

# Portfolio of Original Compositions

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## Portfolio of Musical Works

### Fixed Media

1.	<i>4 Dreams</i> , (2013)	5.1	12'16
2.	<i>Superposition of Two Opposites</i> , (2013)	8-channel	08'36
3.	<i>Synthetic Springs</i> , (2014)	8-channel	09'02
4.	<i>Time paradox</i> , (2015)	8-channel	10'37
5.	<i>The Silver Key</i> , (2015)	16-channel	24'12

### Mixed Media

6.	<i>Wake Up</i> , (2013)	2 Violins and Tape	08'33
7.	<i>Holly</i> , (2014)	Piano, Flute, Percussion and Tape	05'06
8.	<i>Fuzzbox</i> , (2015)	Bass-guitar and Live Electronics	10'12

Total Duration: 88'34



## Portfolio of Musical Works

### USB Content

Fixed Media Works						
1	<i>4 Dreams</i>	2013	5.1	12'16	6 mono files 1 stereo file	24 bit, 44.1 kHz
2	<i>Superposition of Two Opposites</i>	2013	8-channel	8'36	8 mono files 1 stereo file	24 bit, 48 kHz
3	<i>Synthetic Springs</i>	2014	8 channel	9'02	8 mono files 1 stereo file	24 bit, 48 kHz
4	<i>Time Paradox</i>	2015	8 channel	10'37	8 mono files 1 stereo file	24 bit, 48 kHz
5	<i>The Silver Key</i>	2015	16 channel	24'12	16 mono files 1 stereo file	24 bit, 48 kHz
Mixed Media Works						
6	<i>Wake Up</i>	2013	2 Violins and Tape	8'33	1 Stereo file (full tape) Score 1 Stereo file (performance)	16 bit, 44.1 kHz
7	<i>Holly</i>	2014	Ensemble and Tape	5'06	1 stereo file (full tape) Score Max 6 Patch 1 Stereo file (performance)	16 bit, 44.1 kHz
8	<i>Fuzzbox</i>	2015	Bass gui- tar and Live Electronics	10'12	1 Stereo file (performance) Score Max 7 Patch	16 bit, 44.1 kHz
Videos						
1	State-space models	Max		1 min		
2	State-space models	SuperCollider		1 min		
Software Tools						
1	State-space	Max		Inverted pendulum and DC motor Max (abstraction) objects		
2	States	SuperCollider 3.6.5		Class to perform state-space oper- ations		
3	Abstract model	MatLab		Simulation code		

### Printed Scores

1. *Wake Up*
2. *Holly*
3. *Fuzzbox*

## Abstract

This portfolio of compositions investigates the adaptation of state-space models, frequently used in engineering control theory, to the electroacoustic composition context. These models are mathematical descriptions of physical systems that provide several variables representing the system's behaviours.

The composer adapts a set of state-space models of either abstract, mechanical or electrical systems to a music creation environment. She uses them in eight compositions: five mixed media multi-channel pieces and three mixed media pieces.

In the portfolio, the composer investigates multiple ways of meaningfully mapping these system's behaviours into music parameters. This is done either by exploring and creating timbre in synthetic sound, or by transforming existing sounds. The research also involves the process of incorporating state-space models as a real-time software tool using Max and SuperCollider.

As real-time models offer several variables of continuous evolutions, the composer mapped them to different dimensions of sound simultaneously. The composer represented the model's evolutions with either short/interrupted, long or indefinitely evolving sounds. The evolution implies changes in timbre, length and dynamic range. The composer creates gestures, textures and spaces based on the model's behaviours.

The composer explores how the model's nature influences the musical language and the integration of these with other music sources such as recordings or musical instruments. As the models represent physical processes, the composer observes that the resulting sounds evolve in organic ways. Moreover, the composer not only sonifies the real-time models, but actually excites them to cause changes. The composer develops a compositional methodology which involves interacting with the models while observing/designing changes in sound.

In that sense, the composer regards real-time state-space models as her own instruments to create music. The models are regarded as additional forces and as sound transforming agents in mixed media pieces. In fixed media pieces, the composer additionally exploits their linearity to create space through sound de-correlation.

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No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

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I dedicate this work to my parents, Luis and Juana, and my siblings: Luis, Clementina, Elisa, Daniela, Lupita, Valeria and Javier. Thanks for all your love, support, and encouragement.

## Technical Information

The fixed media works are presented in a USB stick in their original high-resolution format: 48 kHz, 24 bit. A stereo mix version is also included for reference purposes.

### Multi-channel Works

#### 5.1 *4 Dreams*

The USB contains 6 mono files, each one labeled with the piece's title and loudspeaker location. The sound files must be addressed to the correct loudspeakers according to Diagram 1.

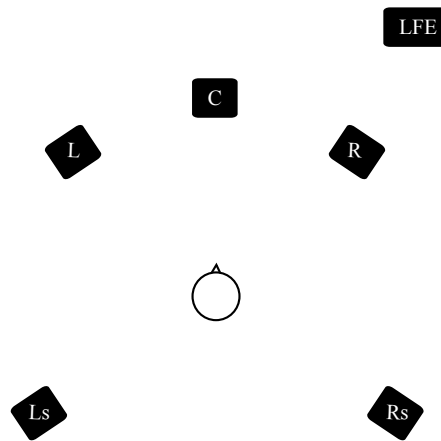


Diagram 1: 5.1 Loudspeaker set up for *4 Dreams*

### 8-channel

*Superposition of Two Opposites, Synthetic Springs, Time Paradox.* For each piece, the USB contains 8 mono files per piece, labeled with the piece's title and loudspeaker location. The sound files must be addressed to the correct loudspeakers according to Diagram 2.

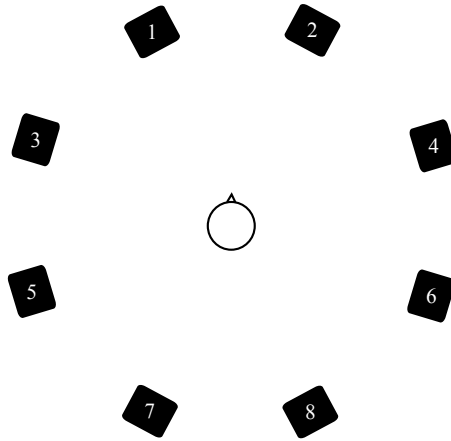


Diagram 2: Loudspeaker set up for 8-channel pieces.

### 16-channel

*The Silver Key.*

The USB contains 16 mono files, labeled with the piece's title and loudspeaker location. The sound files must be addressed to the correct loudspeakers according to Diagram 3.

The distant loudspeakers must be placed on the floor, pointing towards the venue's wall, as shown in Diagram 4. If the particular arrangement for the close loudspeakers is not possible, they should be addressed to higher loudspeakers if available.

For systems with larger number than 16 loudspeakers (such as the MANTIS system), channels 9-12 should be routed to a ring of 8 distant (diffuse) loudspeakers duplicating channels 9-10 for front and channels 11-12 for the rear channels.

### Mixed Media Works

The technical requirements are specified in the scores for *Wake Up* and *Holly*. A Max patch is provided for *Holly*, with the directions included in the patch. For *Fuzzbox*, a patch and a written score are provided. The score includes the directions and technical specifications.

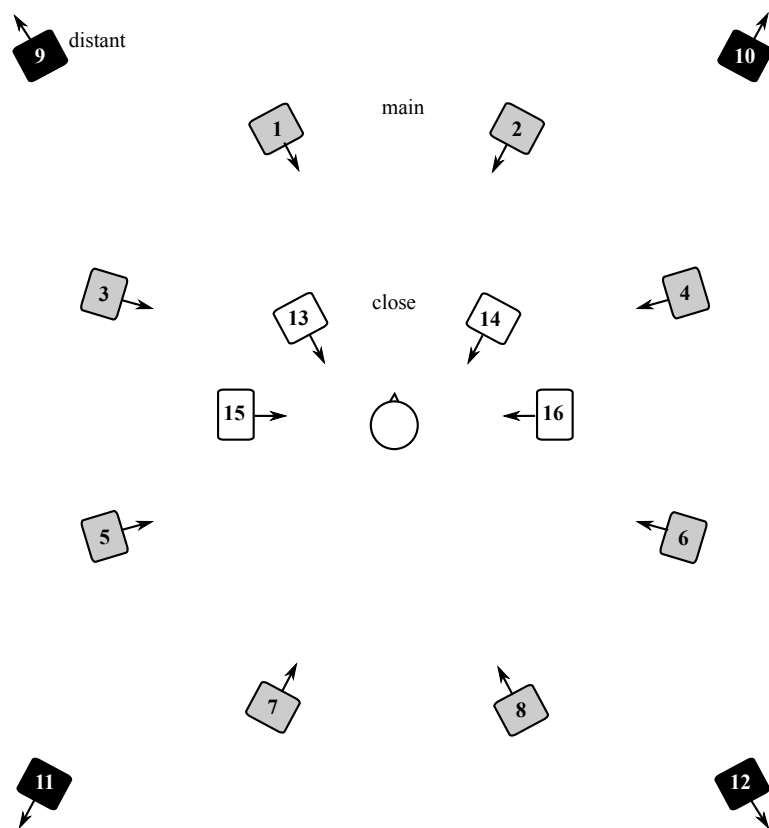


Diagram 3: Loudspeaker set up for *The Silver Key*, top view.

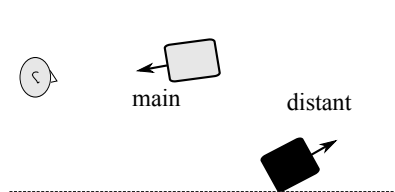


Diagram 4: Loudspeaker set up for distant (diffuse) loudspeakers (side view).



# Chapter 1

## Introduction

### 1.1 Portfolio Contents

In this portfolio, the composer explores the adaptation of state-space models to the compositional process in electroacoustic music. The works include five multi-channel fixed media pieces and three mixed media pieces. In her research, the composer investigates different ways of creating and/or transforming sound based on sonifications of a set of state-space models.

To incorporate state-space models into a music creation context, the composer developed software tools for Max and SuperCollider. The implementation details and examples of their use as a tool for electroacoustic composition are available in two published peer reviewed papers, which are included in appendix C in the commentary.

State-space models are used in control engineering to represent linear dynamic systems, in order to observe them and control them according to specific design criteria<sup>1</sup>. These models are strongly connected with the concept of physical modelling and have been used in recent years in physical modelling techniques to represent musical instruments with linear behaviours<sup>2</sup>.

The research idea and the aesthetics in the compositions have been influenced by the writings of the American composer James Tenney<sup>3</sup>, the composer's background as instrumental composer and her knowledge and formal background in control engineering. Through the pieces in the portfolio, the composer investigates ways of transforming state-space model's behaviours into sound parameters and how these behaviours influence the musical language.

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<sup>1</sup>Katsuhiko Ogata. "Modern control engineering". In: 5th ed. Prentice-Hall electrical engineering series. Instrumentation and controls series. Boston: Prentice-Hall, 2010, pp. 29–32. ISBN: 9780136156734 0136156738.

<sup>2</sup>Stefan Bilbao et al. "Modular Physical Modeling Synthesis Environments on GPU". In: *Proceedings of the International Computer Music Conference*. 2014. URL: [http://www.research.ed.ac.uk/portal/files/17485673/icmc14\\_bilbao.pdf](http://www.research.ed.ac.uk/portal/files/17485673/icmc14_bilbao.pdf) (visited on 25/02/2016).

<sup>3</sup>James Tenney. *Form in 20th Century Music*. Online document. 1969-70. URL: <http://www.plainsound.org/pdfs/Form.pdf> (visited on 10/02/2016).

## 1.2 Research Enquiry

The research questions arise as follows:

- How can state-space models be incorporated in an electroacoustic composition context?
- How does the use of these models influence the compositional methodology?
- How can the model’s intrinsic nature influence the musical language and structure?

The following specific questions arise from the aforementioned:

When using state-space models to represent linear dynamic systems,

- Which models are suitable for the creation of musically meaningful sonifications?
- How can musically meaningful sonifications of state-space models be realised?  
What are the various ways this can be done?
- How does the design and use of these sonifications affect the compositional process and music language/structure?
- How can sonification materials be integrated with other sound sources such as instruments and recorded sounds?

The answers to the research questions are explored through the different pieces in the portfolio.

## 1.3 General Description of the Commentary

The commentary is structured as follows:

Chapter two presents the research context for the use of state-space models in composition and a general overview of state-space models’ theory.

The fixed media pieces are presented in individual chapters, detailing the composition and sonification methodologies.

The mixed media pieces are grouped in chapter 5, to preserve chronological continuity in the research process.

Appendix A presents the implementation process of the software tools for Max and SuperCollider.

In general, the language to describe the musical elements in the works is based on the concepts of Denis Smalley’s “Spectromorphology”<sup>4</sup>, “Space-form and the acousmatic image”<sup>5</sup> and “The audible and the physical: a gestural typology for ‘mixed’ electronic music” (Lewis, et al)<sup>6</sup>. To describe form and structure, the analysis includes vocabulary from “Form In 20th Century Music”, by James Tenney<sup>7</sup>.

