Theory and Practice of Physical Modeling for Musical Sound Transformations: An Instrumental Approach to Digital Audio Effects Based on the CORDIS-ANIMA System

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Abstract. This thesis proposes the use of CORDIS-ANIMA physical modeling formalism as a mean of designing musical sound transformations under the concept of *instrumental interaction*. It provides new results and new discussions in musical signal processing and in the design of digital audio effects. The aim is to investigate the possibilities of physical modeling to provide more "plausible" sound modifications and alternative control procedures.

Keywords: digital audio effects, physcial modeling, musical sound transformation, CORDIS ANIMA, signal processing, instrumental gesture, control, sound processing, mass-interaction formalism

1 Introduction

The idea of sound transformation refers to the process of transforming or modifying a sound into another one with different quality. A more musical oriented definition describes sound transformations as "the processing of sound to highlight some attribute intended to become part of the musical discourse within a compositional strategy" (*Glossary* of EARS web site [1]). In the present research, we do not use this term in the sense of sound morphing.

We define an audio effect as the "How" part -the method- of a sound transformation through processing. This definition is more general than the common ones. For example Verfaille et al. define the audio effect as:

"…we consider that the terms "audio effects", "sound transformations" and "musical sound processing" all refer to the same process: applying signal processing tech-

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niques to sounds in order to modify how they will be perceived, or in other words, to transform a sound into another sound with a different quality” [2].

It is obvious that this does not coincide completely with our definitions for audio effect and sound transformation. In the last definition, an ambiguity probably occurs from the term signal processing. In general, signal processing concerns the techniques and methods for the manipulation of the mathematical representations of signals. Even the terms signal/mathematical representation of signal usually are considered equivalent. Therefore, signal processing is just an approach to design sound transformation and a particular category of audio effects.

For example, it is uncommon to consider the spring reverb, guitar or even an electric network as a signal processing system. On the other hand, we may approach it, represent it and model it as a signal processing system. This distinction is not only theoretical. A helpful example is the acoustical instrument designer: the methods he applies to construct his instruments are not at all signal processing-based. As this thesis concerns more the design of audio effects than the analysis, this distinction is essential.

When we deal with the processing of musical audio signals by digital means, we use the term digital audio effect (DAFX is an synonym for digital audio effects). Someone could say that since we use information-processing systems for the musical transformation of sound, we employ directly signal-processing techniques. We should be prudent once more, as modern digital sound technology has made sound certainly more *immaterial* and more *object-like*. Its production is not any longer bound to instruments and instrumentalists: it can be manipulated with tools acting on its representations*. On the other hand, this does not necessarily mean that we must necessarily employ a signal processing method, or much more importantly, a signal-thinking approach to modify a sound with a digital computer. Of course, we cannot deny that at a low level all these modifications are in fact digital signal processing procedures.

The definition of digital audio effects by Zoelzer is more general:

“Digital audio effects are boxes or software tools with input audio signals or sounds which are modified according to some sound control parameters and deliver output signals our sounds” [3].

We could rearticulate the last definition and describe the digital audio effects as digital systems/algorithms that modify incoming audio signals according to the available control parameters. The control signifies all the possible methods available to the user for accessing the control parameters: graphical user interfaces, abstract algorithms, gestural interfaces, sound features etc.

In the present thesis, we propose a novel approach of musical sound transformation based on the physical simulation of vibrating structures with the aim to investigate the possibilities of physical modeling to provide more “plausible” sound modifications and alternative control procedures [4]. Briefly our method is centered on the numerical simulation of vibrating physical objects: at first the input digital audio signal feeds a properly designed virtual viscoelastic system that matches the general specifications of the desired effect; then a set of mechanical manipulations are taking place which consequently modify dynamically the input sound. Thus this procedure offers a purely

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* anyway the digital computers do not process numbers – digital signal processing does – but symbols

“materialistic” nature in the sound modification. It is the “matter” which is manipulated after all and not the signal.

2 Physical Audio Effect Models

All digital audio effects, even those with direct physical references are always supporting the paradigm of control/mapping. In this paradigm the control surface and the sound processing unit are independent, dissociated and they are related to each other by mapping strategies [5]. Our hypothesis is that the interesting expressive possibilities of acoustic musical instruments are coming from the energetic coupling between the player and the instrument [6][7]; our goal is to apply this type of interaction *called instrumental interaction* [8] to audio effects algorithms.

