do unquestionably better if I did not let myself be deprived of that" ([15, p. 192]).

It is within such context that includes certain criticism to serialism, a need to redeem formal aspects from music history and a solid urge for the citation organically inserted in his musical language that Pousseur starts to investigate ways in which to put together a meta-grammar that would relate all these concepts.

III. Pousseur's steps for developing the Harmonic Networks

Pousseur's first step was to try to build a method with which he would be able to calculate the polarizing forces of the musical intervals due to his belief that even in Webern music one can find the same principles of tonal harmony polarization, differing only in relation to its vectors: while in tonal music such polarizations were used in a convergent or centrifugal manner, in Webern music we will find a game of centripetal or multi-polar polarizations. These polarization studies are too similar to the Edmond Costère theories. Pousseur arranged the intervals in a progressive sequence from more consonants to more dissonants, therefore more polars or apolars, as we can see in Figure 1.

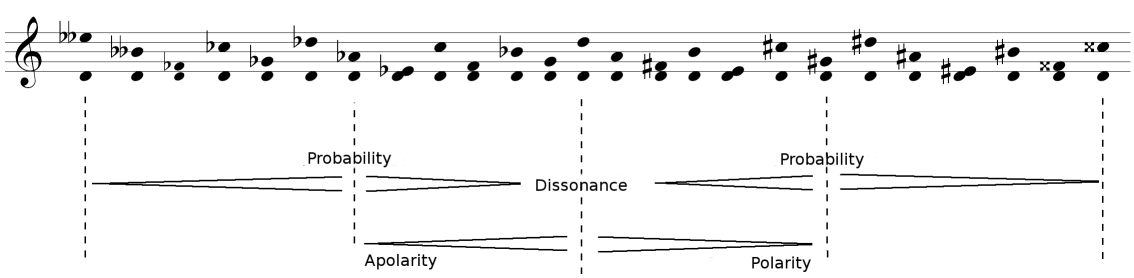

Figure 1: *Interval Polarity Table, adapted from Pousseur, 2009.*

From the table in Figure 1, Pousseur creates a chart of three-sound chords that are set according to their sequence. Still, Pousseur considers that the handling of data deriving from this form of classification would be quite time-consuming for the engendering of compositional materials, especially when expanding the chart to sets of four or more sounds is needed.

He then exposes another method that would become known as Cyclic Permutations, which consist of a sequential transformation of a series of original notes derived from the alteration of some of their elements by a continuous transposition process to a previously selected interval. If a series of notes formed by the chromatic total is elected, keeping some characteristic notes frozen and transposing others step by step to a previously selected interval, a perfect fourth, for example, some interesting transformations occur, as we can see in Figure 2.