As the research is based on the use of state-space models, some vocabulary from control theory will be adapted to the music context.

---

<sup>4</sup>Denis Smalley. “Spectromorphology: explaining sound-shapes”. In: *Organised Sound* 2 (02 Aug. 1997), pp. 107–126. ISSN: 1469-8153. DOI: 10.1017/S1355771897009059. URL: <http://journals.cambridge.org/article.S1355771897009059>.

<sup>5</sup>Denis Smalley. “Space-form and the acousmatic image”. In: *Organised Sound* 12 (01 Apr. 2007), pp. 35–58. ISSN: 1469-8153. DOI: 10.1017/S1355771807001665. URL: <http://journals.cambridge.org/article.S1355771807001665>.

<sup>6</sup>Andrew Lewis and Xenia Pestova. “The audible and the physical: a gestural typology for mixed electronic music”. In: *Proceedings of the Electroacoustic Music Studies Network Conference, Stockholm*. 2012. URL: [https://www.researchgate.net/profile/Andrew\\_Lewis19/publication/276956163\\_The\\_audible\\_and\\_the\\_physical\\_a\\_gestural\\_typology\\_for\\_'mixed'\\_electronic\\_music/links/555c911408ae9963a11205ed.pdf](https://www.researchgate.net/profile/Andrew_Lewis19/publication/276956163_The_audible_and_the_physical_a_gestural_typology_for_'mixed'_electronic_music/links/555c911408ae9963a11205ed.pdf) (visited on 02/10/2016).

<sup>7</sup>James Tenney. *Form in 20th Century Music*. Online document. 1969-70. URL: <http://www.plainsound.org/pdfs/Form.pdf> (visited on 10/02/2016).

## Chapter 2

### State Space Models in Composition

#### 2.1 Language in the Pieces

According to Tenney<sup>8</sup>, form in music is influenced by the means used to create it, but most importantly by our perception. In his opinion “... it is the form of the musical experience that must be dealt with”, rather than the form of “the-thing-itself”. Aesthetic concerns regarding form are manifested in experiential models, “...conscious and unconscious assumptions about the function of a piece of music and about the nature of the musical experience itself”<sup>9</sup>. Tenney introduces new experiential models in the 20th century, including a physical processes model: “Among the formal manifestations of this model is... a kind of environment-music ... in which some physical process is not only the model but actually becomes the source or controlling agent of the sounds themselves”<sup>10</sup>.

Tenney refers to the works of the American composer Alvin Lucier as manifestation of such “physical process” model, derived somehow from physical sciences. A piece like “Music on a Long Thin Wire”, sets a precedent and influence for this research, as it involves a physical element (a wire) as a sound producing/controlling agent.

In this portfolio of works, rather than using a physical object to control sound, the composer “captures” the dynamics of several physical systems using state-space models. This way, the systems can be virtually manipulated in real-time in the computer, providing means of controlling sound based on their behaviours.

The pieces in the portfolio gradually incorporate sonifications of state-space models, falling in the “physical process model” Tenney refers to. In each piece, the composer explores timbres and behaviours for the creation of texture and gesture. The pieces also explore potential new influences in electroacoustic language caused by the model’s behaviours.

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<sup>8</sup>James Tenney. *Form in 20th Century Music*. Online document. 1969-70. URL: <http://www.plainsound.org/pdfs/Form.pdf> (visited on 10/02/2016).

<sup>9</sup>“In pre-20th century music the model often has to do with song and dance forms –the ‘colloquial language’ of folk music. In addition, there is a large body of music whose overall form suggests –explicitly or implicitly– a rhetorical model...most clearly expressed in traditional “sonata-form”, with its “exposition”, “development” and “recapitulation”. (Tenney, *Form in 20th Century Music*, p. 16)

<sup>10</sup>Tenney, *Form in 20th Century Music*, p. 18.

The following sections provide the necessary concepts to understand the use of state-space models in this portfolio.

## 2.2 Introduction to State-Space Models

The creation of the portfolio brings together two concepts present in contemporary electroacoustic music: sonification and physical modelling. Sonification is defined as “...a subtype of auditory displays that use non-speech audio to represent information”<sup>11</sup>. The latter is related to sound synthesis and “... involves a physical description of the musical instrument as the starting point of the algorithm design”<sup>12</sup>. Both concepts are briefly explained in order to establish the context for the research.

## 2.3 Sonification

Sonification is an important tool to convey information and represent/analyse data using sound. Some applications include chaos theory, bio medicine, data mining, seismology and interactive systems to mention a few<sup>13</sup>. Diverse abstract digital sound synthesis techniques such as subtractive, additive, FM, physical modelling techniques, as well as sound transformations are commonly used to represent information<sup>14</sup>. Sonification techniques investigate ways of representing data in meaningful ways and have been increasingly concerned with the aesthetic aspect of sound<sup>15</sup>.

Sound sources based on sonifications have also been adopted in music composition<sup>16,17</sup>. Parameter mapping sonification techniques (also referred to as *musicification*) have also been used for artistic creation. The latter includes sonifying a-temporal datasets (DNA for instance), time-based datasets such as solar activity, tides and meteorological records<sup>18</sup>.

Early tape works using sonifications of stochastic processes are *Diamorphoses*

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<sup>11</sup>Thomas Hermann, Andy Hunt, and John G. Neuhoff, eds. *The Sonification Handbook*. Comeniushof, Gubener Str. 47, 10243 Berlin, Germany: Logos Verlag Berlin GmbH, 2011, p. 9.

<sup>12</sup>Stefan Bilbao. *Numerical Sound Synthesis*. 2009. URL: [www.dawsonera.com](http://www.dawsonera.com) (visited on 10/02/2016), p. 8.

<sup>13</sup>Hermann, Hunt, and Neuhoff, *The Sonification Handbook*, p. 1.

<sup>14</sup>Hermann, Hunt, and Neuhoff, *The Sonification Handbook*, Chapter 9.

<sup>15</sup>Hermann, Hunt, and Neuhoff, *The Sonification Handbook*, pp. 161-164.

<sup>16</sup>Andy Schoon and Florian Dombois. “Sonification in Music”. In: *Proc. 15th International Conference on Auditory Display*. International Conference on Auditory Display. IEM, 2009, pp. 18–22.

<sup>17</sup>Thomas Hermann, Andy Hunt, and John G. Neuhoff, eds. *The Sonification Handbook*. Comeniushof, Gubener Str. 47, 10243 Berlin, Germany: Logos Verlag Berlin GmbH, 2011, pp. 150-152.

<sup>18</sup>Hermann, Hunt, and Neuhoff, *The Sonification Handbook*, p. 390.

(1957-1958)<sup>19</sup> and *Analogique B* (1959)<sup>20</sup> from the composer Iannis Xenakis. More recently, the composer Natasha Barrett has explored the use of multidimensional data’s sonification as tool for spatial sound synthesis and as an aid for electroacoustic composition<sup>21</sup>. Her piece *Topology Chamber 2* (2016), is relevant to the context of this research as it explores the use of sonification in fixed media composition with a multi-channel approach<sup>22</sup>.

Several connections can be drawn between sonification and electroacoustic music, as aesthetics in some sonifications also tend to go “towards the more abstract syntaxes found in electroacoustic music”<sup>23</sup>. Pietro Polotti discusses the “actual and potential relationships between electroacoustic music and sonification”, highlighting the fact that, in both disciplines, a sound design process is involved<sup>24</sup>.

## 2.4 Physical Modelling in Sound Synthesis

The use of mathematical models in sound synthesis started in the late 1970s and early 1980s with C. Cadoz, who proposed lumped mass-spring networks as a musical sound synthesis construct (used in CORDIS (ANIMA) systems<sup>25</sup>). Modal synthesis, proposed by J. M. Adrien and digital waveguides, proposed by Julius O. Smith, appeared in the early 1990’s<sup>26</sup>. Modal synthesis (used in Modalys<sup>27</sup>) and digital waveguides (CSound<sup>28</sup>), to mention some examples, involve a physical description of the instrument as a starting point for design, based on a Digital Signal Processing framework and a frequency domain orientation<sup>29</sup>.

In more recent years, research in this area has been concerned with modelling musical instruments using direct simulations approaches. This implies, in general, the implementation of numerical solutions of a set of differential equations describing the physics of the instrument. These techniques are referred to as finite

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<sup>19</sup>Iannis Xenakis. *Formalized Music: Thought and Mathematics in Composition*. Ed. by Sharon Kanach. Iannis Xenakis 6. Hillsdale NY: Pendragon Press, 1992, p. 48.

<sup>20</sup>Xenakis, *Formalized Music: Thought and Mathematics in Composition*, p. 79.

<sup>21</sup>Natasha Barrett. “Interactive Spatial Sonification of Multidimensional Data for Composition and Auditory Display”. In: *Computer Music Journal* (2016). URL: [http://www.mitpressjournals.org/doi/abs/10.1162/COMJ\\_a\\_00358](http://www.mitpressjournals.org/doi/abs/10.1162/COMJ_a_00358) (visited on 11/07/2016).

<sup>22</sup>Natasha Barrett. *Electronic Music*. URL: <http://www.natashabarrett.org/acousmatic.html> (visited on 11/07/2016).

<sup>23</sup>As in WebMelody from Barra, et, al. (Hermann, Hunt, and Neuhoff, *The Sonification Handbook*, p. 477)

<sup>24</sup>Pietro Polotti. “Closing the loop of sonification and electroacoustic music practices through gesture and embodied interaction”. en. In: *The New Soundtrack* 4.2 (Sept. 2014), pp. 165–180. ISSN: 2042-8855, 2042-8863. DOI: 10.3366/sound.2014.0061. URL: <http://www.euppublishing.com/doi/abs/10.3366/sound.2014.0061> (visited on 07/25/2016).

<sup>25</sup>Bilbao, *Numerical Sound Synthesis*, p. 9.

<sup>26</sup>As cited in (Bilbao, *Numerical Sound Synthesis*, p. 2).

<sup>27</sup>Modalys. URL: <http://forumnet.ircam.fr/product/modalys-en/> (visited on 07/25/2016).

<sup>28</sup>Home | Csound Community. URL: <http://csound.github.io/> (visited on 07/25/2016).

<sup>29</sup>Bilbao, *Numerical Sound Synthesis*, pp. 10-16.

difference time domain, FDTD methods, where “sometimes, the frequency domain is not involved at all...”<sup>30</sup>.

The application of numerical solutions in sound synthesis include the case of a plucked strings, piano string vibrations, percussion instruments, stiff vibrating bars and plates<sup>31</sup>. Nonlinear musical instruments such strings and plates have been studied in-depth by Stefan Bilbao<sup>32</sup>.

## 2.5 Research Approach: State-Space Models, Sonification and Sound Synthesis

In her portfolio of works, the composer investigates the sonifications of state-space models to create or transform sound. As opposed to the common practice in physical modelling, the models in this portfolio do not intend to represent musical instruments. The composer rather represents dynamic linear systems which are regarded as behaviours of physical systems to be sonified using abstract digital sound synthesis.

The composer’s sonification of these models can be seen as a combination of physical modelling techniques using Finite Difference Time Domain methods (FDTD) and sonifications using abstract digital synthesis. The former can produce harmonically rich sound and reproduce instrument timbres accurately, but does not yet allow real-time interactions due to computational expenses. The latter, provides different ways of generating sound by using oscillators or wavetables allowing real-time modulations. By combining physical modelling techniques and abstract sound synthesis, the research takes advantage of the two approaches to leverage processing power.

Figure 2.1 illustrates the intersections and differences between physical modelling techniques (FDTD), state-space models and sonification using abstract digital sound synthesis techniques.

The element in common between FDTD physical modelling techniques and the sonifications in this research is the use of state-space models. However, in FDTD physical modelling techniques the models’ outputs constitute already the audio signal, whereas in the composer’s research the outputs are regarded as modulating/control signals for abstract digital sound synthesis. That is to say, the states are real-time generated data to be sonified.

The models’ outputs could also be produced at audio rates, in such case no

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<sup>30</sup>Bilbao, *Numerical Sound Synthesis*, p. 16.

<sup>31</sup>As cited in Bilbao, *Numerical Sound Synthesis*, p. 17.

<sup>32</sup>Stefan Bilbao et al. “Modular Physical Modeling Synthesis Environments on GPU”. In: *Proceedings of the International Computer Music Conference*. 2014. URL: <http://www.research.ed.ac.uk/portal/files/17485673/icmc14.bilbao.pdf> (visited on 25/02/2016).