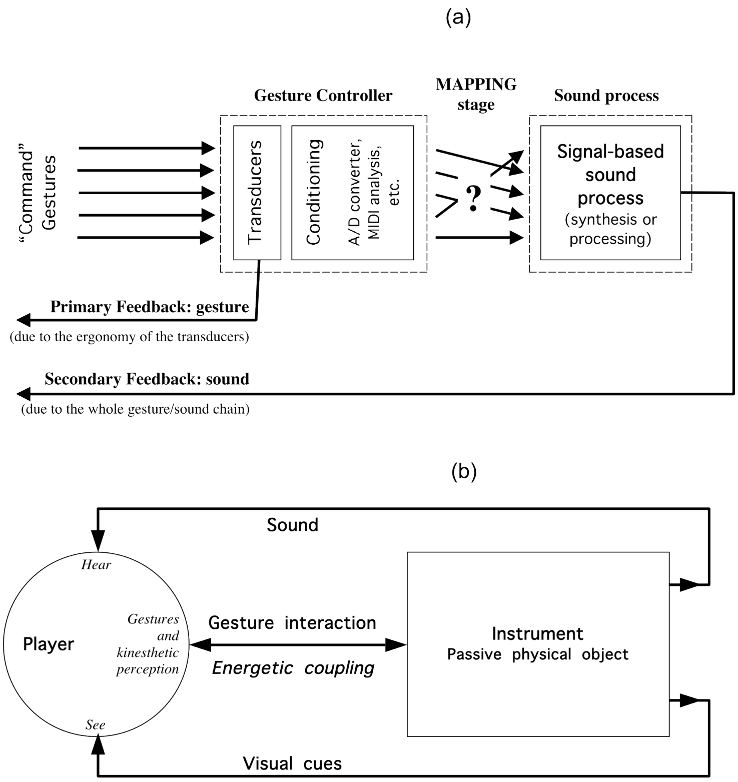

Fig. 1. (a) Usual structure of a contemporary real time sound system (b) the traditional instrumental relation (from [9])

The initial concept is to establish a physical interaction between the user-musician and the audio effect unit that has virtual material substance. This is feasible of course only by the use of suitable *ergotic interfaces* – gestural interfaces that permit this type of interaction- or by gesture models. We should understand that in this type of "control" no mapping layer exists between gesture and sound since no representation is involved in this situation, but only physical processes (figure 1). The parametric control is replaced by the mechanical modifications or transformations of the object that plays the role of the audio effect.

In the rest of this thesis we will often employ the term physical audio effects model. From our scope, a relevant definition is the following:

Physical audio effects model refers to any digital audio effect algorithm that is designed to simulate a physical system, including the physical interaction with that system, which transforms input sound signals.

3 CORDIS-ANIMA Physical Audio Effect Models Design

We presented the concept of Physical Audio Effects. Our purpose was to demonstrate a general conceptual framework that is independent as much as possible from any modeling and simulation system architecture. In this chapter we will present the adopted system architecture. Moreover, we will introduce the design and simulation process. Therefore the goal of this research from the beginning was double:

Define a system architecture and an approach for the design and the development of physical audio effect algorithms clearly oriented for musical purposes. In this context, we claim that the digital audio effect design procedure is essentially a creative and artistic process. We seek for a modeling practice that starts from scratch and that permits a straightforward exploration for new sonic possibilities based on sound transformation techniques. A stream processing architecture where the system is briefly a collection of blocks that compute in parallel and communicate data via channels was a preferable choice, as we believe it facilitates many of the "artistic" conception of the sound processing algorithms.

Design and simulate physical audio effects models that specify the following requirements:

× the signal processing part of the effect is a simulated passive physical object
× they support instrumental interaction
× they are real-time
× they are modular
× they are as intuitive as a physical object
× they are reasonably simple from a functional point of view

CORDIS-ANIMA (CA) modeling and simulation system feature many of these characteristics so it has been chosen as the ideal for the fulfillment of our aims. The description of the general formalism [10] attests clearly that present research and the "raison d' être" of CA system share very common goals. Hence it was a natural choice to propose a system architecture that was totally based on the CA system.

In figure 2 is illustrated the proposed system architecture. In the core of the system is positioned the CA models that transform the input sounds $x_{si}(n)$. These sound signals if necessary are calibrated in amplitude before entering the model by the block *sound input calibration*. In a similar manner, a calibration appears for the gestural signals $x_{gi}(n)/y_{gi}(n)$ by the block *gesture i/o calibration*. Remember that the central concept of this research is the possibility of establishing an instrumental interaction between the audio effect model and the human operator through the depicted gestural port. Therefore, the novelty appears in this part of the architecture.