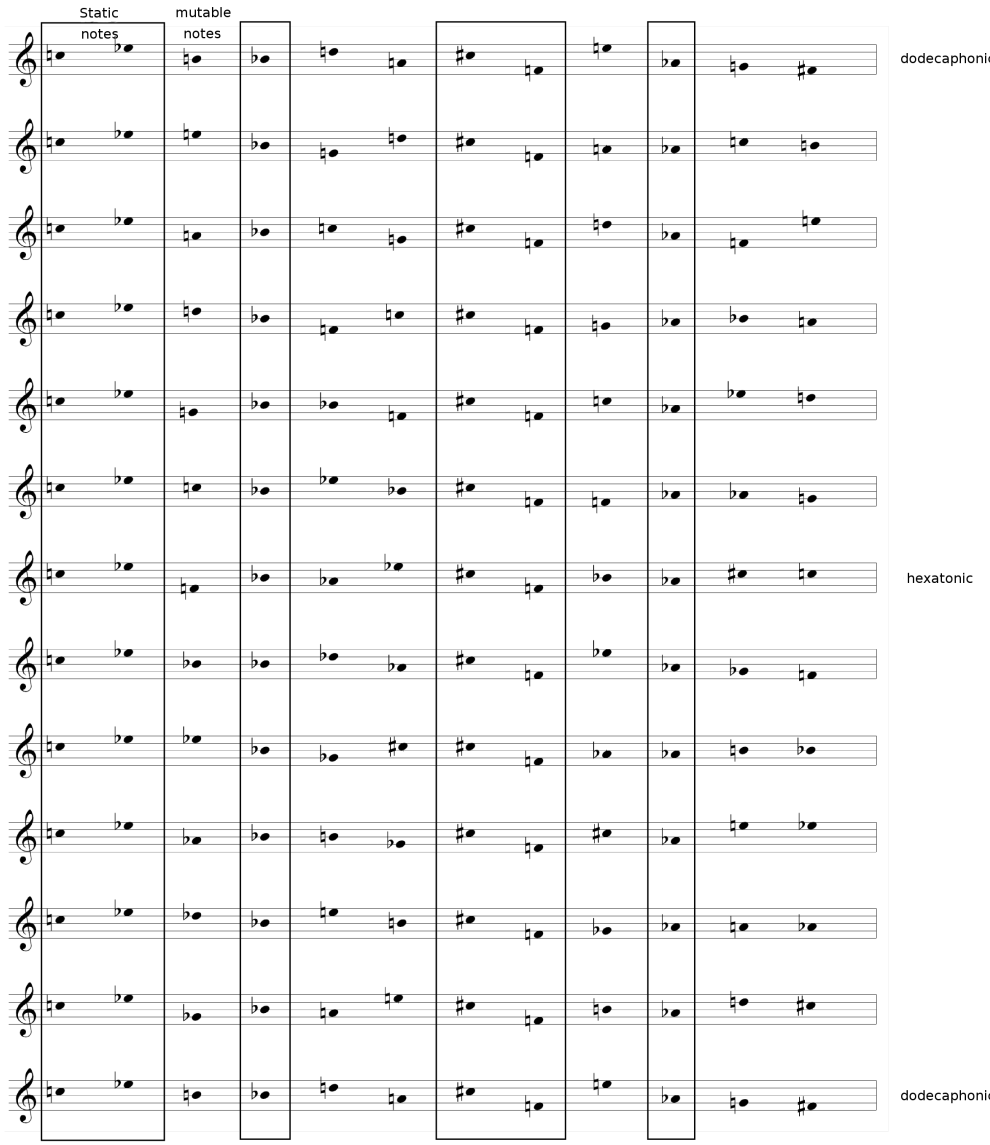

Figure 2: *Cyclic Permutations process, adapted from Menezes (2002).*

It is observable that, when the sixth permutation is reached, a group of notes expresses a hexatonic set and then, at the end of the permutation process, is back at the original series. Besides the several properties originated as new notes appear in each permutation, Pousseur, with this process, is closer to his attempt to find a relationship system between different harmonic spaces, a process that is built with a gradual, directional passage, from a relational system to another, and, in this case, from a chromatic set to a reduced six-note set (hexatonic).

From these two processes, Pousseur proposes a relationship form that will contribute to his harmonic networks. By setting interval sequences of the same size on an horizontal and a vertical axis and make transpositions at another interval fixed rate, in the fashion of the cyclic permutations, Pousseur was able to verify the emergence of several relationship properties or certain "harmonic fields" that result in true relationship networks. Here is, thus, the prototype of a harmonic network, still two-dimensional that was later defined:

> [. . .] a network, as understood here, is a distribution of notes (to be specified later as to what they represent) formed by several axes (starting with two) that are each characterized as a chain of a single interval.[7] ([14, p. 249]).

While characterizing this relationship space obtained through crossing both axes two-dimensionally, Pousseur notes that there is a harmonic logics that emerges from the distances between the notes that relate to each other in a closer or more distant fashion:

> We cannot forget, however, that the principle of the method itself resides in the wish to build nodes of all kinds so that the effective elementary musical relationships, therefore "in time", (analyzed or composed, melodic or harmonic) are the closest possible, expressing themselves especially among the network neighboring tones, in one direction or another.[8].

Such network pitch relationship structures are set up as both a compositional as well as analytical tool. In order to build such networks, certain intervals are fixed on each one of the axes and bring, each one of them, their polarizing, neutral or non-polar characteristic. From this process, a complex net emerges, or in other words, a relationship network depending on the distance that it is found from the center of net, that is, depending on its neighboring level. Several harmonic spaces can be represented, characterized or found in a two-dimensional network, as can be observed in several of Pousseur's example, in special in his 1998 text, "Applications analytiques de la 'Technique des réseaux"'. In this work, which complements his speculations on harmonic networks presented in Apoteose by Rameau, Pousseur demonstrates how networks can be used in musical analysis with examples from the works of Bartók, Debussy, and Webern. He also demonstrates their potentialities to express tonal and even modal spaces. In such context, Pousseur explains how a two-dimensional network can easily represent a modal relationship space and how the insertion of a third axis becomes effective for characterizing the tonal space, demonstrating that the inclusion of this third axis would be equivalent to the development of perspective in visual arts.