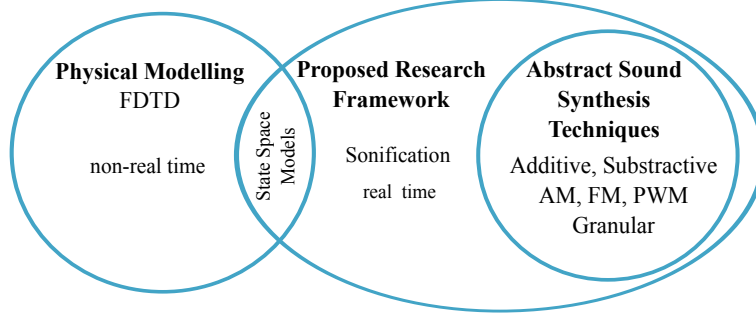


Figure 2.1: Intersections and differences between the proposed research framework, FDTD physical modelling and abstract digital sound synthesis techniques.

sonification would be necessary. This last option is not explored in the portfolio as the computational expense is a limitation for real-time interactions at audio sample rates. In addition, if sonification is not used, each model becomes a unique object which would define very specific sonic characteristics. In order to have variety in sound sources, diverse models need to be designed and implemented. Such tasks would involve further modelling and algorithm design for more complex systems, falling out of the scope of a PhD focused on music. The research rather focuses on various sonification possibilities for a set of models so the composer can concentrate on the compositional process while still making use of state-space models.

## 2.6 State-Space Models Basic Concepts

This section provides an brief introduction to the concept of state-space models.

### 2.6.1 State-Space Definition

State-space models are used to represent linear dynamical physical system's behaviour in a compact way. Provided the system is linear and time invariant, it is possible to formulate a matrix equation that describes the system's behaviour. The matrix representation is called the state-space of a continuous system's dynamics and can be written as follows:

$$\begin{aligned}\dot{x}(t) &= Ax(t) + Bu(t) \\ y(t) &= Cx(t) + Du(t)\end{aligned}\tag{2.1}$$

Where  $x(t)$  represents the state vector and the dot indicates the derivative operation. A and B are constant matrixes defining the very specific nature of each system. Matrix C determines the model's outputs and D is a feedback matrix



connecting the output to the input<sup>33</sup>. The variable  $u(t)$  is used to represent the system's input vector. The letter  $t$  implies that the matrix equation lays in the time domain.

In order to simplify the understanding of state-space models for this research, each model can be seen as a “black box” which receives a set of inputs and provides a set of outputs called the “state vector”. The box can be thought of as containing the matrixes representing the system and the rules (matrix equations) describing the behaviour.

This simplification is shown in Figure 2.2, where the inputs are represented with the letter  $u$  and the states with the letter  $x$ . The most relevant concept to understand is that a system's state-space is the set of all states of the system. In other words, the state-space is equivalent to having the collection of values of all the variables describing the system over time. Usually these times are defined by the sampling period. For instance, if the sampling period is fixed to one second, the states of the system will be calculated every second, meaning that all the variables describing the system's behaviour will be updated every second.

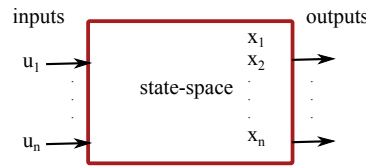


Figure 2.2: State-Space model simplified representation.

### 2.6.2 Transient State and Steady State

In order to better understand state-space models' behaviours in a music creation context, it is important to define two concepts: transient state and steady state. A state-space model is considered in its transient state when one or more inputs change from one initial value to a final value, producing changes in the systems' states. After a certain amount of time, if the input remains unchanged, the system reaches the steady state and the systems' states settle, remaining unchanged over time<sup>34</sup>. For instance, a mass-spring-damper system can be used to illustrate the aforementioned concepts as its state-space model is widely used in the portfolio compositions. The mass-spring-damper system is depicted in Fig. 2.3a.

Following the idea of the “black box” to represent this system, the input is the force applied to the mass. The state-space for this model consists of the mass

<sup>33</sup>Katsuhiko Ogata. “Modern control engineering”. In: 5th ed. Prentice-Hall electrical engineering series. Instrumentation and controls series. Boston: Prentice-Hall, 2010, pp. 29–32. ISBN: 9780136156734 0136156738.

<sup>34</sup>For a formal definition see Ogata, “Modern control engineering”, pp. 159-160.

position (displacement) and velocity<sup>35</sup>. The outputs in the box are the system's states, mass position and velocity, as shown in Figure

2.3b.

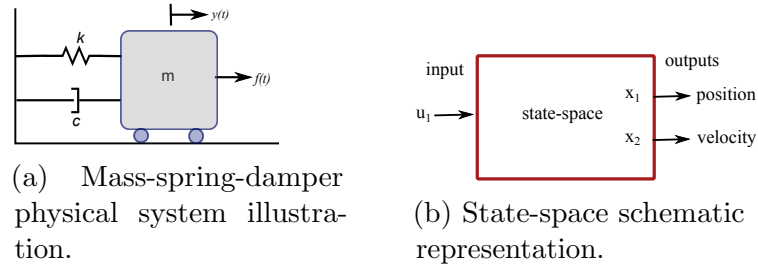


Figure 2.3: Spring-mass-damper system representations. In the physical system illustration  $m$  is the mass,  $k$  is the spring's constant,  $c$  is the damper's damping coefficient,  $f(t)$  represents an applied force and  $y(t)$  represents the mass' position

Considering the system is still, if a force is applied to the mass<sup>36</sup>, it will move in the direction of the force bringing the system to the transient state. The reader can think of this as if virtually pushing the mass on wheels depicted in figure 2.4 towards the right. This would bring the mass to a bouncing movement due to the spring's action. The transient state consists of exponential decaying oscillatory behaviour of the position and velocity. This fact is shown in Figure 2.4, where the transient state occurs from 0 to approximately 45 seconds. The oscillations eventually stop if no further force is applied and the system can be considered in its steady state. Steady state in this system means that the mass stops moving.

It is important to mention that, in general, if the input keeps changing the system will be kept in its transient state without settling. Additionally, steady states vary depending on the nature of the system, with the only condition that the settled behaviour remains unchanged over time. Both transient and steady state are taken into account when designing sonifications. Transient states are in general related to more energy in sound or more harmonic content. Steady states represent arrival points in terms of sound evolution once the input stops changing. These concepts will be associated to music parameters in various ways in the pieces.

<sup>35</sup>Robert L. Williams and Douglas A. Lawrence. *Linear State Space Control Systems*. Hoboken NJ: John Wiley and Sons, Feb. 2007, p. 7.

<sup>36</sup>For this particular example, an input going from 0 to 0.2 was applied in simulation with  $m=1$ ,  $k=1$ ,  $c=0.2$ .

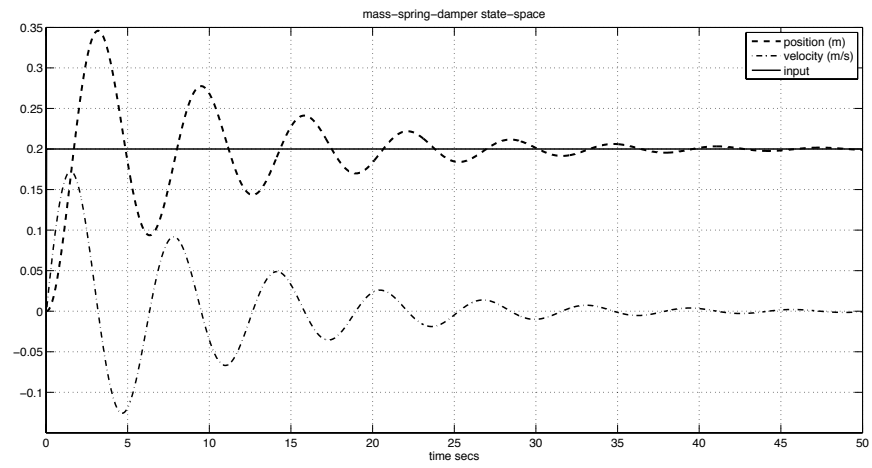


Figure 2.4: Mass-spring-damper response simulated in MatLab, showing transient and steady state for a step input.

## Chapter 3

### 4 *Dreams*

4 *Dreams* is the first piece and experiment to incorporate state-space models sonifications in the portfolio of compositions. The work takes sounds from sonifications of a DC motor model and explores the integrations with recorded concrete objects. The piece explores at the same time the concepts of long and short resonances, motion and movement in a 5.1 format. In a metaphoric sense the piece is inspired by the idea of four episodes of a daydream.

#### 3.1 The DC motor

A DC motor is a device that converts electrical energy into mechanical energy and is present in a variety of moving electronic devices<sup>37</sup>. The motor model requires an input to start movement. For this piece the input means a desired velocity. The states in the model are the motor's velocity and the current (electrical energy) flowing in its armature. For every input the model reaches the desired velocity with a smoothing effect. Figure 3.1 shows the state-space of the DC motor where the smoothing effect is observed for a varying input.

This model was chosen because its behaviour is well known by the composer, so rather than modelling an unknown system she could focus on sonification experiments.

#### 3.2 Sound Sources

##### 3.2.1 Recordings

With the intention of having contrasting sound typologies, the composer recorded several objects in the studio: an oud, a set of crotales, a plastic bracelet, voice, and a cereal box. Some of the objects provide pitched, harmonic sounds, and some

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<sup>37</sup>See for instance: (Electrical4u. *Working or Operating Principle of DC Motor* | *Electrical4u*. URL: <http://www.electrical4u.com/working-or-operating-principle-of-dc-motor/> [visited on 03/23/2016]).

For more formal definitions see (Bill Messner and Dawn Tilbury. *Control Tutorials for MATLAB and Simulink - Motor Speed: System Modeling*. URL: <http://ctms.engin.umich.edu/CTMS/index.php?example=MotorSpeed&section=SystemModeling> [visited on 07/20/2016]) and (Farid Golnaraghi and Benjamin C Kuo. *Authomatic Control Systems*. 9th. John Wiley and Sons Inc, 2010, p. 199)

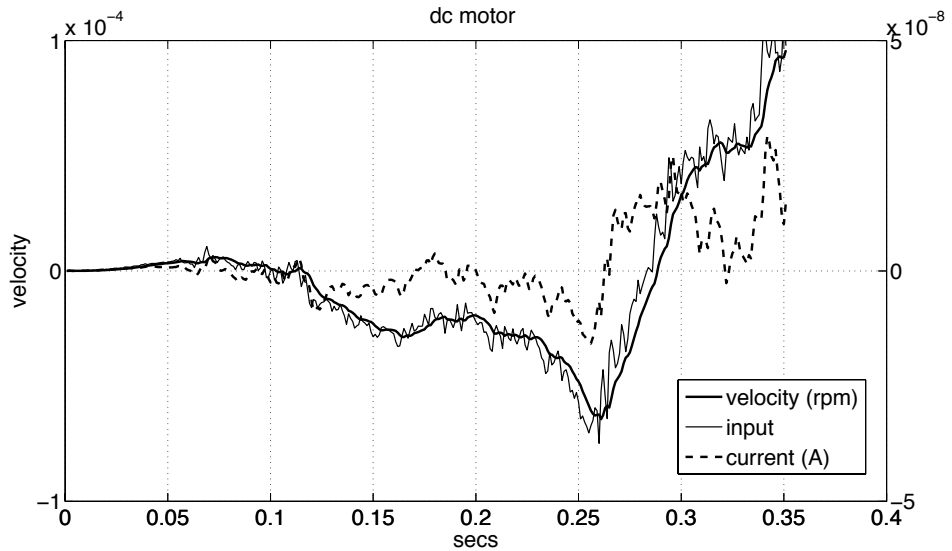


Figure 3.1: State-space of a DC motor simulated in Matlab, with a noise signal as input.

others are “noisy-like” and inharmonic.

The composer recorded an oud in the studio, with the intention of capturing different melodic fragments, arpeggios and scales played by the performer. A set of single strikes of thirteen crotales of different pitches was also recorded. Each crotale was recorded individually, striking it once and letting the sound decay naturally, as the composer was interested in the resonance of these instruments.

A female voice saying the latin phrase “ergo sum” was also recorded, as well as a male voice asking random questions.

The composer intended to define the sections in the piece through the predominance of specific concrete objects; a behavioural section using the bracelet, a gravitational section using crotales, an immersive space with vocal sounds and a tonal-pitch section using the oud.

### 3.2.2 Synthetic Sources

#### Sonification Parameters

The composer created three stereo synthesisers in SuperCollider to represent the states of the DC motor. Table 3.1 shows the synthesisers and the music parameters modulated using the model. The synthesisers were chosen so the composer could experiment with noise, resonance and decay times as counterparts for the recorded materials. Additionally, the composer used a *Streson* synthesiser<sup>38</sup> to enhance texture.

<sup>38</sup> “String resonance filter”. (*Streson*. URL: <http://doc.sccode.org/Classes/Streson.html> [visited on 07/05/2016])

Sonification Pairs	
Synthesiser	Music Parameter
AM-white noise	resonance frequency, pulse frequency
wave-table synthesiser	playback rate
resonator bank	frequency, resonance frequency

Table 3.1: Sonification pairs used for *4 Dreams*.

### 3.3 Compositional Methodology

Although the model provides two states, the composer only used the model’s velocity to prioritise learning sonification strategies.

The composer created an input sequence for the model in MatLab and ran a simulation to calculate only 500 samples to produce a fixed data set with velocities to be sonified.

The data set was imported in SuperCollider, and used to modulate the synthesisers presented in Table 3.1. The composer’s intention was to create sound objects with different typologies but based on the same data set.

