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Cellular Automata Sound Synthesis with an Extended Version of the Multitype Voter Model

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ABSTRACT

In this paper we report on the synthesis of sounds with cellular automata (CA), specifically with an extended version of the multitype voter model (MVM). Our mapping process is based on DSP analysis of automata evolutions and consists in mapping CA histograms onto sound spectrograms. This mapping allows a flexible sound design process but due to the non-deterministic nature of the MVM such a process acquires its maximum potential after the CA run is finished. Our extended version model presents a high degree of predictability and controllability making the system suitable for an in-advance sound design process with all the advantages that this entails, such as real-time possibilities and performance applications. This research focuses on the synthesis of damped sounds.

1. INTRODUCTION

Cellular automata are mathematical/computational models suitable for modelling processes and phenomena occurring in nature. Algorithmic techniques for the simulation of natural systems have experienced a major boost over the past few decades because of the increase of computer power. Such techniques have been successfully applied in different areas including audio and music technology, where they have contributed new insights in the search for innovative yet natural evolutions of musical material [1].

In the 1950s several different kinds of systems equivalent to CA were independently introduced. The best-known way in which CA were introduced (and which eventually led to their name) was through work by John von Neumann in trying to develop an abstract model of self-reproduction in biology –a topic which had emerged from investigations into Cybernetics [2].

Cellular automata are normally implemented as a regular grid of cells in one or more dimensions. Each cell may assume any state from a finite set of *n* values. CA evolve in successive generations at every time unit. For each generation, the values of all cells change simultaneously according to a set of transition rules that takes into account the states of the neighbouring cells. The transition rules can be deterministic or non-deterministic. With a deterministic rule, for a given configuration of cell states, the updated cell state is always the same. With non-deterministic rules the next state is not only dependent on the neighbourhood but also on some random inputs and/or probabilistic components. A probabilistic rule gives the probabilities that each cell will transition to the next possible state. The states of the cells may represent different colours and therefore, the functioning of a two-dimensional cellular automaton may be displayed on the computer screen as a sequence of images, like an animated film.

Cellular automata have been of interest to musicians working with digital audio, in particular composers, because of their emergent structures –patterns not created by a single rule but through the interaction of multiple units with relatively simple rules. This dynamic process leading to some order allows the musician to explore new forms of organization. In sound synthesis, CA are normally used for controlling over time the parameters of a software-based sound synthesizer. Many of the synthesis techniques demand enormous amounts of control data for obtaining interesting results, making it difficult to be controlled manually. CA represent a solution to this problem because with few parameter specifications it is obtained massive amounts of structured data. The goal is to transfer the structured evolution of CA onto the sound synthesis domain. This is always done through a mapping, a set of correspondences between different domains.

There have been different mapping attempts [3] ranging from direct assignments of CA values, like in Lasy [4], to higher-level approaches intending to map the overall CA behaviour, like in Chaosynth [5]. We are interested in the second type of approach. Our research strategy is based on the analysis of CA evolutions by means of digital signal processing techniques in order to discover structural information of their organization. Then we proceed with the mapping of the analysis results onto appropriate synthesis parameters.

This paper is organised as follows. In Section 2 we explain our mapping method, which is based on CA analysis with the histogram technique and, aims at the design of sound spectrograms. In section 3 we present the automaton upon which this study has been carried out, the multitype voter model. In section 4 we describe the musical features as well as the drawbacks found from the histogram analysis of such an automaton. In section 5 we present our extended version model. As the control is the main problem of CA, in this section and the following we comment controllability aspects of the sound design process. Sounds are rendered using additive synthesis. Finally, Section 7 concludes this paper.

2. MAPPING PROCESS: FROM HISTOGRAMS TO SPECTROGRAMS

Our mapping method is based on a statistical analysis of the CA evolution. The functioning of a two-dimensional automaton is considered as a sequence of digital images and it is analysed by histogram measurements of every CA image. Such a CA analysis gives a histogram sequence.

The histogram of a grey level digital image is a graphical representation of the number of occurrences of each grey level[1] in the image. By dividing the number of occurrences by the total number of pixels of the image, the histogram is expressed in probabilistic terms giving an estimate of the probability of occurrence of each grey level in the image –the sum of all the histogram bins is equal to one.