> But from the moment the polyphonic practice intensifies, despite the initial resistance posed by clergymen, who wanted thirds to continue to be used (therefore considered) as "dissonances" (pre-attractive) and that only eighths and fifths were recognized as perfect consonances, the acoustic experience (with its sound combinations exalted by the resonance of architecture at times) would impose itself: for about two centuries, thirds have reached their place (almost) equally prominent, and the triad system starts to settle. This revolution can be theoretically expressed by the junction, in the fundamental diatonic network, of a third dimension (which strangely happened at the same time as visual arts discovered depth: and that could hardly have been by chance!).[9]

[7] [. . .] "un réseau, au sens ou l'entend ici, est une distribuition de notes (on précisera plus tard ce qu'elles représentent) selon plusieurs (pour comencer deux) axes qui se caractérisent chacun comme une chaîne d'un seul et même intervale."

[8] "Il ne faut toutefois pas oublier que le principe même de la méthode réside dans la volonté de construire le lacis de telle sorte que les relations musicales élémentaires effectives, donc 'en-temps', (analysées ou composées, mélodiques ou accordiques) soient les plus serrées possibles, s'expriment principalement entre notes voisines du réseau, dans un sens ou dans l'autre." ([14, p. 249])

[9] "Mais dès que la pratique polyphonique s'intensifia, et malgré la résistance opposée d'abord par les cléricature, qui voulait que les tierces continuent à être *utilisées* (parce que *considerées*) como des 'dissonances' (pré-atractives) et que

In his final tridimensional version, harmonic networks consist of axes on which sequences of notes from pre-determined intervals are set. Pousseur's initial proposal consists of a selection of axes that he considers the expression of intervals that are "fundamental of the aural acoustic space, not only in their exploration of tonality, but also in their more probable natural potential". In other words, he considers the relationships by thirds and fifths, as he proposed in his two-dimensional networks, but he includes the octave as a factor of great importance for the characterization of the tonal space. Therefore, the network would be composed by three axes that will be expressed tridimensionally here as X, Y, and Z. If we place the perfect fifth interval on the X axis, the perfect eighth on the Y, and the major third on the Z, we will obtain a relationship network as presented in Figure 3.

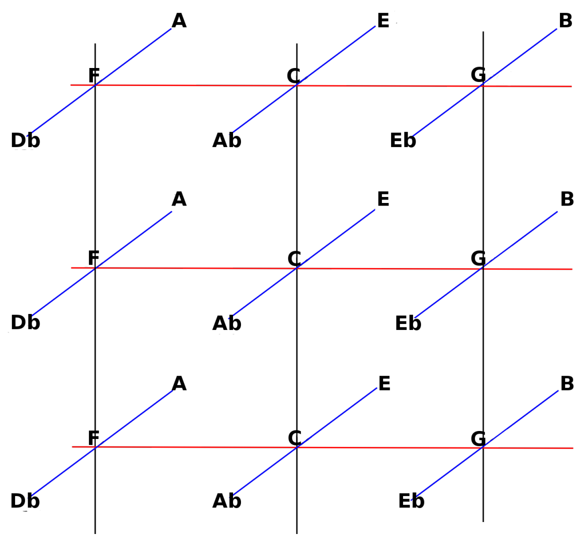

Figure 3: *Harmonic Network with P5 in X-axis, P8 in Y-axis, and M3 in Z-axisPerfect Fifth, Perfect Octave and Major Third.*