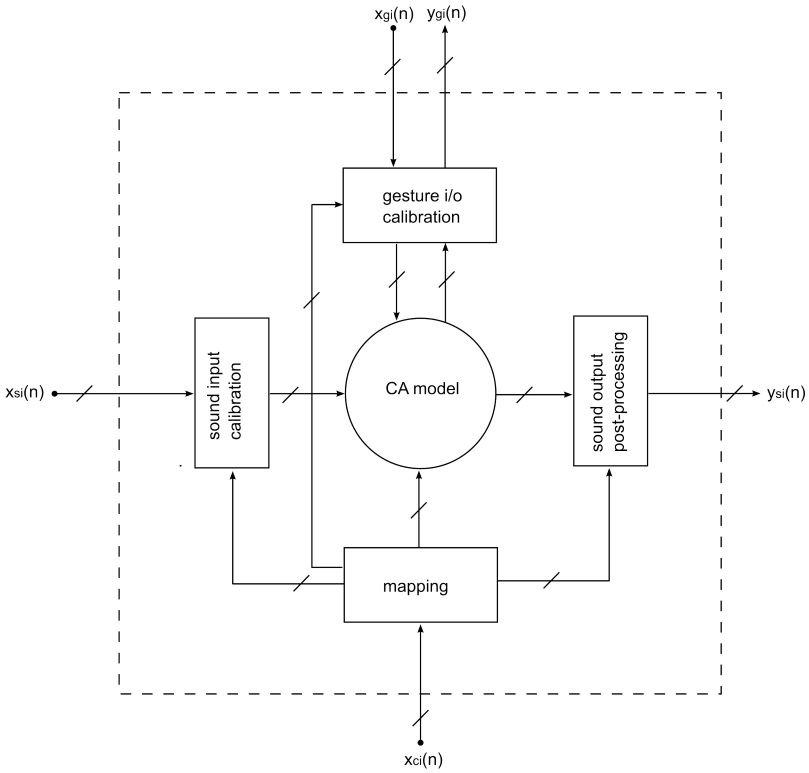

Fig. 2. The proposed system architecture ($x_{si}(n)$: input sound signals, $x_{gi}(n)/y_{gi}(n)$: gestural input/output signals, $x_{ci}(n)$: control signals, $y_{si}(n)$: output sound signals)

Apart from the gestural signals we have certain control signals $x_{ci}(n)$ that modify dynamically (during the simulation) or non-dynamically some CA model parameters. It is evident that it is more a matter of meaning than a technological issue to decide which of CA parameters can be altered dynamically. Moreover they control several other parameters of the i/o calibration modules and of the sound output post-processing module. The mapping module was necessary in order to pass from certain perceptual parameters to CA ones.

It is evident that according to the proposed system architecture of figure 2, two different approaches are taking place to control the physical audio effect model. The first one employs some forms of mapping between the users actions and gestures into appropriate parameter values needed to ***drive*** the sound processing algorithm. This practice is used more to tune the models statically. Nevertheless it has been used slightly for dynamic sound modifications, as we will see later on.

The second approach suggests a completely novel tactic to ***interact*** with the digital audio effect. In this scenario we are not driving the sound processing algorithm: the term control is not the proper one to describe this situation. Following the generic concept of physical audio effects and the theory of instrumental interaction this new paradigm of designing, thinking and interacting with digital audio effects has been emerged.

Evidently specific technologies are needed to implement this new type of digital audio effects. Appropriate and accurate force feedback devices must be developed and used. This problem, in an artistic context applied to sound synthesis, was confronted for the first time in 1978 by Florens. Since then a number of similar devices have been developed under the name TGR in the same laboratory (ACROE) [6][11][12].

The input/output gestural signals during this thesis were simulated by a collection of simple CA gestural models. This fact does not affect at all the generality and the validity of this research. It would be preferable of course to run additionally several other experiments with the presence of a human operator. What is interesting though with the gesture modules is that they permit a more analytical and rigorous study under completely controllable and measurable conditions.

It is also interesting to mention that the generic concept of instrumental interaction is still valid for the simulated offline gestures. That means that the simulated gestures should not only be considered as a mean to study methodically the instrumental interaction as we indicated before. It can also be approached as a type of physically based waveform generator that interacts with the audio effect without the intervention of the human user. This approach is very close to the problematic of composing the instrumental gesture.