The modulation of the synthesisers was achieved by programming several sequences where the values in the data set were mapped into the parameters shown in Table 3.1. Sonification experiments included trying different scaling factors for the data, different parameters to be modulated, and testing different modulation rates (meaning how fast the sequences are run). The composer recorded the sonic outcome of the experiments, and selected materials she found suitable to be integrated with the recorded materials. After selection, the rest of the composition was completed using the DAW Reaper.

### 3.4 Spatialisation

For the 5.1 format, some sonifications were spatialised using the built-in Surround Pan tool in Logic and then exported to Reaper. However, most of the spatialisation was based on stereo pairs: two stereo pairs for the front channels (shown in red dotted lines), a stereo pair for the rear (continuous red line), a right stereo pair (front and rear) and a left stereo pair (shown in blue). The mid front was sometimes regarded as a monophonic central sound.

All channels contributed to the LFE loadspeaker. Stereo sounds and/or sonifications were deliberately placed in specific pairs as part of the compositional process.

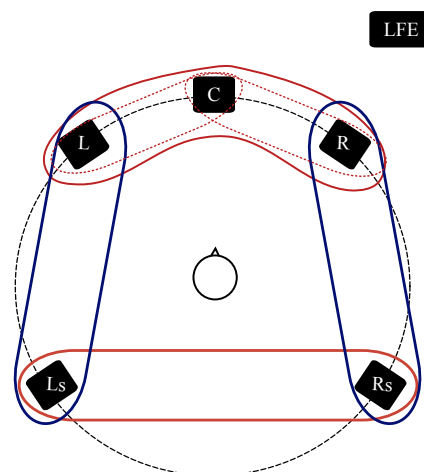


Figure 3.2: *4 Dreams* 5.1 loudspeaker setup.

### 3.5 Terminology

The composer uses some concepts introduced by James Tenney to refer to some structural elements in the portfolio. In his article “Form in 20th Century Music”<sup>39</sup>, he presents four hierarchical levels: the sound elements, clangs<sup>40</sup>, sequences<sup>41</sup> and higher levels such as sections/movements<sup>42</sup>.

Sound elements in the pieces correspond to the first hierarchical level. The particular combination of sound elements constitute the second level: clangs. The combination of clangs determine the third level: sequences. It is this third level which is relevant for the form/structure analysis in the portfolio, as well as the higher levels. Lower levels will be described using the terminology from Denis Smalley.

### 3.6 Structure

*4 Dreams* is divided in four main sections, each one corresponds to a dream episode. The sequences comprising each section are “metamorphic”<sup>43</sup>, meaning that there is partial similarity between the sequences. This implies that lower levels also share a certain degree of similarity, for instance, in timbre, behaviour or frequency range.

<sup>39</sup>James Tenney. *Form in 20th Century Music*. Online document. 1969-70. URL: <http://www.plainsound.org/pdfs/Form.pdf> (visited on 10/02/2016).

<sup>40</sup>“Meaning any collection of sound-elements perceived as a primary aural gestalt” (Tenney, *Form in 20th Century Music*, p. 6).

<sup>41</sup>“A series of several clangs perceived as a larger, if looser, gestalt” (Tenney, *Form in 20th Century Music*, p. 8).

<sup>42</sup>Tenney, *Form in 20th Century Music*, p. 10.

<sup>43</sup>Sequences where “...one clang is, in fact, related to another by some process of shape-variation” (Tenney, *Form in 20th Century Music*, p. 8).

Figure 3.3 shows the structure in the piece. The letter “s” indicates sonification materials. In each section sonifications were used to define spatial characteristics and behaviours. In section 1, sonifications define a behavioural space<sup>44</sup>; in section 2 they create diagonal forces in a gravitational space; in section 3 they define an immersive space evoking a cave, and in section 4 they contribute to the tonal-pitch space.

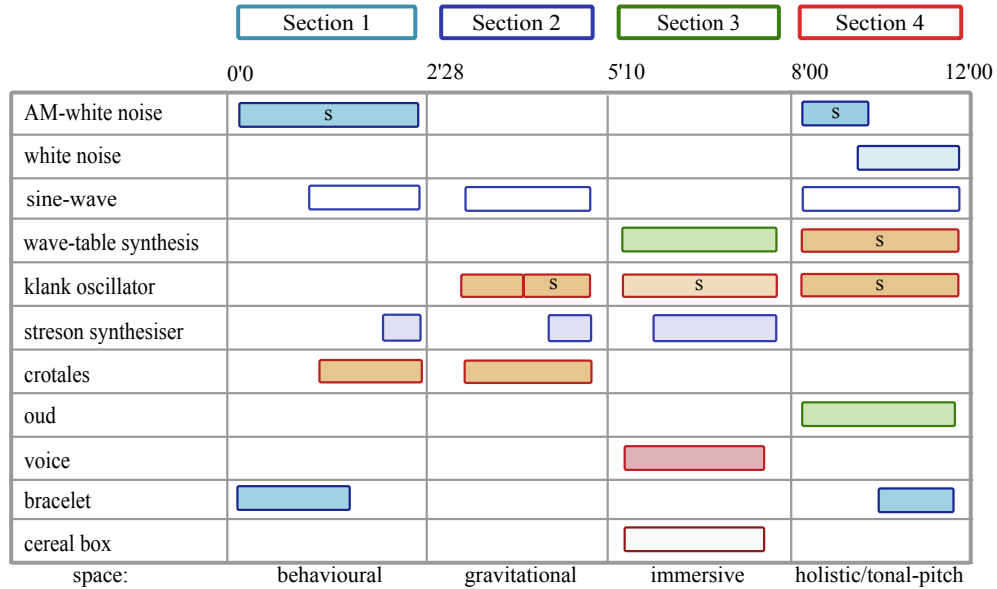


Figure 3.3: 4 Dreams - structure.

Regarding higher levels, the piece’s structure can be identified as metamorphic<sup>45</sup>. The morphological relationships between sections can be observed in Figure 3.3, where colours represent sounds with similar identifiably timbre qualities and/or behaviours. Sections relate to each other by sharing specific timbres or behaviours or by re-defining the role of elements previously introduced.

A more detailed description of each section is presented in the following paragraphs.

### Section 1 (0'0-2'26)

The composer creates behaviours and textures based on noise, harmonic and inharmonic sounds.

Sonifications are based on white noise, modulated in amplitude with a saw-wave. The velocity in the model was mapped to modulate the frequency in the saw-wave. At the same time a resonant filter (modulated by the model) was

<sup>44</sup>A zone of perspectival space produced by the interaction of sounds which, spectromorphologically and texturally, indicate collaborative, group identity (Smalley, “Space-form and the acousmatic image”, p. 55)

<sup>45</sup>When there are perceptible morphological relations of various kinds in a piece (as in most music), the structure may be called metamorphic (Tenney, *Form in 20th Century Music*, p. 13).



applied to the noise to create timbre variations. These modulations translate into a perceived pulse-like behaviour for low velocities (0'04) and more textural material for higher speeds (0'16).

Sonifications were used to create a textural flocking motion<sup>46</sup>. The texture was reinforced through “bracelet” sounds, as they seemed to share morphological characteristics. When agitated, the bracelet produces pulse-like noises that blend with pulse texture created with the sonification (0'36).

The composer uses crotales as a contrast in timbre (1'15). Crotale objects enhance movement and thicken the texture already created by the noise and bracelet. Several low frequency synthetic objects are used to create stronger gestures.

## **Section 2 (2'26-5'27)**

The composer combines long resonances from recorded crotales with artificially created crotale-like synthetic objects of various time decays and frequencies (3'07).

The composer created arpeggio-like objects (3'20) by triggering crotale-like sounds in a sequence where the triggering frequency was taken from the model's data set. Pitch-shift transformations were applied in Reaper to incorporate glissandi.

The composer shortened the decay time in the resonators, and triggered them at higher rates to produce frog-like objects (4'08).

The section defines a gravitational space, where the planes are determined by the spectrum of recorded and synthetic objects and their resonance lengths. Diagonal forces<sup>47</sup> are created by the frog-like and arpeggio-like objects that create illusions of descending or ascending motion. Noise-based sonification textures and low-frequency sine waves add additional planes and intermittent diagonal forces.

To create spatial contrast, the composer combines static objects in fixed channels with moving objects placed in two or more channel pairs simultaneously (4'38).

## **Section 3 (5'27-8'17)**

This section incorporates sonifications based on a resonator bank, and on the “wave-table synth”.

In the resonator bank, 12 resonators take a new frequency from the model's data set, in a programmed sequence. The “wave-table synth” was used to transform

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<sup>46</sup>Flocking describes the loose but collective motion of micro- or small object elements whose activity and changes in density need to be considered as a whole, as if moving in a flock (Smalley, “Spectromorphology: explaining sound-shapes”, p. 117)

<sup>47</sup>The motion of spectral energy towards or away from a spectral region which acts as a plane (Smalley, “Space-form and the acousmatic image”, p. 55).

oud sounds, modifying the playback rate according to the model’s data set.

The composer uses the long resonances from the bank to evoke a cave-like immersive distal space<sup>48</sup> space (6’06).

Oud, “frog-like” sounds resembling drops, and voice, are regarded as objects inhabiting the cave. They are presented to the listener in the proximate space<sup>49</sup> to enhance spatial depth.

The voice is first an abstract object (6’36) used as onset for textures, and slowly becomes more articulated to present the phrase “ergo sum” (7’36), stating “therefore I am”. This is considered the piece’s center.

To close the section, the composer uses a cereal box object to suggest the idea of collapse and falling in the close space, and to increase tension by incorporating an ascending glissandi motion (7’44).

#### **Section 4 (8’17-12’16)**

The composer explores texture and defines a tonal pitch immersive space<sup>50</sup>.

Sound materials include sonifications based on the “wave-tables synth”. These are used to create melodic contours and texture based on a crotale note (9’05).

These contours are superimposed to oud objects also presenting melodic qualities to create or enhance texture (10’07). The composer uses sonifications based on the bank oscillator to reinforce spatial depth and thicken the texture.

The above elements also create a holistic immersive space, where some objects appear to be closer and others more distant, while the listener is surrounded by enveloping, vectorial sounds.

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<sup>48</sup>The area of perspectival space farthest from the listener’s vantage point in a particular listening context (Smalley, “Space-form and the acousmatic image”, p. 55).

<sup>49</sup>The area of perspectival space closest to the listener’s vantage point in a particular listening context (Smalley, “Space-form and the acousmatic image”, p. 56)

<sup>50</sup>The subdivision of spectral space into incremental steps that are deployed in intervallic combinations –a sub-category of spectral space (Smalley, “Space-form and the acousmatic image”, p. 56).

## Chapter 4

### *Superposition of Two Opposites*

This 8-channel piece was originally inspired by an image representing a superposition of two opposite “twisting” light modes<sup>51</sup>. The image depicts several circular arrays of coloured lights floating in a dark background.

As a metaphor for the superposition of light and darkness, the piece explores sonifications of an abstract model having two oscillating states and its superpositions with concrete objects.

The concept of opposites is explored by contrasting fast gestures with slow moving textures, harmonic with inharmonic sounds and closer with more distant objects.

#### 4.1 Sound Sources

##### 4.1.1 Recordings

The objects recorded for this piece are the following: vocal sustained pitches, cello and viola glissandi; sets of chords, harmonics and single notes from an electric bass-guitar; and a metallic necklace shaken, rubbed against the palm and dropped into a jewellery box. This collection provides contrasting sound typologies to create the idea of opposites.

##### 4.1.2 Synthetic Materials and Sonification

The composer chose a *GrainFM*<sup>52</sup> synthesiser and wave-table synthesis based on an audio buffer for sonification purposes, both from SuperCollider. The parameters modulated by the abstract model are shown in table 4.1.

The *GrainFM* synthesiser was chosen because the composer found the sound qualities engaging, as it allows “granular synthesis with frequency modulated sine tones”. The wave-table oscillator was chosen with the purpose of transforming sounds.

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<sup>51</sup>From the Quantum Information and Foundations of Physics –Zeilinger Group. See: (Universität Wien. *Physik & Musik: Superposition of two opposite “twisting” light modes*), (Gruppe Anton Zeilinger). URL: <http://call4sounds.neuesatelier.org/2013/08/superposition-of-two-opposite-twisting.html> [visited on 07/20/2016]).

<sup>52</sup>*GrainFM*. URL: <http://doc.sccode.org/Classes/GrainFM.html> (visited on 07/05/2016).

Sonification Pairs	
Synthesiser	Parameter
<i>GrainFM</i>	rate, modulating frequencies
wave-table synthesis	playback rate, buffer read start point

Table 4.1: Sonification pairs used for *Superposition of Two Opposites*.

## 4.2 Compositional Methodology

The investigation of sonification possibilities was very important in the compositional process. Rather than choosing a physical system, the composer designed an abstract model. This means that the numbers in the matrixes are not related to any physical system and the states only provide two different oscillating behaviours. An example of the behaviour of this model is shown in Figure 4.1, where the model’s input is a short sound file (0.5 seconds of recorded fire).