This way, we will have the possibility to represent any set of notes in a relational space. It is interesting to note that, depending on the choice of intervals for each one of the axes, we will reach a set of relationships that express a certain harmonic space, and even a theoretical system. In this initial network proposed by Pousseur, we will reach, in a very immediate manner, the representation of a tonal space. Let's take, for instance, the notes from the C major triad, building the network starting at C, we will be able to find such notes in the more central positions of the network. It is possible to infer, therefore, that similarly to Riemann ([16]) or Schoenberg ([**?**]), to mention a few, that present in their tonal functionality charts as regions closer or more distant, in Pousseur's networks we will also find the representation of the acoustic space both between the notes and between the harmony expressed by the distance in relation to the central axis of the network. And yet, interestingly enough, when the axes are modified, we will find other acoustic spaces available with their relationships also expressed in terms of their distance from the center.

seules les octaves et quintes soient reconnues comme consonances parfaites, l´expérience acoustique (avec ses sons de combinaison souvent exaltés par le résonance des architectures) s'imposa: au bout de quelque deux siècles, les tierces avaient acquis leur place (presque) également prééminente, et le système des triades avait commencé à se mettre en place. Cette révolution peut s'exprimer théoriquement par l'ajout, au réseau diatonique fondamental, d'une troisième dimension (qui suivent bient étrangement au moment même où les arts plastiques découvert également la profondeur: ce ne peut guère être dû au seul hasard!)" ([14, p. 255])

Besides the networks graphic representation, as in Figure 3, they can be represented in musical writing, as in Figure 4.

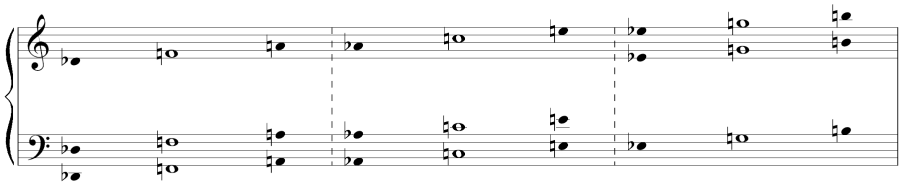

Figure 4: *Pousseur's Harmonic Network with axis: P8, P5 and M3, represented in music notation.*

We can notice in Figure 4 that the Y axis, which in Pousseur's original network is equivalent to the eighth interval, is represented vertically. Each one of the notes from this axis is "projected" in an infinite sequence of ascending and descending eighths. The X axis, equivalent to perfect fifths, is represented by the horizontal sequence of the white notes (F, C, G in the example), that is also projected indefinitely to both directions. Finally, the Z axis, equivalent to major thirds, is represented by the ascending and descending major thirds that are formed between the white and black notes. One must mentally project a virtual axis of thirds, in this example, that emerges diagonally and progresses, as on the other axes, indefinitely in both directions.

The basic operation proposed by Pousseur for the generation of material for composition consists of locating any intervallic set up, either chordal or melodic, in its structure. Figure 5 exemplifies the process of locating a musical excerpt (with numbered notes) and how such notes are located in the network structure.

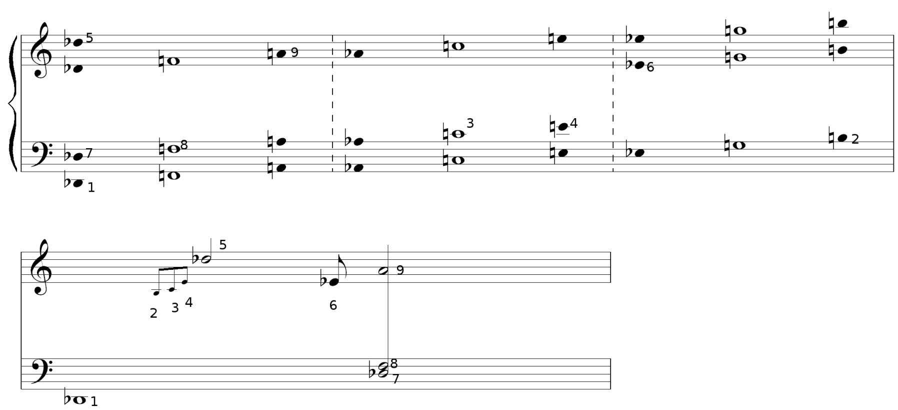

Figure 5: *Localization of a musical excerpt in a Original Harmonic Network.*

Once the notes from the musical excerpt in the reference network structure are "projected", the process of "deformation" of the network basic structure starts, and, by locating the same positions marked in the previous stage, the musical excerpt reconfigured by the deformation of the network axes will be revealed. As exemplified in Figure 6, we can observe the new musical excerpt obtained from a network on which the axes were modified from perfect fifth to augmented fifth, eighth to major seventh, and major third to minor third.