The design of our physical audio effect models has been carried out by the CA modeling and simulation system. One of the fundamental characteristics of this formalism is that the modeling modules are in the same time the elements of the simulation procedure. Moreover the algorithmic models can be implemented in a computer system in the form of hardware, firmware and software without further approximations and structural modifications.

The stream processing architecture of CA permits directly a distributed computation. A hardware implementation was designed in 1982 but soon after less special-purpose computer systems were preferred. In a general-purpose platform, the algorithm is easily implemented as a computer program using a very simple repetitive sequential scheme [6]. The real-time gestural control, demands more sophisticated architecture with additional DSP cards and real-time operating systems.

The present thesis is not concerned with the implementation aspects of physical audio effect models. However the simulation was a fundamental part of the design procedure. Hence the choice of flexible computer simulation software was crucial. The option of programming directly in a general-purpose language was not a suitable solution; we were looking for a more simple and direct method to construct, modify and analyze complex system models. Specialized visual block diagram languages proved to be the ideal solution for our model-based design approach. Common solutions for signal processing applications are LabVIEW* , Simulink** and Scicos***. For

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* www.ni.com/labview

** www.mathworks.com/products/simulink

*** www.scicos.org

the present research we have used Simulink. Figure 3 depicts a screen shot of the proposed and used design environment in Simulink.