In general terms our mapping method works as follows: the bins of the histogram sequence are considered to be bins of a spectrogram. With an appropriate automaton, in the histogram sequence it is possible to find structural elements resembling spectral components of a sound. For example, from a histogram analysis of the hodge podge machine there were discovered structural elements similar to sinusoidal components and others similar to noise components such as noise bands and transients [6]. This makes such a mapping process distinctive; in most other cases there is not an intuitive correspondence between the components of the automaton and the components of a sound.

With these structural elements we can design the time varying frequency content of a sound; we can build a

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[1] Apart from this definition, in this paper we refer to colours instead of grey levels because we usually display the CA in the computer screen using a palette of different colours.

spectrogram. This spectrogram can be rendered into sound using different synthesis techniques –the structural elements of the histogram sequences become control data for the synthesizer.

We would like to note that our mapping process is not restricted to CA. It constitutes a new sound synthesis technique on its own right, which we refer to as Histogram Mapping Synthesis (HMS).

3. THE MULTITYPE VOTER MODEL

The automaton developed in this research is based on the multitype voter model. In 1953, geneticist Kimura introduced the stepping stone model [7]. This process was studied extensively by other geneticists over twenty years before being rediscovered by probability theorists Clifford and Sudbury in 1973 [8] where it was called the invasion process and by Holley and Liggett in 1975 [9] under the name the voter model [10].

The voter model is interpreted as a model of opinion formation. A collection of individuals is defined, each of which has one of two possible opinions on a political issue. These possible opinions are denoted by 0 and 1. An individual reassesses his view in a rather simple way: he chooses a “friend” at random with certain probabilities and then adopts his opinion [11]. When the voter model is generalized to more than two opinions it is known as multitype voter model.

It can be also seen as a model of competition. The interpretation is clear from the point of view of the invasion process; different species compete for the territory and the result of conflict is the invasion by one of the species of territory held by the other.

These models can be simulated by means of a probabilistic cellular automaton in two dimensions. The MVM can be implemented with the following transition rule: a number between 0 and 1 is chosen as to be the update probability for all cells. Then, for each cell in the grid, a random number between 0 and 1 is generated at every time step. If the random number generated for the given cell is higher than the update probability, then the state of the cell changes to that of one of its neighbours selected uniformly at random. (Neighbour is defined as the four orthogonally adjacent cells: north, east, south, west) [12].

From a uniform random distribution of cell values, or colours, as the initial configuration, the automaton self-organizes in areas (or clusters) of single colours (Figure 1). As the rule is iterated, some areas will increase their space while others will decrease to the extent that they can disappear. In the end, one colour will prevail over the others when, according to the voter interpretation, consensus occurs.

The random inputs and probabilities in the rule make that different runs with the same settings result in different evolutions.