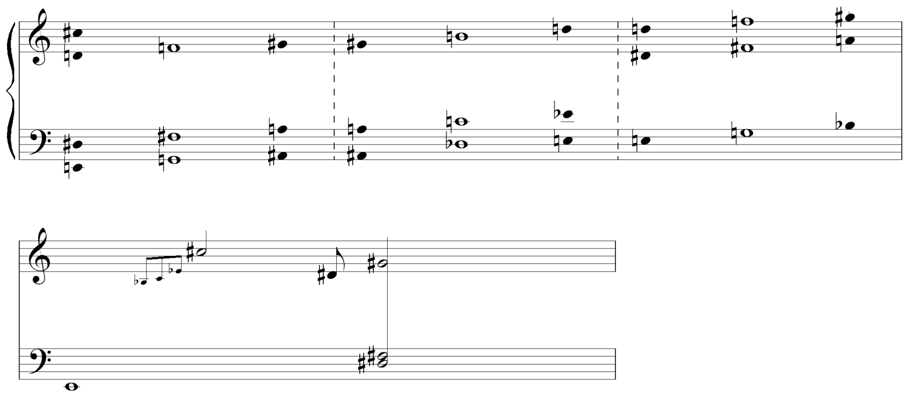

Figure 6: *Musical excerpt recovered from a "deformed" Harmonic Network. X-axis in aug4, Y-axis in M7 and Z-axis in m3.*

The possibility of changing the constitution of its axes and re-locate notes previously placed in an original network on a transformed network constitutes one of the most relevant contributions from network techniques to contemporary music. Here we finally find the relational tool that Pousseur looked for in order to rhyme Monteverdi and Webern. The networks are set up as the meta-grammar that connects the several harmonic spaces projecting a structure obtained from one of these spaces into another. When notes from a chord, or a highly tonal excerpt are located on an obviously tonal axis (5J, 8J, 3M), and, later, finding the same positions on another network with transformed axes, so that we will obtain a much less tonal acoustic space — as, for instance, a network of axes formed by the triton, major seventh, and minor second —, we will reach a collection of notes that are much closer to the non tonal pole, as Pousseur intended: a way to relate different harmonic universes from a single meta-grammar. Besides, the melodic patterns are, in general, kept proportionally steady, except on rare occasions, when transformations on a given axis are of a much higher caliber than the transformations on the other axes.

Such properties allow us to speculate how to implement the harmonic networks as computational algorithm in a way as to use such tool both for Algorithmic Composition, as well as to expand its functionalities to the use in electroacoustic works in real-time.

IV. Implementing the Pousseur's Harmonic Network in Supercollider Language

The harmonic network computational algorithm was implemented on the SuperCollider audio programming language, which is widely used by composers all over the world. Because it is an OpenSource application, it is readily available for free for all operational systems, (Macintosh, Windows, and Linux), what increases the portability of works and tools created in them considerably. SuperCollider ([24]) is both an environment for development and a programming language created and launched in 1996 by James MacCartney. It is a very powerful computational tool both for audio and video signal synthesis and processing in differed time, as well as for applications in real-time, presenting great functionalities for the algorithmic composition. One of the most interesting characteristics of such programming language is that it can be expanded, including new functionalities, from its own language. On other systems, as PureData or Max/MSP, the creation of new functionalities depends on a wide knowledge of programming languages (such as C or C++), software compilation. The disadvantage is that learning to work on SuperCollider is a little more time consuming than dealing with graphic systems such as PureData or Max/MSP, but not so different from understanding how to use languages such as Csound, for example.