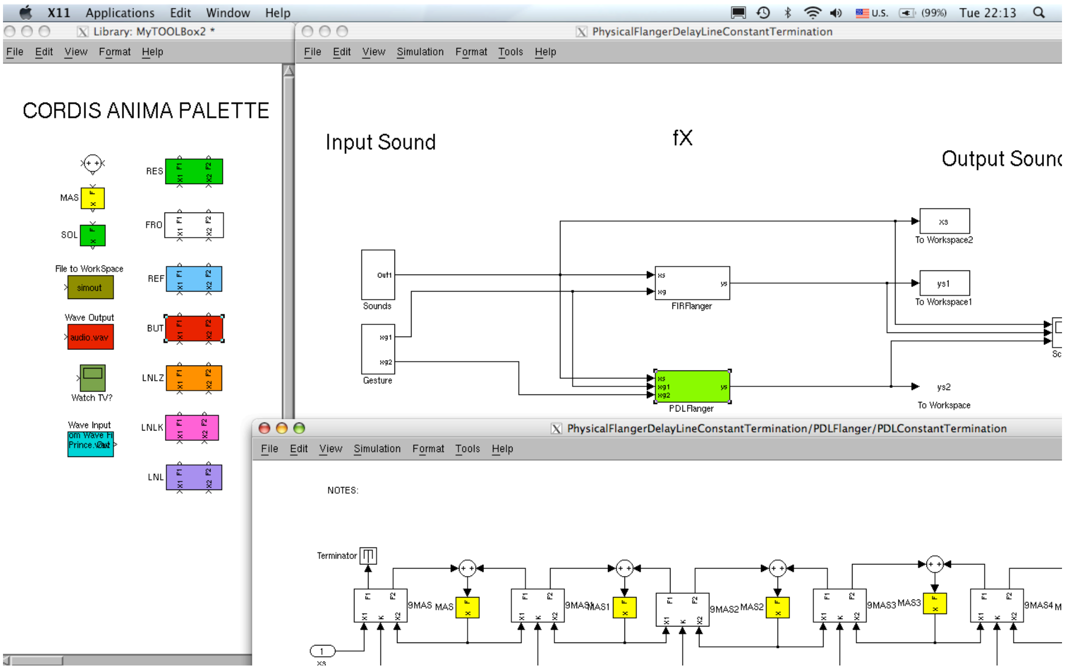

Fig. 3. Screenshot of the designed environment in Simulink

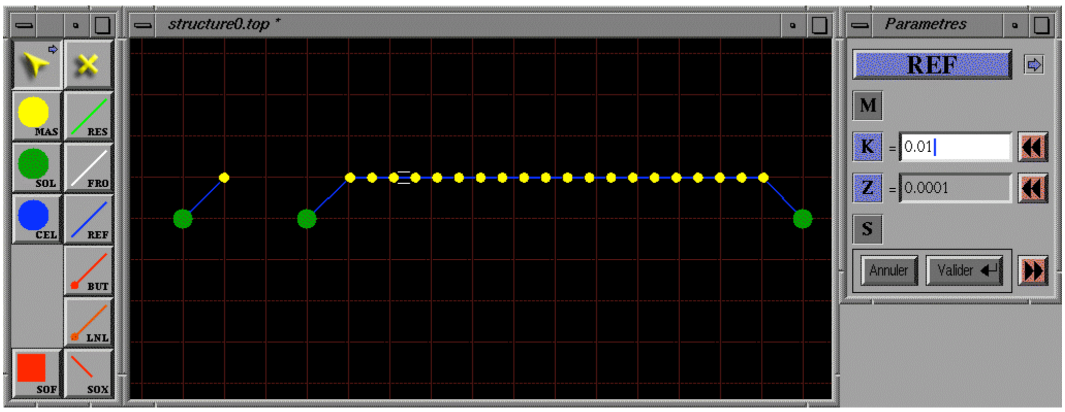

Fig. 4. Genesis screenshot

Initially, our aim was to use only the special CA version that appears in GENESIS software [13] (figure 4). We found out that it was often neither possible nor essential for the goals of our research, to stay strictly attached to this environment. Without doubt, it would be preferable to have the facility to simulate directly our models with

GENESIS in order to be available straightforwardly to the number of artists that use it. Even if that proved impractical and unachievable for several models, the concept of "Physical Thinking" promoted by this software, has always been respected and guided all parts of this research.

4 CORDIS-ANIMA System Analysis

The aim of this part of the thesis is to enlighten some special and particulars features of CA formalism by exploiting it mathematically [14]. CA models are studied and presented using several useful system representations like CA Networks, Finite Difference representations, Kirchhoff representations, digital signal processing block diagrams, State Space internal descriptions, System Function input/output external descriptions and, Wave Flow Diagrams. This mathematical analysis and formal approach was crucial in the context of our research on the digital audio effect.

In every physical modelling technique, mechanical and acoustical systems governed by physical laws are modelled using several mathematical formalisms and simulated with the use of numerical methods and digital computers. Vibrating structures like all kind of elastic bodies, strings, membranes, bars and plates can be considered and approximated as linear deformable objects. Each physical modelling scheme represents those physical objects differently in a discrete-time and discrete-space form. Those various structures may often be in the end mathematically equivalent or more generally they may show a high degree of functional equivalence even if they represent and realize the physical object using different formalisms and strategies.

In signal processing [15] two structures are defined as equivalent if they have the same transfer function. However, their realizations may not at all be equivalent: dissimilar realizations leads to system configurations with different complexity* and different memory requirements. Each structure also presents different finite word-length effects (round-off noise, limit cycles, coefficient sensitivity) [16], and poses different stability issues.

Furthermore, each system structure supports and permit diverse control procedures. For example in digital filtering several structures with tuneable frequency response characteristics provide independent tuning of the filter parameters (cut-off frequency, bandwidth) [15]. In the context of physical modelling, several schemes like CA provide spatial accuracy while others such as the commuted DGW do not, although they are effective computationally. The aim of the present PhD research could be reposed alternatively through the problematic of the system structures:

How can we redesign the basic digital audio effects algorithms or design new ones using system structures that offer physical instrumental interaction?

It is clear from all these reasons that it is appealing in many cases to pass from one formalism to another and represent a certain model with other mathematical schemes.

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* The complexity of a system structure is indicated by the number of multipliers and by the number of two-input adders

Another interest is to combine several of the physical modelling approaches into one hybrid model.

A further essential motivation for the use of several formalisms is the analysis. It is evident that as every formalism offers a different type of system description, it is useful to choose the appropriate one for the desired analysis purposes. These purposes may be strictly scientific and can help in the study and the development of the physical modelling scheme or more artistically to offer modelling techniques based on the paradigm of synthesis by analysis. These reasons stimulated us to study how the CA formalism is transformed to other representations.

Apart from the fact that even if the model has an equivalent mathematical description the different configuration will produce slightly different *simulacrum* -as we have already mentioned previously-, there is a much more vital and essential reason. Each formalism permits and allows a different way of manipulation, control and thinking due to its structure and to the mental image that it conveys to the user. Consequently one user can use other representations for the analysis, along with the concept of its model and then pass it to a preferable physical modelling scheme for further manipulation and musical creation.

We present only the CA network representation since we have very limited available space in the present article. In CA formalism a physical object is modelled as a modular assembly of elementary mechanical components [10]. Hence it is straightforward to represent the model as a topological network whose nodes are the punctual matter elements <MAT> and the links are the physical interaction elements <LIA> (figures 5 and 6). The simulation space used for sound and musical applications is limited to just one dimension. In the present thesis CA systems are strictly one-dimensional. Forces and displacements are projected on a single axis, perpendicular to the network plane. Consequently the geometrical distance between two <MAT> elements is reduced to their relative distance on the vibration axis.