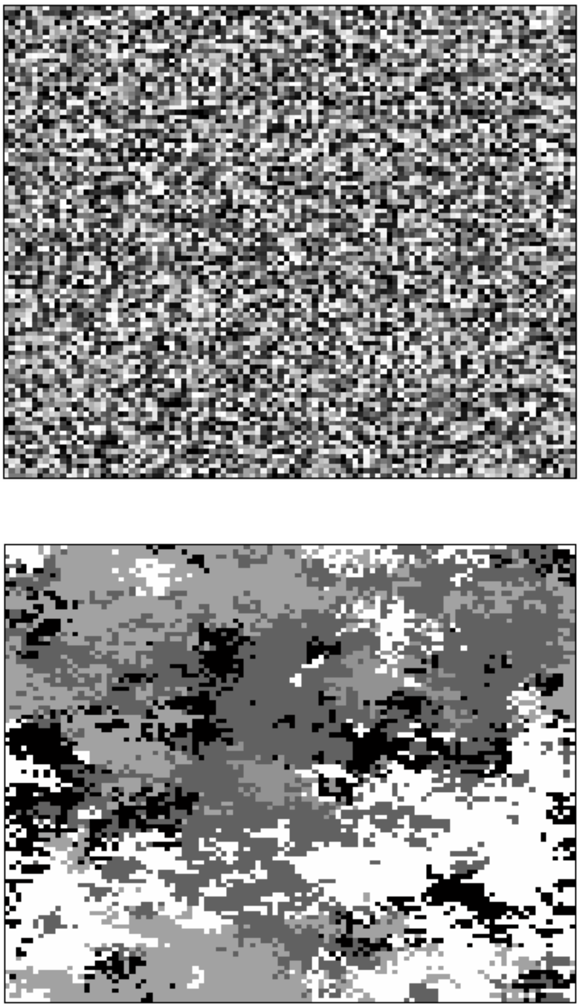

Figure 1: Two configurations of a multitype voter model evolution. From a random input (top) it self-organizes in coloured areas (bottom).

4. FEATURES OF THE MULTITYPE VOTER MODEL HISTOGRAM SEQUENCES

The histogram sequences of the MVM present interesting features that make them suitable for sound synthesis. Here we summarise some of them; for a dedicated study see [13].

Figure 2 shows the histogram sequence of an automaton achieving consensus. We can see that the bins of the histogram sequence may represent the time varying amplitudes of sound partials[2]. In addition, note that the MVM allows us to work with as many colours (i.e. partials) as we want. Secondly, note that the disappearance of colours during the run of the automaton is reflected in the histogram sequences as release patterns for the partials. In our example, we can exclude the most prominent partial and we get a structure with release patterns for all the rest of the partials.

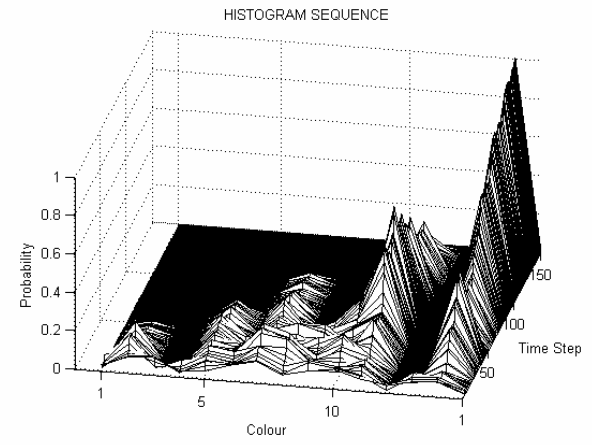

Figure 2: Histogram sequence of a 10x10 automaton with 15 colours achieving consensus.

On the other hand, the non-deterministic nature of the MVM, although bringing a rich variety of results from a same automata definition, entails some limitations. For example, in order to exclude the most prominent partial we have to wait until the end of the run to see which colour covers the whole automaton. Consequently, we can not consider real-time applications. Secondly, we can not predict when and how the rest of the partials will fade out. Sometimes they may fade out gradually creating a damped structure but some other times a number of partials may remain steadily for longer creating a sustained structure (Figure 3). In this research we focus on the production of damped structures.

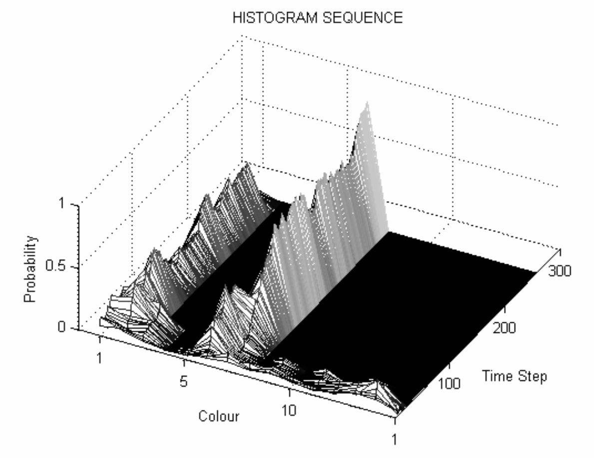

Figure 3: Another evolution of the same automaton of Figure 2. Considering the exclusion of the most prominent partial, the Figure 2 could be a structure for a damped-like sound, whereas this one is rather a structure for a sustained sound.

5. AN EXTENDED VERSION OF THE MULTITYPE VOTER MODEL

Originally, in the MVM the update probability (UP) is assigned equally to all the cells. We have developed an extended version of the model based on the assignment of colour-dependent UPs.