One of the problems found in computationally implementing the networks[10] was the location of the chosen notes in its structure. Pousseur does not specify which procedure should be adopted, since the notes are recurring in distinct areas of the network, especially if we consider that the harmonic networks are endless in all directions of their axes. It is for this reason that we have chosen, and for practical purposes — and we do believe that Pousseur has done the same, since he considered that the neighborhood, therefore the shortest distances from the center of the network, is an important characteristic in representing the harmonic space in mind —, to always locate the desired notes in the closest position to the central axis. Therefore, the selected algorithm solves such dead-lock, as we shall see below.

i. The algorithm explained

The computational implementation of a problem from the real world depends on its representation. At first, the original network is an infinite space and, as such, cannot be represented computationally. For this reason, we chose to adopt the MIDI scale with 128 notes (from 0 to 127) to limit the network sample space.[11] The second issue to be considered was the selection of the best method to calculate the distances between the different spots on the network and, thus, create the sample space from the original network.

The creation of the original network depends on the entry of 4 parameters: central note and axes X, Y, and Z step sizes (intervals). For example: a network starting with values 60, 5, 8, and 12 is equivalent to a network with a middle C as its central note (60 on the MIDI representation) and axes X, Y, and Z equivalent to the perfect fourth (5 semitones), major sixth (8 semitones), and the perfect octave (12 semitones).

From the initialization and delimitation of the sample space scope (size), three data structures were used to create the initial network. The first consists of a list with the 128 possible notes, used to mark the notes that are already part of the network and the ones that still are not, as shown in Figure 7.

This way, we can go through the network and check which nodes are already part of the network and mark them on this data structure. The selected algorithm, as we will see in more detail below, starts from the network central axis and searches, step by step, each note that constitutes the network, going upwards and downwards on each of the axes, until it locates all the desired notes. When the algorithm locates one of the desired notes on a certain spot, it will not look for that note anymore. That means that, as the algorithm looks for notes starting from the network center, the first example of a certain note that is found by the algorithm will be the closest to the central axis.

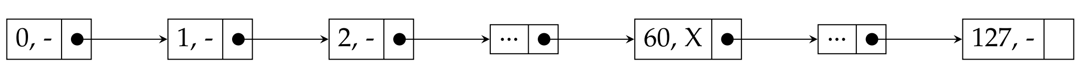

Figure 7: *List of visited nodes (X), and not visited nodes (-). Middle C (60 in MIDI scale) marked as visited.*

[10]The implementation of Pousseur's harmonic network counted on the invaluable help of the computer scientist Flávio Schiavoni who worked on this project suggesting very helpful algorithmic models.

[11]Sample space is a common term in computing that usually refers to the minimum and maximum limits of a set of data on a string, array, or even on the computer memory. What determines the sample space is of great importance in computational algorithm, especially when dealing with data that can be virtually infinite. The control of such space must be carefully taken care of so that execution errors are avoided, especially the ones originated from the overlap of information in the computer memory.

The second data structure used was a list of notes to be visited. As we find a note, it is added to this list, and informs that all the axes (ascending and descending intervals) will be visited next. Such list is a *fifo* (first in, first out) in which all new data added to the end of the list is first consumed.

As we simulate the behavior from the example above (60, 5, 8, 12), we put the central note in line and initialize the algorithm through its ascending perfect fourth, descending perfect fourth, ascending minor sixth, descending minor sixth, ascending perfect octave, and descending perfect octave. Each note that has not been visited will be placed in line so that its axes can be visited. At the end of the visit of the first note, since none of the axes has been visited yet, we will reach a line as the represented in Figure 8.

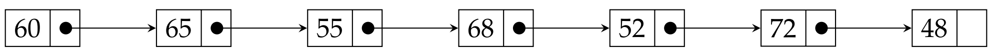

Figure 8: *Visited list in the first algorithm step. Values are added in order to visit: Starting note 60; X-axis ascending and descending (60 + 5; 60 - 5); Y-axis ascending and descending (60 + 8; 60 - 8); Z-axis ascending and descending (60 + 12; 60 - 12).*

At this moment, we mark the initial node as visited in the list of visited nodes (first data structure), removing it from the list of notes to be visited, and moving to the next element in line to be visited. The list of visited nodes, when we move to the second element, is represented in Figure 9.

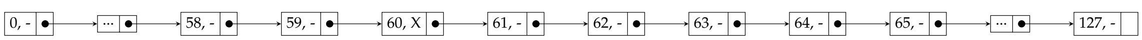

Figure 9: *List of visited nodes in the second step of algorithm.*

Note that only the central note (60) is marked as visited. That stops us from trying to visit it again.