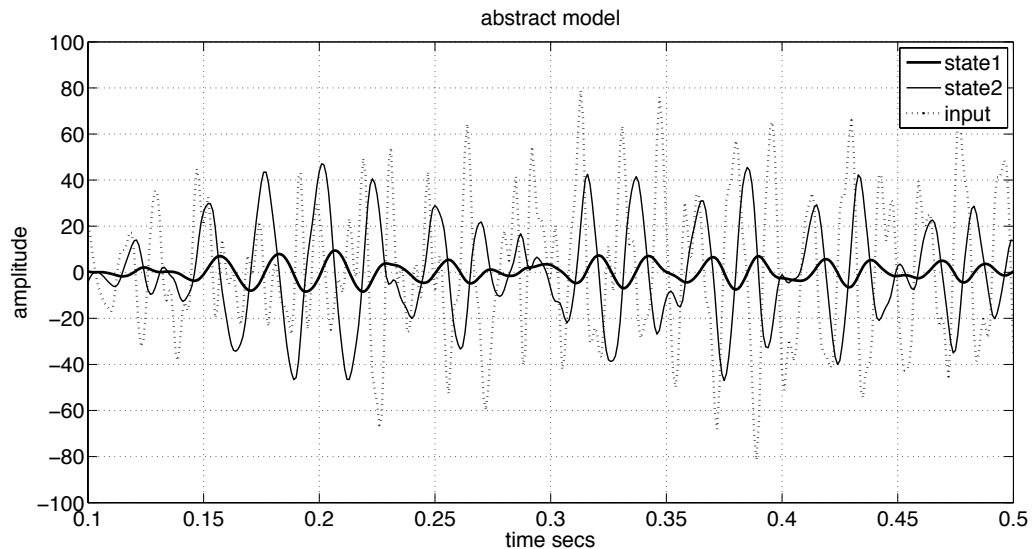


Figure 4.1: Abstract model’s state-space simulated in MatLab.

The composer ran several simulations in MatLab using different inputs for the model. In all cases, the model was kept in its transient state to produce oscillating behaviours. The model’s states corresponding to each simulation were imported as data sets in SuperCollider for their sonification.

In practice, three *GrainFM* synthesisers with slightly different carriers were mixed to produce rich sounds. The composer mapped the model’s *state1* to the rate at which grains were generated and *state2* to the modulating frequency of two of the three oscillators. Each state was independently scaled according to the parameter they were modulating and affected the three synthesisers simultaneously. These mappings are reflected in changes in timbre and/or undulating behaviours in sound.

The composer performed several experiments, trying different reading rates and various data sets. The sequences were sometimes interrupted to freeze specific timbres that the composer found sonically engaging.

The wave-table oscillator was mostly used to transform the necklace recordings. For this sonification the composer mapped *state1* to the file's playback rate and *state2* to the reading starting point in the audio buffer. This results in changes in timbre, varying lengths of sounds and undulating perceived motions.

The composer created a stereo but also an 8-channel version of the wave-table sonification, to be able to create spatial textures. Several experiments similar to the ones for the FM oscillator were also performed.

The composer selected various fragments that she found suitable to create contrast to the recorded sources. The rest of the composition was performed in Reaper and consisted of superimposing these sonifications with recorded objects. Some minor alterations, using filtering or very subtle time stretching, were sometimes applied to the sonification materials.

### 4.3 Spatialisation

The spatialisation was based on four stereo channel-pairs (shown in red dotted lines in Figure 4.2) and a pair of 4-channel groups (front and rear), shown in red continuous lines. The composer grouped channels this way to have stronger back and front images (3'38). She also located materials in specific channel pairs to have more localised sound sources (2'45) and in some sections, they were duplicated to fit the 4-channel groups (0'52). Sonifications based on wave-table synthesis were already fitting the ring of 8 and were used to create enveloping textures.

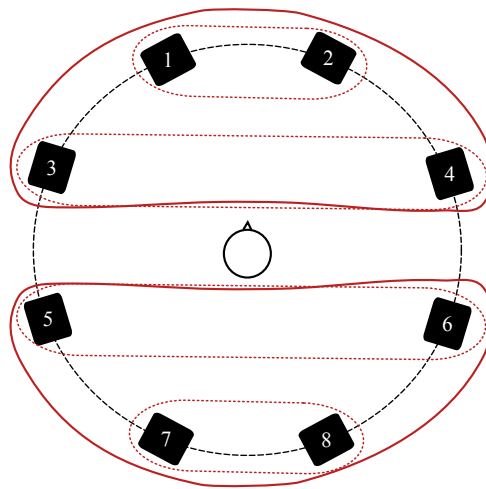


Figure 4.2: Spatialisation pairs for *Superposition of Two Opposites*.

## 4.4 Structure

The piece can be divided in three sections. Figure 4.3 shows the structure and sound materials used per section. It can be observed that sonifications based on the “*GrainFM* synth” are present through the whole piece, providing cohesion in timbre and behaviour.

Sonifications based on wave-table synthesis are also present in all sections although in minor proportion. This materials present morphological similarities with the necklace object (they have similar colours in Figure 4.3) and also provide cohesion regarding behaviours.

The piece’s structure can be defined as metamorphic. Its sections keep morphological similarities as they all share similar sound sources. Additionally, the sonification materials contribute to cohesion as they all represent the model’s behaviour.

However, the combination of sonifications and concrete objects define particular morphological characteristics for each section: string glissandi and necklace for the first section, voice for the second and bass-guitar for the third.

Regarding space, the piece can be thought of as having spatial simultaneity in all sections, encompassing the listener in a circumspace<sup>53</sup> created by the presence of close, distant, moving and static objects.
















	Section 1	Section 2	Section 3
	0'0	3'55	5'34
Wave-table			
GrainFM			
Voice			
Strings			
Bass-Guitar			
Necklace			

Figure 4.3: Structure and sound materials for *Superposition of Two Opposites*.

More details for the sections in the piece are provided in the following paragraphs.

### Section 1 (0'0-3'55)

The composer composed this section by superposing short granulated-like necklace textural sounds and slow glissandi objects.

The piece opens with a gestural driven introduction based on stereo and 8-channel textures made of necklace sounds (wave-table sonifications). The composer

<sup>53</sup>In perspectival space –the extension of prospective and panoramic space so that sound can move around the listener and through or across egocentric space (Smalley, “Space-form and the acousmatic image”, p. 55).

uses these short sounds, scattered over 8 channels to create throw/flip motion, accumulation and dissipation effects.

The composer superposed long pitched sounds and glissandi objects to create slowly ascending/descending textures. The slow motion creates contrast with the enveloping texture made of short, moving necklace objects (1'18).

As the section evolves, motion gradually decreases, presenting more localised necklace objects with larger durations and in a closer space (3'33). To increase tension the composer introduces glissandi objects that reach higher pitches while slowing down their ascending motion (3'46). These objects are abruptly interrupted by a short gesture, bringing the section to an end.

## **Section 2 (3'58-5'34)**

This section is texture-carried and made of superpositions of *GrainFM* materials, bass guitar and voice.

The section opens with a quiet soft texture created with time stretched 8-channel (wave-table) sonifications. The composer enhances this texture using soft high-frequency oscillators of a similar frequency range as to the time-stretched 8-channel object (4'00).

Texture incrementally thickens with a superposition of layers made of time-stretched voice objects and *GrainFM* objects, that slowly widen the spectral content. Gestures based on necklace objects and bass guitar chords are used as onsets for motion (4'48).

A superposition of undulating *GrainFM* and voice objects with diverse transpositions creates a layered motion texture of convergent/divergent characteristics.

The composer creates opposites by contrasting vocal static layers with undulating *GrainFM* objects. The layers gradually fade out to finalise the section.

## **Section 3 (5'34-8'26)**

The section continues in a textural-carried way and consists of superpositions of bass-guitar, *GrainFM* and necklace objects. It departs from a tonal-pitch space and slowly incorporates inharmonic objects.

The composer creates a layered texture by adding transposed arpeggios, long notes from the bass guitar and *GrainFM* objects. The latter creates a flocking motion illusion whereas the long notes provide the spectral foundation. Necklace gestural objects emerge as a contrast for the thickened texture (6'34) and represent a return to the beginning of the piece. The gestures become faster and shorter as the layers in the texture slowly dissolve (8'07). The section closes with a granular 8-channel texture based on the necklace object and wave-table sonifications.

A sequence of harmonics from the bass-guitar emerge amongst this texture bringing the piece to an end.

## **4.5 Early Conclusions**

After experimenting with sonification techniques for the creation of the first two fixed media pieces, the composer thought that a better way of integrating the models in the compositional process would be directly implementing them in music programming languages. This would allow experimenting with the models and their sonifications in real-time, rather than being restricted to data sets.

The composer also became aware of certain organicity in the products of the sonifications. This is a consequence of using real or abstract physical systems which are represented through the models.



## Chapter 5

### State-Space Models in Mixed Media Pieces

This chapter presents three mixed media pieces where the composer explores ways of integrating state-space models and sonification materials with specific sets of instruments. The models are used as instruments and as sound transforming agents.

For *Wake Up*, the composer implemented two real-time state-space models in Max: a DC motor and an inverted pendulum.

For *Holly*, the composer implemented a real-time spring-mass-damper model in SuperCollider. In both pieces, sonifications were used to compose a tape part.

For *Fuzzbox* the real-time inverted pendulum model in Max is used as a live sound transforming agent.

#### 5.1 *Wake Up*

In this piece the composer uses the inverted pendulum model as a real-time sound transformation agent to explore combinations between string sounds and sonification materials. These sources are integrated in the piece through timbral superpositions and the creation of textures based on granulated sounds. The composer created an evolving synthetic part, sometimes having a distinctive morphology due to the influence of model's behaviour and other times fusing with the string duo.

The combination of synthetic and instrumental materials are inspired by Henri Pousseur's "Rimes pour différentes sources son ores", where he explores timbral relations between instruments and tape<sup>54</sup>.

##### 5.1.1 Real-Time State-Space Models

Max was initially chosen as it facilitated the creation of a GUI<sup>55</sup> and interface for the composer. The composer felt the implementation of state-space models could

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<sup>54</sup>David Ernst. *The Evolution of Electronic Music*. 8666 Third Avenue, New York. N. Y. 10022: Schirmer Books, 1977, p. 125.

<sup>55</sup>A visual way of interacting with a computer using items such as windows, icons and menus, used by most modern operating systems. (Oxford-Dictionaries. *Graphical User Interface*. URL: [http://www.oxforddictionaries.com/definition/english/graphical-user-interface#graphical-user-interface\\_\\_2](http://www.oxforddictionaries.com/definition/english/graphical-user-interface#graphical-user-interface__2) [visited on 04/07/2016]).

be straight forward in Max. This implementation includes an OSC<sup>56</sup> send capability as the composer preferred designing some of the sonifications in SuperCollider. In other words, Max was used sometimes as the GUI/interface for SuperCollider.

Figure 5.1 shows the implementation in Max 6. The inputs for each model can be directly entered in the number boxes, increased/decreased using the mouse, or controlled via MIDI interfaces. The models' states are calculated in real-time according to the inputs.

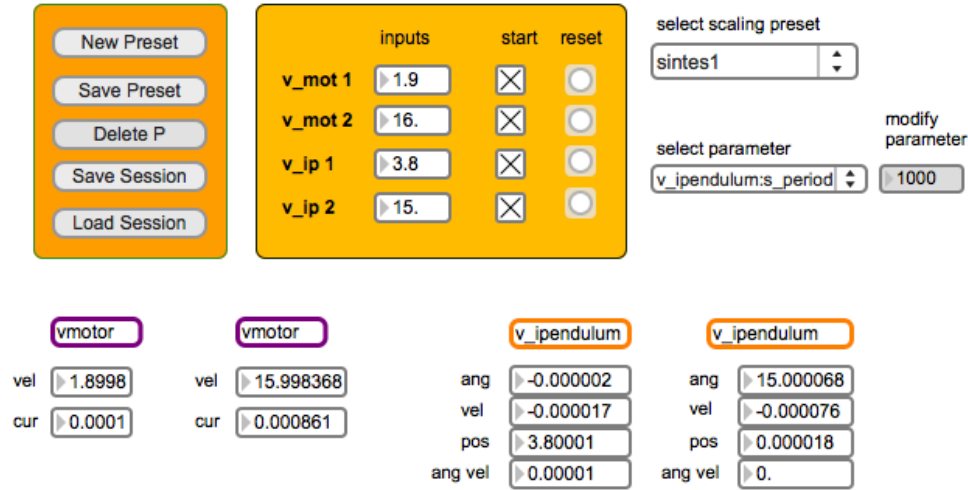


Figure 5.1: State-space models implemented in Max 6.

#### 5.1.1.1 The Inverted Pendulum

The DC motor model used for *Wake Up* was explained in Chapter 3, section 3.1. This section presents a brief description of the inverted pendulum.

The inverted pendulum consists of a pendulum mounted on a mobile cart as shown in Figure 5.2(a). The reader can think of this system as if balancing a pen in the palm and attempting to keep it in a vertical position<sup>57</sup>. The pen is equivalent to the inverted pendulum and the palm is equivalent to the cart. To keep the pen vertical the palm needs to move very quickly to prevent the pen from falling.

The composer thought this system could provide engaging behaviours for sonification, as it requires several hand movements to keep the pendulum in an upright position.

<sup>56</sup>Open Sound Control. See: <http://opensoundcontrol.org/introduction-osc>.