From the point of view of the invasion process that means having different species with different degrees of vulnerability; a colour with a low UP has a high probability of “being eaten” by a neighbour. With this, we gain control over the extinction of colours; in the histogram sequences, partials corresponding to colours with low UPs will decrease at the expense of those with higher UPs. Note that with this, we are modelling a process observed in acoustic instruments in which energy passes between the various modes of vibration, some increasing in amplitude, some decreasing [14].

Among the different UP distributions that are possible, in this research we focus only on those that produce damped sound structures. One way to ensure obtaining these kinds of structures is to reserve one colour to which we assign the maximum UP value with UP=1 –

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[2] Assuming this premise, for the rest of the paper we may use the term ‘partials’ for referring to histogram bins.

note that a colour with UP=1 represents an invincible species; a cell with that colour never changes its colour. With this we ensure that this colour will win. Also with this, we know in advance –useful for real time applications– the location of the most prominent partial that will be excluded from the histogram sequence. If we consider all the rest of the partials, we get a damped structure –remember that the sum of all the histogram bins is equal to one and we are excluding an always-increasing bin.

UP values inversely proportional to the colour values is an example of such UP distributions (Figure 4).

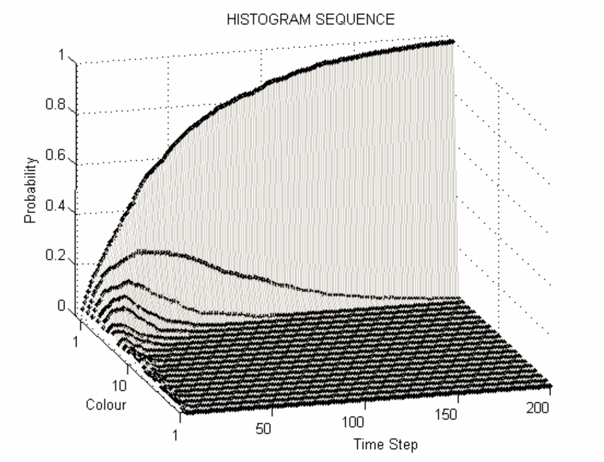

Figure 4: Histogram sequence of a 30x30 automaton with 20 colours. The UPs are inversely proportional to the colour values.

The next example serves to illustrate the potential of the control with the UPs for the design of histogram sequences. With a different UP distribution the previous histogram sequence can be improved so as to provide a more consistent sound spectral structure. We establish 3 regions: one region corresponding to low partials with UP=0.8, another region in the middle with UP=0.7 and, the last region with UP=0.4. Finally, the first colour will have UP=1.

We have observed that large grids of cells produce smoother curves in the histogram sequences than small ones. Also, the release times of partials within the same region are very similar in the former case, and present some variations in the latter. In our example we work with a relatively large size and then we introduce small variations in the UP values with a bounded random generator, in order to get different release times for each partial (Figure 5).

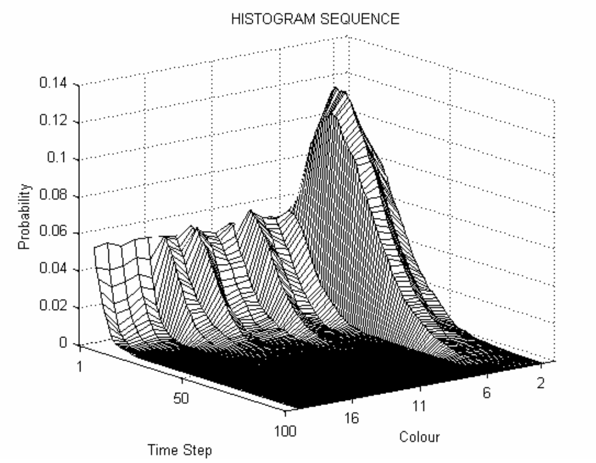

Figure 5: Histogram sequence of a 100x100 automaton with 20 colours having excluded the first partial. The UPs were assigned with random values around three main regions.