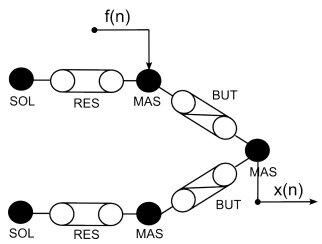

Fig. 5. A CA network

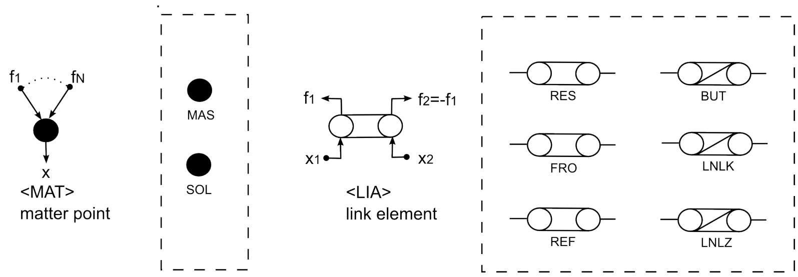

Fig. 6. CA modules

5 CORDIS-ANIMA Physical Audio Effect Models

An essential part of the research was the re-design of several classic digital audio effects [17][18][19]. It would be probably better to talk about a redefinition of classic effects through the prism of physical modeling and of haptic gestural interaction and not about a re-design.

We have chosen certain basic effects to realize as CA models. It is evident that it is not possible to provide a physical model for every audio effect algorithm. We cannot imagine for example a physical analog of time-segment processing algorithms such as granulation or brassage. Then again, it is necessary to mention that many very important existing effects are experienced physically. Reverberation and the Doppler Effect are two remarkable examples.

The studied and the synthesized digital audio effects using the CA formalism is listed below briefly below:

- **Elementary Signal Processing Operations:** Unit Delay Element, Constant Multiplier, Adder and Subtracter, Memoryless Nonlinear Element
- **Basic Low-Order Time-Invariant Filters:** Highpass, Lowpass, Bandpass
- **Synthesis of High-Order Time-Invariant Filters:** Cascade-Form, Parallel-Form, String-Form
- **Time-Variant Filters:** Wah-Wah, Time-Variant Resonators ("Pressing-String" and "Sticking-String" Models)
- **Amplitude Modifiers:** Bend Amplitude Modification Model, Mute Amplitude Modification Model, Pluck Amplitude Modification Model
- **Delay-based Audio Effects:** Delay Model, Comb Filter Models, Flanger Models, Spatialization and Pick-Up Point Modulation
- **Nonlinear Audio Effects:** Nonlinearities without Memory (Waveshaping), Nonlinearities with Memory: (Clipping)

6 Conclusions

This study introduced for the first time the concept of instrumental interaction in the domain of digital audio effects. It is a novel and original contribution to the computer music domain. A number of simple classical digital audio effects have been designed and approximated that provide haptic inputs/outputs to the user. Moreover, their structure has permitted an ergotic interaction loop in which energy is exchanged between them and the user. The CA system has been employed for the design and synthesis of all the proposed models. Our thesis was that the energetic coupling between acoustic instrument / instrument player and the tactile-proprio-kinesthetic gesture feedback is essential and could be transferred into the digital audio effects system.

This research provided a global review of musical sound transformation algorithms focusing more on their design processes. We started our "exploration" from a general but strong philosophical basis – the “need” for instrumental interaction-, we proposed a simple classification of audio effects, and progressively we developed a theory and a framework for the design of physical digital audio effect models. In the end we proposed several models that approximate classical audio effects and presented a few new ones.

The input/output gestural signals during this thesis were simulated off-line by a collection of simple CA gestural models. We have reported that this fact does not affect the generality and the validity of this research. However, it is necessary to run several additional experiments with the presence of a human operator. Therefore the implementation of the proposed algorithms in real-time simulation system equipped with force-feedback interface is probably the most necessary future work. The importance of instrumental control in digital audio effects must be verified by formal observations and experiments and by less formal/less controlled conditions -in order to eliminate the perturbations of the system coming from our measures- such as during a musical performance. We believe that through this physical dynamic control of the audio effect process, a virtuosity will emerge that will contribute to the quality and the finesse of sound transformation.

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