On each step of the algorithm, the respective ascending and descending axes of each one of the notes on this list will be included in the list to be visited. In the case of the note 65 (ascending perfect fourth from the initial note), the values as illustrated in Figure 10 will be included.

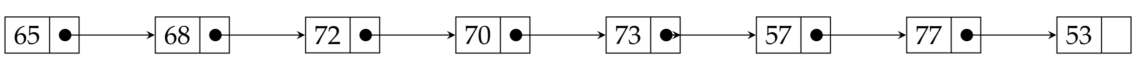

Figure 10: *Included values in the List of nodes to visit after the second algorith step.*

As we start the second visit from the note 65, the first interval will be an ascending perfect fourth (+5) and the second, descending perfect fourth (-5). As we check the descending perfect fourth, we will note that the resulting note (60) has been previously visited and, for that reason, will not be placed in line to be visited again. The algorithm operation can be visually represented as demonstrated in Figure 11.

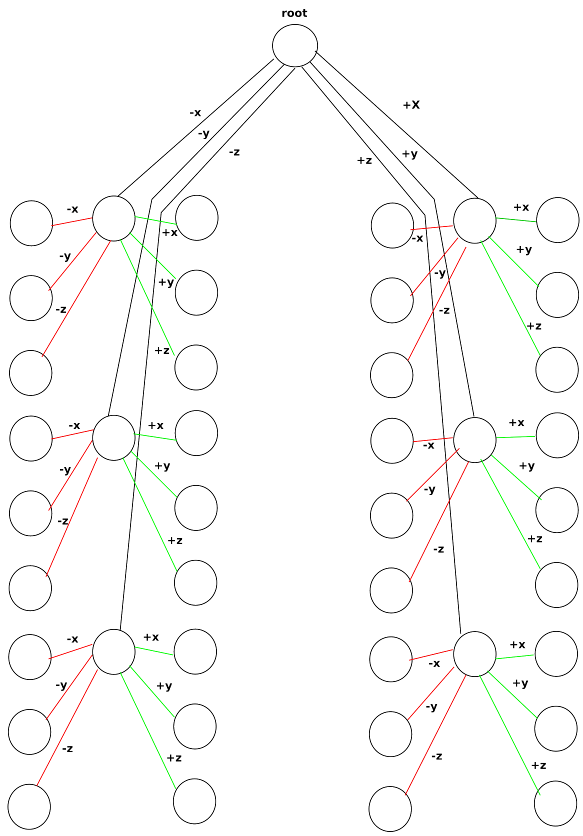

Figure 11: *Visual representation of the algorithm.*

The third and last created data structure is the one that represents the path to each one of the notes. We use the representation of a tree for this structure. The trees are abstract data structure that can be represented in several different ways. Independently from the kind of representation, every tree has a root note (central note) and several offspring that can be reached from the center. The nodes that have not produced offspring are called leaves and the nodes that are not the central node, but that have produced offspring, are called branches. A tree data structure must be navigable starting from its root node, in a way that all the other nodes can be reached from this base root node. The connections between the nodes can have a label and the sum of these labels is to indicate which path from the central node was taken in order to reach any other node.

Because the universe of nodes is finite, an initial limitation for this implementation, we can represent a tree by means of a vector (or array). This way, each one of the notes is marked in order to show which path must be taken to reach the root of the tree. We start by marking the root with a label R (root). The other intervals are marked by the labels f and F (first), s and S (second), and t and T (third), being that the upper case indicates the ascending intervals and the lower case, the descending one. Thus, our path tree, after the first interaction, can be represented by Figure 12.

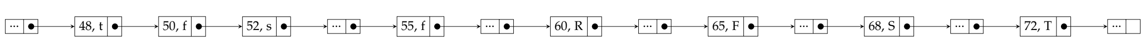

Figure 12: *Path tree after first algorithm step.*

This representation indicates that, in order to depart from note 55 and reach the root node, we have to move an ascending perfect fourth (inverse path to the one stored in the vector). In order to move from note 50 to the root, we move an ascending perfect fourth (f) to note 55, and another ascending perfect fourth (f) to note 60. This way, the path from the note to the root will be (ff). Since each note will only keep one path to reach the root (as determined by the algorithm), the representation in array is enough and has a low computational cost. Note that we are using a relative representation of the network, that is, we represent the first, the second, and the third interval, independently from the choice of intervals for the axes, what turns such piece of information into a metadata that will be used for the exchange of information between distinct networks.