<sup>57</sup>Eduardo Javier Mejorada Dozal. *Adaptive Control with Supervision*. ProQuest, 2008. URL: <http://search.proquest.com/docview/304667059?accountid=12253> (visited on 07/18/2016), p. 6.

The model requires an input to start movement, in this case a desired position, for the cart to reach. The cart then moves to the desired position while trying to keep the pendulum upright. The state-space is defined by the cart's position, cart's velocity, pendulum's angle and pendulum's angular velocity (Figure 5.2(b)).

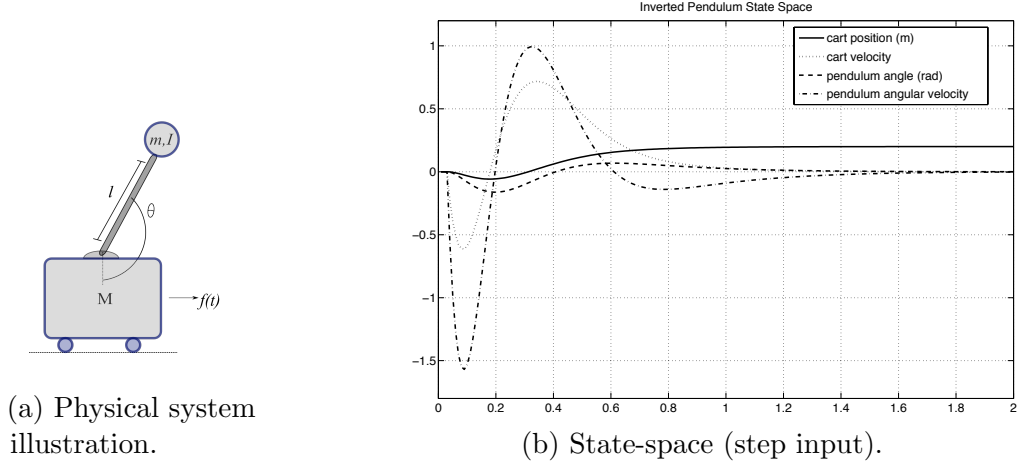


Figure 5.2: Inverted Pendulum system's representations. Where  $f(t)$  is a force applied to the cart,  $M$  is the cart's mass,  $m$  is the pendulum's mass and  $l$  is the pendulum's length.

### 5.1.2 Sound Sources

To create the tape, the composer recorded several violin samples in the studio. The violin performer was asked to play staccato sounds and motifs, pizzicato arpeggios, harmonics and melodic motifs ad libitum and with varying dynamics. The purpose was to capture a diverse set of sounds from the violin for further transformation based on the models. To help with coherence and unity, the tape also includes two additional complementary synthetic sources: noise modulated with a ringing filter<sup>58</sup> and a wave-shaper<sup>59</sup>, both from SuperCollider.

### 5.1.3 Sonification

The DC motor was sonified in SuperCollider using a *TGrains* buffer granulator<sup>60</sup>. The motor's velocity was scaled to control the position in the buffer where the grain envelope reaches maximum amplitude and the current was mapped into the grain duration. The intention was to create granular sounds with smooth evolutions and transitions.

<sup>58</sup> *SuperCollider 3.2 help files*. URL: <http://danielnouri.org/docs/SuperColliderHelp/UGens/Filters/Ringz.html> (visited on 04/10/2016).

<sup>59</sup> *Shaper*. URL: <http://doc.sccode.org/Classes/Shaper.html> (visited on 07/05/2016).

<sup>60</sup> *TGrains buffer granulator - SuperCollider 3.2 help files*. URL: <http://danielnouri.org/docs/SuperColliderHelp/UGens/Playback%20and%20Recording/TGrains.html> (visited on 04/07/2016).

Sonifications of the Inverted Pendulum were achieved in Max 6, using a 2d.wave object. This object splits an audio buffer in several rows and allows control over playback rate (x-phase) and the row used for playback (y-phase)<sup>61</sup>. The model’s states were mapped as shown in Table 5.1<sup>62</sup>.

Inverted Pendulum Model Mappings	
state	2d.wave object
position	start point in a buffer
velocity	y phase
angle	x phase
angular velocity	No. of rows

Table 5.1: Mappings for the inverted pendulum using a 2.dwave object.

The above mappings were chosen after trying several possibilities. The composer thought these provided rich sounds in particular, resulting in a hybrid morphology between the violin timbres and the model’s behaviour. For this piece, the model was mostly kept in its transient state to produce behavioural evolutions.

#### 5.1.4 Compositional Process

The piece was conceived regarding the tape as an additional force to the violin duo. This idea was influenced by the fact that real-time interactions with state-space models were possible and the models could be regarded as instruments when sonified in real-time. To achieve homogeneity in sound materials, the sonifications were based on violin recordings.

The composer designed several mappings for each model and experimented simultaneously with sound transformations, timbres and the model’s real-time capabilities. Several of these experiments were recorded and considered as starting materials for the compositional process.

The instrumental and electronic parts were composed simultaneously, going back and forth between experiments with instruments and models’ sonifications.

The composer explored different timbral juxtapositions either by contrasting the strings with timbres of very synthetic quality or by superimposing similar string timbres produced by the tape and the instruments<sup>63</sup>. The tape extends the

<sup>61</sup>cycling74. *2d.wave~ Reference*. URL: <https://docs.cycling74.com/max5/refpages/msp-ref/2d.wave~.html> (visited on 07/18/2016).

<sup>62</sup>For more details see: (Rosalia Soria-Luz. “State-Space Models: Virtual World for Composition”. In: International Computer Music Association, 2015, pp. 178–181. URL: <http://hdl.handle.net/2027/spo.bbp2372.2015.035> [visited on 10/02/2016])

<sup>63</sup>In this regard Simon Emmerson says: “A juxtaposition without mediation is still a relationship. There are, of course, compositions which confront the issue in a different way and

instrument's timbre into the electroacoustic world through sound transformations rather than using extended techniques.

### 5.1.5 Notation

The piece is notated in the traditional instrumental format for the two violins, adding a stave that combines note based and graphical notation for the tape. Figure 5.3 shows an example of the notation in the piece. The tape is in a fixed stereo format, meaning that the performance needs precise timing to accomplish synchrony.

The figure displays a musical score for three parts: Violin 1 (Vln. 1), Violin 2 (Vln. 2), and Tape. The score is written on three staves. Violin 1 and Violin 2 are in treble clef. The Tape staff is in bass clef and includes a graphical waveform representation. The score includes various musical notations such as pizzicato (pizz), arco, triplets (3), and dynamic markings (mf, mp, ff). The Tape staff features a combination of note-based notation and a graphical waveform representation.

Figure 5.3: *Wake Up*, score and notation example.

### 5.1.6 Structure

*Wake Up* consists of two main sections that produce a developmental structure<sup>64</sup>.

The piece starts presenting the tape with a distinctive timbre and behaviour with respect to the violin duo. The tape gradually evolves with changes in timbre and behaviour towards clearer similarity to violin timbres and language, until they finally overlap at the end of the piece.

The violin duo rather departs from a textural section as a foundation for the tape and gradually become more idiomatic. Tape materials and duo blend into similar timbres and behaviours towards the end of the piece. This can be observed in Figure 5.4, where green represents a more synthetic timbre and behaviour in the tape, turning into red to indicate similarity with the violins.

juxtapose soundworlds without any attempt at any formal timbral integration” (Simon Emmer-son. *Living electronic music*. Aldershot, Hants, England ; Burlington, VT: Ashgate, 2007. ISBN: 978-0-7546-5546-6 978-0-7546-5548-0, p. 109).

<sup>64</sup> “...these developmental structures proceed rather like some natural process in which the gestalt units at the lower level undergo perceptible changes also, as well as creating changing shapes at the higher level.” (James Tenney. *Form in 20th Century Music*. Online document. 1969-70. URL: <http://www.plainsound.org/pdfs/Form.pdf> [visited on 10/02/2016], p. 14)

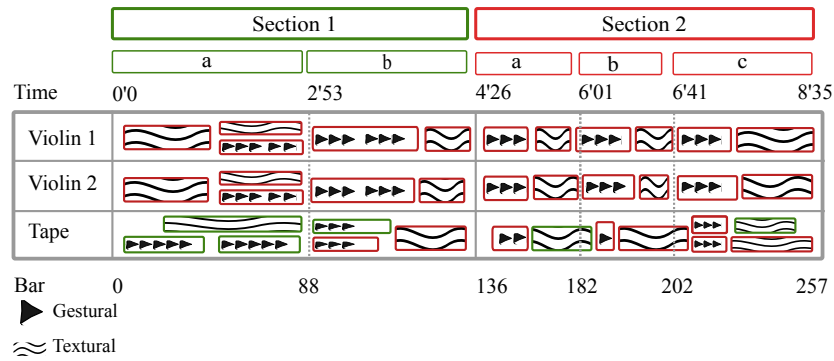


Figure 5.4: *Wake Up* - structure.

### Section 1a (0'0-2'51)

The piece opens with a texture-carried amalgam of several synthetic timbres and the violin duo. Synthetic materials include sonifications of the inverted pendulum model.

To explore timbre possibilities, the composer creates textures through an agglomeration process. Synthetic textures combine high-pitch granular sounds, sonification materials (0'18, bar 10); the “wave-shaper synth” used to thicken the texture and expand the spectrum to lower frequencies (0'43, bar 23) and shaped noise, used to produce an enveloping space. The violin duo provides glissandi pitched sounds to create divergent/convergent motion with respect to the tape contents.

The piece moves into a more gestural-carried stage (1'17, bar 39), to produce transfer<sup>65</sup> processes. Some elements in the tape are perceived as a third instrument, evolving with a distinctive morphology.

### Section 1b (2'51-4'23)

In this section, the tape gradually becomes closer to the violin's timbre (2'51, bar 85). The section is built on superpositions of two untransformed violins and a third virtual one, transformed via sonification.

The tape is based on sonifications of the DC motor. The composer creates enveloping textures based on pitched, pizzicato sounds and sonifications that create the impression of time-stretched or granulated pizzicatos (3'56).

<sup>65</sup> “Transfer involves continuing sounds by transferring the sounding energy from one sounding body to another (for example...piano notes or textures continued by the electronic part, or indeed the piano picking up and continuing sounds from the electronics)”. See: (Andrew Lewis and Xenia Pestova. “The audible and the physical: a gestural typology for mixed electronic music”. In: *Proceedings of the Electroacoustic Music Studies Network Conference, Stockholm*. 2012. URL: [https://www.researchgate.net/profile/Andrew\\_Lewis19/publication/276956163\\_The\\_audible\\_and\\_the\\_physical\\_a\\_gestural\\_typology\\_for\\_'mixed'\\_electronic\\_music/links/555c911408ae9963a11205ed.pdf](https://www.researchgate.net/profile/Andrew_Lewis19/publication/276956163_The_audible_and_the_physical_a_gestural_typology_for_'mixed'_electronic_music/links/555c911408ae9963a11205ed.pdf) [visited on 02/10/2016], p. 9)

## Section 2 (4'26-8'35)

Section 2 alternates between gesture-carried and texture-carried sections, using sonifications of the DC motor.

The composer uses the smooth behaviour of the model to transform short motives played by the performers and to create texture based on the short motives transformations (for instance a quintuplet at 4'55, bar 148). The model is also used to alter the playback rate of recorded short gestures, extending the instruments timbre to lower frequencies (6'03, bar 185). This, combined with the fragments played by the violins create diverse spectral layers and gestural textures.

The composer made variations in the model's inputs to create gesture and provoke faster changes to increase tension and energy (6'46, bar 210). By slowing down the model's evolution, the composer also created melodic contours based on a violin note. These contours merge with the duo, creating a tonal-pitch textural space towards the end of the piece (7'44, bar 233).

Textures, spectral layers and space in this section were enhanced by the additional synthetic materials, specially the “wave-shaper synth” (5'30, bar 166) and shaped noise (7'06, bar 214).

In general, the piece creates an artificial holistic space where instruments and synthetic sounds integrate. The violin duo needs amplification to compensate for the spatial dislocation produced between synthetic sound coming from the loudspeakers and the instruments.

## 5.2 *Holly*

*Holly* is a piece for flute, piano, hyoshigi and tape, written for the English ensemble Psappha. The work takes inspiration from the character “Holly”, a female magic elf from the book series *Artemis Fowl*. The piece explores the integration of state-space models as an instrument and as a sound transformation agent in a larger instrumental ensemble.

### 5.2.1 Sonification

The tape explored sonifications of the mass-spring damper model<sup>66</sup> explained in Chapter 2, section 2.6.2. The sonifications were realised using SuperCollider and based on a wave-table synthesiser and a wave-shaper<sup>67</sup> as shown in Table 5.2.

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<sup>66</sup>The model was implemented in Max/MSP and the sates were forwarded to SuperCollider via OSC as the composer had a preference for the sound synthesis quality in SuperCollider.