With these settings, different runs of the automaton give the same type of structures (with three regions) but with differences in the release times of the partials and in the amplitudes that the partials reach. These differences, that we can make larger or smaller, are perceived as timbral variations. Thus, we have designed an instrument able to produce similar but not identical tones and therefore, capable of generating more natural sequences of notes in a performance.

6. ADDITIONAL CONTROL AND SYNTHESIS

Apart from the control provided by the UPs for the design of histogram sequences, another important aspect of controllability that our technique affords is the possibility of developing a sound design process from the structural elements of the histogram sequences. Conceptually, the first steps to be performed are the assignment of frequencies to the partials and, the specification of the sound duration. From here, other spectral transformations are possible. Time stretching, pitch shifting and amplitude modifications of each partial are straightforward to implement. With all these we would be able to design different spectrograms.

For this research we have chosen additive synthesis of sinusoidal components, but other synthesis techniques can be considered to be controlled by these histogram sequences. This is a venue that we might explore in the future.

With the damped structures obtained we have synthesised good imitations of plucked strings sounds (when the frequencies of the partials are assigned following the harmonic series) and also of bell sounds (when there are partials with non-harmonic ratios of frequencies).

7. CONCLUSIONS

In this paper we have reported on the synthesis of sounds by the computer simulation of natural systems with CA. The MVM exhibits rich dynamics from a very simple rule and few input parameter specifications. We have presented an extended version of the MVM based on the assignment of colour-dependent UPs. From a histogram analysis we have obtained damped structures suitable for the design of spectrograms.

Although the control is the main problem of CA, we have been able to develop a flexible sound design process with emphasis on the possibility of controlling over time the spectrum complexity. The predictability and controllability achieved allows us to do such a design process in advance, which is useful for sound and instrument design and, has potential for real-time and performance applications. We have synthesized damped sounds with dynamic spectra and controlled complexity including energy transfer between the partials.

8. REFERENCES

[1] Miranda, E. R. and Biles, J. A. "Evolutionary Computer Music". Springer-Verlag, London (2007)

[2] Wolfram, S. "A New Kind of Science Online". Accessed on February, 2009, at http://www.wolframscience.com/reference/notes/876b.

[3] Burraston, D. and Edmonds, E. "Cellular Automata in Generative Electronic Music and Sonic Art: A Historical and Technical Review". Digital Creativity. 16, 165–185 (2005)

[4] Chareyron, J. "Digital Synthesis of Self-Modifying Waveforms by Means of Linear Automata". Computer Music Journal. 14, 25–41 (1990)

[5] Miranda, E. R. "Generating Source Streams for Extralinguistic Utterances". Journal of the Audio Engineering Society. 50, 165–172 (2002)

[6] Serquera, J. and Miranda, E. R. "Spectral Synthesis and Control with Cellular Automata". Proceedings of the International Computer Music Conference - ICMC, Belfast (2008)

[7] Kimura, M. "Stepping-stone Model of Population". Annual Report of the National Institute of Genetics. 3, 62–63 (1953)

[8] Clifford, P. and Sudbury, A. "A Model for Spatial Conflict". Biometrika. 60, 581–588 (1973)

[9] Holley, R. A. and Liggett, T. M. "Ergodic Theorems for Weakly Interacting Infinite Systems and the Voter Model". The Annals of Probability. 3, 643–663 (1975)

[10] Cox, J. T. and Durrett, R. "The Stepping Stone Model: New Formulas Expose Old Myths". The Annals of Applied Probability. 12, 1348–1377 (2002)

[11] Liggett, T. M. "Interacting Particle Systems". Springer-Verlag, New York (1985)

[12] Cox, J. T. and Griffeath, D. "Recent results for the stepping stone model". In Percolation Theory and Ergodic Theory of Infinite Particle Systems. Springer, New York (1987)

[13] Serquera, J. and Miranda, E. R. "Evolutionary Sound Synthesis: Rendering Spectrograms from Cellular Automata Histograms". Proceedings of EvoWorkshops 2010 / EvoMUSART, Lecture Notes in Computer Science. Springer-Verlag, Berlin (to appear)

[14] Aldoshina, I. et al. “The analysis of peculiarities of Russian bells acoustic parameters”. 114th AES Convention. Amsterdam (2003)