After the algorith have created the whole data, the Harmonic Network, using the structure *list of nodes to visit*, *visited nodes*, and the *path tree* , we will use only this last to the operations that relates different Harmonic Networks. The algorithm uses the *Tree of patches* in a reverse order to found the patch of one note to the central note and stop running, *posting* on screen the simbolic representation of the patch traversed in the Harmonic Network structure.

ii. Using the Harmonic Networks

In order to illustrate the network operation in SuperCollider, let's take a look at the example given by Pousseur in his text, demonstrating how it is obtained by using the implementation presented here. Pousseur makes use of the initial part of the integrationist song *We Shall Overcome*, a symbol of the North American African-American resistance, as reproduced in the first system of Figure 13 and with repetitions eliminated in the second line of the figure.

Figure 13: *Excerpt of the song We Shall Overcome. Adapted from Pousseur (2009).*

Pousseur places the notes of these chords in an initial network (that will be referred to as original), constituted by the X, Y, and Z axes with perfect fifth, perfect octave, and major third intervals respectively. Then, he remaps the same positions in a network with axes X, Y, and Z transformed, respectively, in perfect fifth, major seventh, and major third.

Such operation is accomplished in our implementation as follows (using the notes of first chord):

```
(
var original, transformed, positions, notes;
original = Pousseur(60, 7, 12, 4);
positions = original.notes2path([48, 55, 60, 64, 67]);
transformed = Pousseur(60,7, 11, 4);
notes = transformed.path2notes(positions);
)
```

By executing the code above, the result will be:

```
[ 49, 56, 60, 64, 67 ]
```

Describing the code, line by line:

The initial and final parentheses that limit part of the code and the first line that creates the variables where the operations resulting values are kept are requirements of the SuperCollider language that will not be approached here. In the third line, we create the original network, determining the network central note (60 = middle C in frequencies expressed in MIDI values) and the X, Y, and Z axes as: 7 = perfect fifth, 12 = perfect octave, and 4 = major third, respectively. In the following line, we request that the function *notes2path* find notes 48, 55, 60, 64, and 67 (respectively C3, G3, C4, E4, and G4 in MIDI pitches) in the original network and save the result under the *positions* variable. After that, we create the transformed network with the central note also in C4 and axes: perfect fifth, minor seventh, and major third. Finally, we request that the function *path2notes* search in the transformed network for positions that were stored in the *positions* variable, obtained from the original network, resulting in the transformed notes: 49, 56, 60, 64, and 67, respectively: D♭3, A♭3, C4, E4, and G4.

This code strand demonstrates the basic use of the implementation of networks, but it is not the implementation itself. The SourceCode is available in the following address: `https://sourceforge.net/projects/scpousseur/`, either for SuperCollider as for PureData.

V. Conclusion

After framing the main question in the introduction of this paper, which is "how can we create live electronic music that incorporates both temporal malleability and performance freedom, without disregarding the structural speculation of musical materials?", we can now present Pousseur's Harmonic Network as a possible answer. Harmonic Networks are a versatile tool for creating musical structures that, as presented in this text, can relate both the Harmonic and Melodic materials in several complex manners, making it possible for sound artists to find a way to generate music materials for live-electronics, regarding Harmonic Relations at the same complexity level as the high levels of elaboration in the "instrumental dimension" (remembering Bruno Maderna). The proposal presented here does not intend to invalidate or criticize the improvisational or the Sonification process so current in live-electronics. It only aims at demonstrating other processes that include the harmonic speculation of structures to be applied in this musical poetics.

In several live-electronic works that I composed in past years, I have used Harmonic Networks in several different varied procedures. Some works use the Harmonic Networks associated with information from amplitude sensors, rhythmic density analyzers, and others, to create several layers of harmonic and melodic synthesis that are related to the instrumental dimension. In some other works, Harmonic Networks are related with algorithms that classify, in real-time, the overall harmonic dissonance and consonance (Harmonic Tension) resulting from Harmonic Networks transformations and associate their results with several kinds of information detected from the instrumental performance. Such algorithm of Harmonic consonance and dissonance classification is though a topic for a next paper.

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