<sup>67</sup>“Waveshaping is a popular synthesis and transformation technique that turns simple sounds into complex sounds by changing their shape” (Burk et al. *Music and Computers*. URL: [http://music.columbia.edu/cmc/MusicAndComputers/chapter4/04\\_06.php](http://music.columbia.edu/cmc/MusicAndComputers/chapter4/04_06.php) [visited on 05/10/2016])

These two synthesisers were chosen to provide distinctive morphologies for the tape. The “wave-shaper synth” was meant to create sound with synthetic qualities whereas the “wave-table synth” was used as a means of sound transformation.

Synthesiser	model’s state	Music Parameter
wave-table+delay	position	buffer read start point
	velocity	delay time
wave-shaper+delay	position	wave frequency
	velocity	delay time

Table 5.2: Mappings for the mass-spring-damper model.

The composer explored changes in timbre through delay effects. The idea was to produce changes in the delay time, from very short (a few milliseconds) to long times (1 to 2 secs) using the model’s velocity.

### 5.2.2 Compositional Process

In preparation for the compositional process, several samples of each instrument in the ensemble were created using software instruments<sup>68</sup>. These samples include piano arpeggios and chords in the highest register; long and short flute notes and single sounds of wooden blocks, as a hyoshigi sample was not available.

The composition started with experimenting with sound transformations based on the various instrument samples using the wave-table synthesiser. The composer explored timbre and behaviour characteristics simultaneously while exciting the model in real-time. A similar experiment was performed to explore timbres with the wave-shaper synthesiser.

Some excerpts from these first experiments were selected as starting materials for composition. The general process was going back and forth between the score and further experimentation with the sonifications to find suitable tape counterparts for the instrumental parts and vice-versa.

### 5.2.3 Performance and Notation

To allow flexibility for the performers, the tape was divided in 12 tracks to be played using a Max 6 patch (see Figure 5.5). The ensemble also requires amplification, to compensate for the spatial dislocation between the tape and the ensemble. The amplification enhances the performer’s gestural space binding them to the electronic sounds. Ideally one microphone per instrument is necessary.

<sup>68</sup>The samples were taken from the EastWest student library. See: (*Hollywood Orchestra*. URL: <http://www.soundsonline-europe.com/Hollywood-Orchestra> [visited on 05/09/2016]).



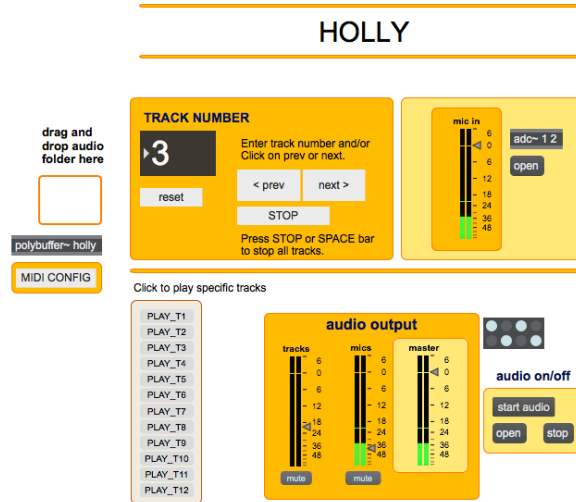


Figure 5.5: Max patch module for tape playback.

The score includes an additional staff for the tape. This staff includes a combination of graphical and note based representations of the synthetic sounds. The score and parts include a symbol in the tape indicating the track number. Figure 5.6 shows a fragment of the score including the above mentioned characteristics.

Figure 5.6: *Holly*, notation and score example.

## 5.2.4 Structure

The piece can be divided in three main sections that explore specific instrument transformations. Regarding the structural relationships, the sections in the piece can be described as metamorphic. All sections are morphologically related as the timbre of the instruments is constant. This similarity includes the tape, as the

model's behaviour imprints morphological characteristics to the sounds. Sound transformations present a hybrid morphology from the model and the instruments' timbres (for instance at 0'52, bar 27).

Each section focuses on the transformation of specific instrument samples as shown in Figure 5.7. The tape enhances the instruments but also interacts with the rest of the ensemble as an additional force due to its behaviour, especially at the beginning of section three. The piece creates additional holistic spaces upon the ensemble space as a result of an electronic element from the tape.

	Section 1		Section 2	Section 3
Time	0'0	1'42	2'56	5'06
Tape Focus	Flute	Piano and Hyoshigi	Bass Drum	
	Gesture-Carried Energy Transfer	Streaming Texture	Gravitational Space	
Bar	1	52	89	154

Figure 5.7: *Holly* - structure

### Section 1 (0'0-1'42)

The first section is gesture-carried to create a subtle hustle atmosphere. The composer created composite initiation gestures by combining piano and percussion strikes.

The piano striking gestures<sup>69</sup> produced by briefly hitting the piano harp with the palm ensure the production of harmonic content in both low and high frequencies that will be reinforced by the bass drum. The hyoshigi is used as an energy propeller element also enhancing the existing harmonics (0'03, bar 2).

The flute and piano develop in a higher frequency plane along with the tape. In this first section the tape is based on synthetic sounds imitating/continuing the pianos's gestures but also enhancing the flute by transforming the sampled flute's timbre through delay effects (0'47, bar 25). The tape has a distinctive synthetic 'personality' as an additional force in the overall gestural counterpoint.

### Section 2 (1'42-2'55)

Section 2 is focused on sequences of piano and tape gestures and textures.

The piece presents streaming textures<sup>70</sup> using the piano and tape, both undulating and going in the same direction and ending or beginning with strong

<sup>69</sup>Striking gestures imply that the striking object makes perpendicular contact with the sounding body, in order to ensure a 'clean' and momentary contact (Lewis and Pestova, "The audible and the physical").

<sup>70</sup>"Streaming refers to a combination of moving layers and implies some way of differentiating between the layers, either through gaps in spectral space or because each layer does not have the same spectromorphological content" (Denis Smalley. "Spectromorphology: explaining sound-shapes". In: *Organised Sound* 2 [02 Aug. 1997], pp. 107–126. ISSN: 1469-8153. DOI:

gestures (1'50, bar 56). Notes in the piano's low register and percussion sounds were used to create composite gestures which are continued by the tape.

The tape has initially a synthetic character based on the "wave-shaper synth" to create the streaming texture. As the section evolves, instrument and tape create iterating textures based on piano and percussion sounds (2'43, bar 82). These textures are transitional material towards the next section.

### **Section 3 (2:55-5'06)**

This section was constructed by the agglomeration of undulating and static layers based on the tape, flute, piano and bass drum (2'54, bar 88). The composer created wider spectrum textures combining harmonic sounds from the instruments and inharmonic sounds from the tape.

As the layers dissolve and converge (3'46, bar 114) a contrasting texture based on the *hyoshigi* and its transformed counterpart emerges. Towards the end of the section the bass drum takes over as the main gestural agent (4'28, bar 135). Gradually, additional texture layers are incorporated again. First a layer produced by the transformed wooden sound and then short, loose gestures from the piano, *hyoshigi* and flute. All layers finally converge as a return to the beginning. All the instruments converge in a crescendo gesture to close the piece.

## **5.3 *Fuzzbox***

This piece presents an exploration of the use of state-space models in a live electronics context. The composer explores interactions between a performer and a model. A bass guitar is transformed using the inverted pendulum model to explore the possibilities for sound transformations and the way the music language is influenced by the model's behaviour.

### **5.3.1 The Bass Guitar**

The bass guitar was selected as the composer was keen on the idea of putting this instrument in an electroacoustic context. This instrument has been included in the electroacoustic repertoire in live-electronics sets by the composer and performer Pierre Alexandre Tremblay<sup>71</sup>, and in works by the composer Éliane Radigue<sup>72</sup>.

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10.1017/S1355771897009059. URL: [http://journals.cambridge.org/article\\_S1355771897009059](http://journals.cambridge.org/article_S1355771897009059), p. 117).

<sup>71</sup>PA Tremblay. URL: <http://www.pierrealexandretremblay.com/worklist.html> (visited on 11/07/2016).

<sup>72</sup>Eliane Radigue. *Elemental II - Eliane Radigue, performed by Kasper Toeplitz @ Sonic Acts XII*. Vimeo. URL: <https://vimeo.com/1796133> (visited on 11/08/2016).

The musical intention in *Fuzzbox* was the exploration of textures and spectral layers based on bass guitar short percussive slap-sounds and their live-transformed counterparts based on delay effects. A second approach was the exploration of glissandi, when some are produced by the performer and others through pitch shift transformations based on the model's behaviour.

### 5.3.2 The Inverted Pendulum as Second Performer

The musical idea relies on the interaction between the performer and the model and on the exploration of different musical relationships of cause, effect and independence.

Simon Emmerson has already referred to a computer "...not only as a partner, but as an improviser of unexpected and unimagined material"<sup>73</sup>. For this particular case, the model can be regarded as a second bass-guitar performer, not only for the audience, but also for the performer. This is particularly true when applying long delay times (from 1 to 3 secs) as the transformed sound will arrive as a response to a played material but with a distinctive identity depending on the model's current input. The performer can then react to this transformed sound.

Live processing based on the model's behaviour transforms the bass guitar glissandi capabilities, as a glissando in a typical bass guitar would produce percussive sounds as the finger passes over the frets. The pitch-shift based on a model's behaviour facilitates a smooth glissandi effect of a single note played by the performer. There is also an effect on the instrument's register, as the pitch-shift process allows the creation of sounds outside of the bass-guitar's register, emphasising the concept of the hyper-instrument.

### 5.3.3 The Inverted Pendulum as a Live Transformation Tool

The live electronics approach considers the state-space model as a "smart" controller that affects live transformations. The composer chose the inverted pendulum because it provides a smooth behaviour; it is slightly oscillatory in its transient state and non-oscillatory in steady state (see chapter 5, section 5.1.1.1). In steady state, the model's position is the one inputted by the user and the remaining states are zero. This allows for the prediction of live sound transformations and evolutions according to the model's input and its four states, mapped to diverse sound processes.

The transformations are based on the composer's inverted pendulum object

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<sup>73</sup>Simon Emmerson. *Living electronic music*. Aldershot, Hants, England ; Burlington, VT: Ashgate, 2007. ISBN: 978-0-7546-5546-6 978-0-7546-5548-0, p. 112.

(Max abstraction), a *groove~* object<sup>74</sup>, a live-recorded audio buffer and delay effects; all implemented in Max 7. The sound processes to be controlled simultaneously by the model are: pitch-shift, playback rate and delay time. Pitch shift and playback rate are both parameters of the *groove~* object to transform a live-recorded audio buffer (Figure 5.8).

The composer chose these transformations to accomplish glissandi effects by modifying pitch-shift factors and to produce smooth timbre colouration when combined with changes in the playback rate. Delay effects also cause timbre changes depending on the delay time and they are an ideal tool to create texture.

Figure 5.8 presents a schematic diagram of the implementation for the live-electronics process. The composer deals with numerical processes related to the model in one patch and audio processes in another.

In the numerical process side, a patch containing the inverted pendulum model provides four states generated in real-time according to the model's input. These states are then scaled and sent to a second patch where they are mapped into audio processes (see Figure 5.8).

In the audio processes side, the scaled model's states are mapped into audio processes using delays and the *groove~* object. In the practical implementation two *groove~* objects with their respective delays are present in the patch, both driven by the same model but with slight numerical variations in the mappings.

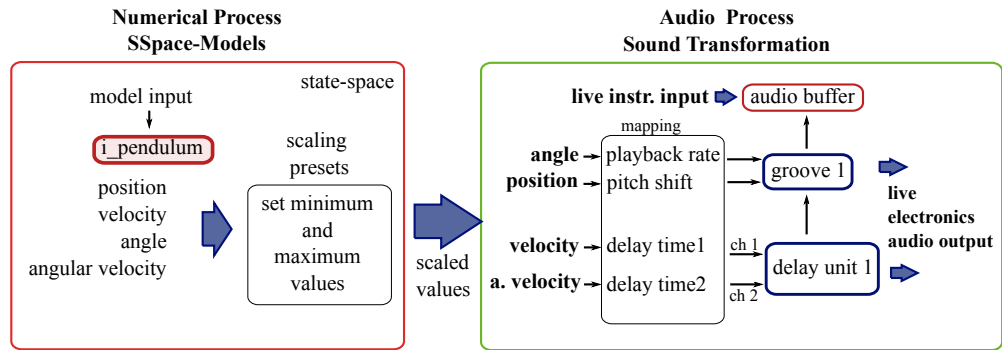


Figure 5.8: Live electronics approach. Schematic diagram to show the live electronics process.

Figure 5.9 shows the (sub) patch handling the inverted pendulum's processes, presets and parameter scaling. The patch also provides a graphical representation of the model's position and angle. This is useful for the composer to visualise the model's behaviour over time and make decisions regarding the mappings.

The magnitude and quality of the sound transformations depend on the model's input, model's sample period and the mapping of its four states.

<sup>74</sup>“Variable-rate looping sample playback”, (cycling74. *groove~* Reference. URL: <https://docs.cycling74.com/max7/maxobject/groove~> [visited on 07/19/2016])

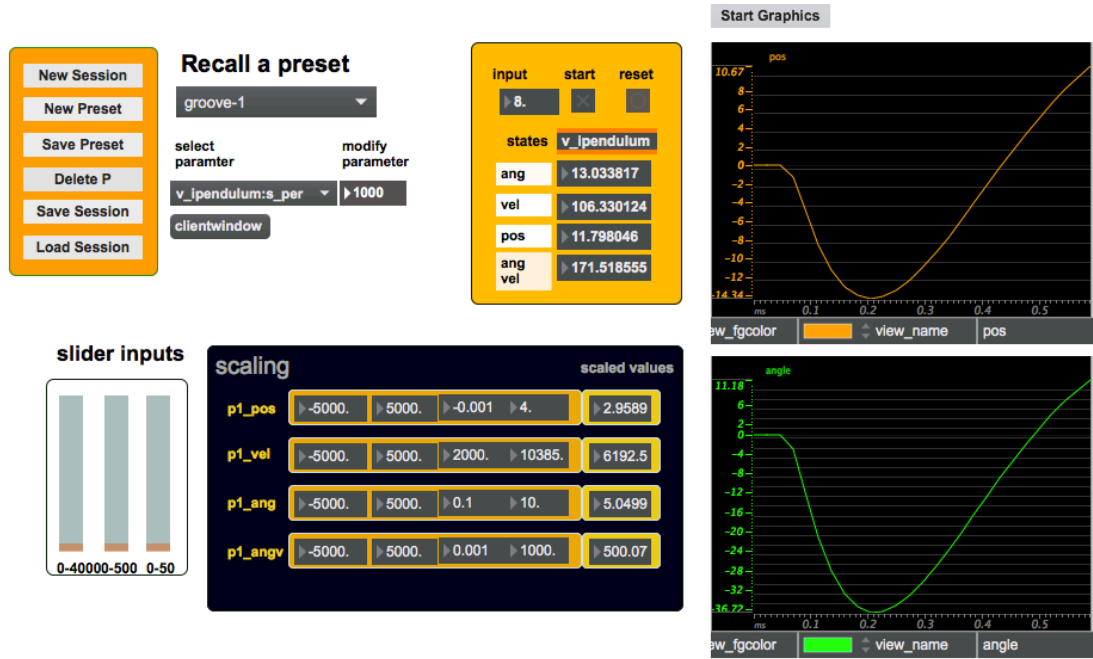


Figure 5.9: Patch for the inverted pendulum's model.

In order to produce different behaviours, the model's input needs to be constantly changed. This aspect is handled using a *function* object from Max<sup>75</sup>, which allows the model's input to be pre-defined via a breakpoint function. The model's behaviour and therefore the transformations's magnitude will evolve according to contents of the *function* object. The specific shape of the breakpoint function is pre-determined by the composer.

For instance, to create percussive slap based textures the model requires a short sample period and abrupt changes in the input, to produce fast changes in model's states. For glissandi materials, the input requires smoother changes in the input and larger sample periods, that produce slower smooth behaviours. For a free improvisation section the model is driven by a combination of smooth and abrupt behaviours.

The (sub) patch provides five scaling presets, designed for specific materials. For instance, 'groove 2' is suitable for percussive sounds, such as short harmonic sounds or slap. For these materials, the mappings produce short delay times and fast evolutions. The preset 'groove 3' is suitable for long notes or chords, as it produces slowly evolving behaviours that reflect in glissandi effects and timbre colourations. The other three produce different timbre colourations and delays suitable for all kinds of materials.

The slider inputs in Figure 5.9 are used to test manually the model's inputs

<sup>75</sup>cycling74. *Max 7 - function Reference*. URL: <https://docs.cycling74.com/max7/maxobject/function> (visited on 07/19/2016).

prior to deciding the contents in the *function* object.

Figure 5.10 shows the (sub) patch dealing with mappings, audio processes and live input/output. The mappings in general are designed in such way that states associated with lower input values create shorter delay times, smaller pitch-shifts and low playback rates.

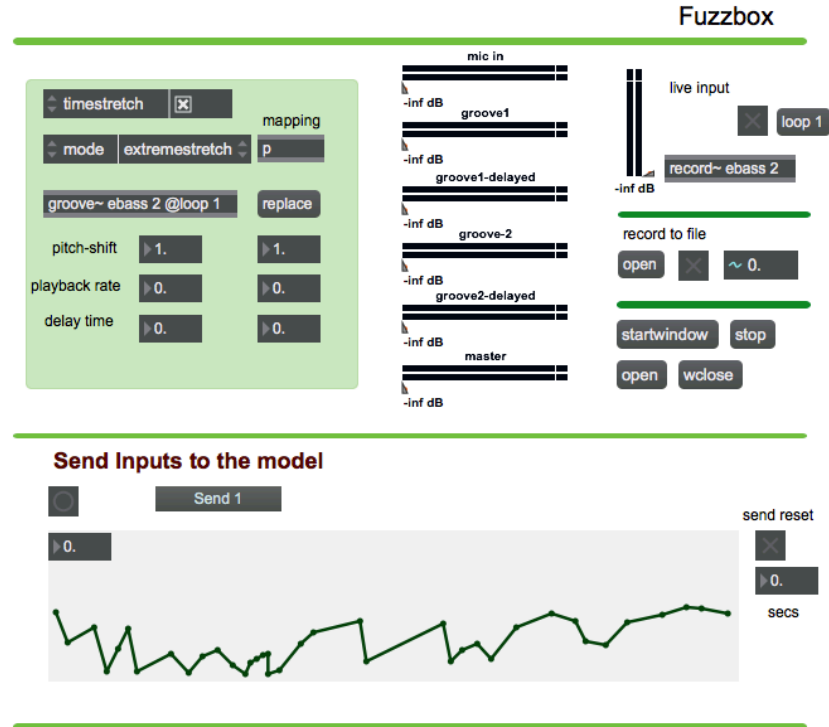


Figure 5.10: Patch for sound processing.

This patch also contains the *function* object, responsible for sending pre-defined inputs to the model, as it was more practical for the composer to observe sound transformations in direct relation to the model's input. The mappings were decided based on observations of the model's behaviour and tests on how the states affect the sound qualities. The position, for instance, is directly related to the input. This parameter was chosen to affect the pitch-shift. If the input is small, then a small pitch-shift will be applied and vice-versa.

For the performance, the bass guitar player does not see the model's evolution, instead sees a stopwatch showing the elapsed time in the main patch. The numerical and audio processes are sub-patches of the main patch. This way, the model can be perceived as a second independent performer. Depending on the mapping of the model's states, different modalities of the same transformations offer different sound qualities. The performer is then free to interact or react to them in real-time.

### 5.3.4 Structure

The materials for the performance are based on bass guitar improvisations and pre-defined sound transformations, according to the model's states and input. The idea of improvisation in relationship with the pendulum's model takes inspiration from the concept of "decisions in the now" mentioned by the composer Kaffe Matthews<sup>76</sup> and from personal experience from the composer, an experienced bass guitar performer. In spite of the model's input being pre-defined, the improvised bass guitar part will catch different transformations at different moments depending on the performer's pace and the model's current state.

However, regarding sound typology, there is a general structure to be followed by the performer in order to accomplish three defined sections. The piece's structure becomes an open work<sup>77</sup>, where materials per section and sound transformations are pre-defined by the composer, leaving the work's completion to the performer.

### 5.3.5 Score

In order to create a musical structure based on three sections, the following guidelines should be followed to create 3 sections:

- Start with short slap sounds mixed with short slap glissandi. Include soft and loud dynamics. Listen to the sound transformations initiating a dialogue between the performer and the live-pendulum. The sound material should grow from a lower to a higher energy state, producing a textural agitated climax towards the end of the section. Push the foot pedal to switch to the next preset.
- Slowly decrease energy and start a transition towards longer sounds including the full range of the instrument and harmonics. Then begin a section combining long notes in different registers and glissandi gestures of diverse duration with different dynamics. The aim is the creation of a layered texture based on sounds produced by the bass-guitar and glissandi produced by the model's behaviour. The performer may interact with the model as decided in that moment. Push the pedal to switch to the next preset.

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<sup>76</sup>About interacting with the computer Kaffe says: "One of the big attractions about working with a computer was that the machine ... would do things and make sounds I would never have imagined on my own... It was about collaborating with this instrument that could produce stuff ... I started putting the machine in situations where it was going to produce sounds that I wasn't thinking of" (Huberman, 2004). As cited in: (Emmerson, *Living electronic music*, p. 112)

<sup>77</sup>To this regard, Umberto Eco refers to open music works as those with "considerable autonomy left the to individual performer in the way he chooses to play the work" and alludes to the open works of Luciano Berio (sequence for solo flute), Karlheinz Stockhausen (Klavierstück XI) and Henri Pousseur (Scambi) as examples. See (Umberto Eco. *Opera Aperta*. Cambridge, Massachusetts: Harvard University Press, 1989, p. 1).



- End with a free improvisation creating diverse interactions (call and response, counterpoint) with the model’s behaviour and corresponding transformations.

For a total duration of around 10 minutes, each section should have a similar length, however some flexibility is allowed (see full score for more details). For the first section the corresponding presets in the patch will be ready. The performer needs to switch presets corresponding to following sections (MIDI foot pedal).

## Chapter 6

### *Synthetic Springs*

In this 8-channel piece, the composer explores different ways of creating the idea of motion through synthetic sounds. The piece was composed mostly using real-time sonifications of the mass-spring-damper model explained in chapter 2, section 2.6.2. The composer uses synthetic sounds to represent the model’s dynamics, creating the concept of synthetic springs.

In a more metaphoric view, the composer thinks of the idea of motion as representation of life renewal when Spring arrives, after a long freezing Winter.

#### 6.1 Sound Sources

##### 6.1.1 Synthetic Materials

The composer chose three synthesisers of different morphologies to represent the model’s behaviour. The synthesisers are presented in Figure 6.1 along with the music parameters explored with each one.

Sonification Pairs	
Synthesiser	Music Parameter
4-channel AM/FM synthesiser	timbre/pulse/texture/space
stereo FM synthesiser	timbre/pitch
8-channel VOSIM synthesiser	timbre/pitch/texture/space

Table 6.1: Sonification pairs used for *Synthetic Springs*.

The composer used AM/FM synthesis to create sounds of percussive pulse-like qualities which fluctuate in time, rather than being metric. FM modulation was used to represent continuous undulating sounds and as a contrast in timbre. The composer had special regard for the Voice Simulation, *VOSIM* generator implemented in SuperCollider<sup>78</sup> as it allows expressivity and timbre control based on sine-pulses<sup>79</sup>.

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<sup>78</sup> *VOSIM*. URL: <http://doc.sccode.org/Classes/VOSIM.html> (visited on 07/21/2016).

<sup>79</sup> Werner Kaegi. *The MIDIM system*. International Computer Music Association. 1983. URL: <http://hdl.handle.net/2027/spo.bbp2372.1983.019> (visited on 07/21/2016).

This synthesiser was used to create harmonic (section 2) and inharmonic objects (section 4) and to make organic transitions between continuous and discontinuous motion.

#### 6.1.1.1 State-space tool for SuperCollider

The sonifications were achieved using a real-time interaction tool implemented by the composer in SuperCollider<sup>80</sup>. As the sonifications involved multi-channel synthesis, the composer felt more comfortable with this language’s approach, where multi-channel arrays can be typed in one line of code.

#### 6.1.2 Piano Strings

In addition, the composer recorded several piano strings by placing a stereo set of DPA<sup>81</sup> microphones inside the piano’s housing, underneath the strings. Each microphone was placed around 50 cm from each other, both localised in the piano’s housing middle. Several strings were played (one at a time) using a bass guitar pick, holding down the sustain pedal and letting the sound decay naturally. The composer wanted to capture the harmonics created by the piano as they would be heard from inside the piano housing and use them to enhance the spatial depth in the piece. She was also interested in the “thin” quality of a single piano string (as opposed to the 3 strings hit simultaneously by the hammer), played like a guitar string.

### 6.2 Compositional Methodology

As part of the compositional process, the composer performed several sonification experiments, trying diverse scaling and mapping possibilities for the model and the three synthesisers. Rather than relying on a fixed data set to represent the model’s behaviour, the composer was able to generate the behaviours in real-time, with the affordance of being able to excite the model, change the sampling period and observe/experiment with timbres and evolutions in real-time.

For instance, the composer investigated the changes in sonic energy or in harmonic content as a result of abrupt changes in the input. It was observed that the smaller the sampling period became, the faster sounds evolved, enriching the spectral content. This fact is shown in Figure 6.1, with a stereo excerpt of the sonification using the *VOSIM* synthesiser. At around 12 seconds the sampling

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<sup>80</sup>Rosalía Soria-Luz. “Multichannel Composition Using Sonification and State-Space Models”. In: *Proceedings of SMC Conference*. 2015. URL: <http://smcnetwork.org/node/1929> (visited on 25/02/2016).

<sup>81</sup>DPA FMK4060 Microphone Kit.

period is decreased and then an abrupt change is produced in the input. The fast evolution of the model produces richer spectral content with respect to the one in its steady states.

It can also be observed how the model evolves towards steady state decreasing again harmonic content. At second 24, another abrupt change is produced, creating more transients and enriching the spectrum.

The composer recorded all the experiments and then continued the compositional process in Reaper by selecting and combining sonification materials.

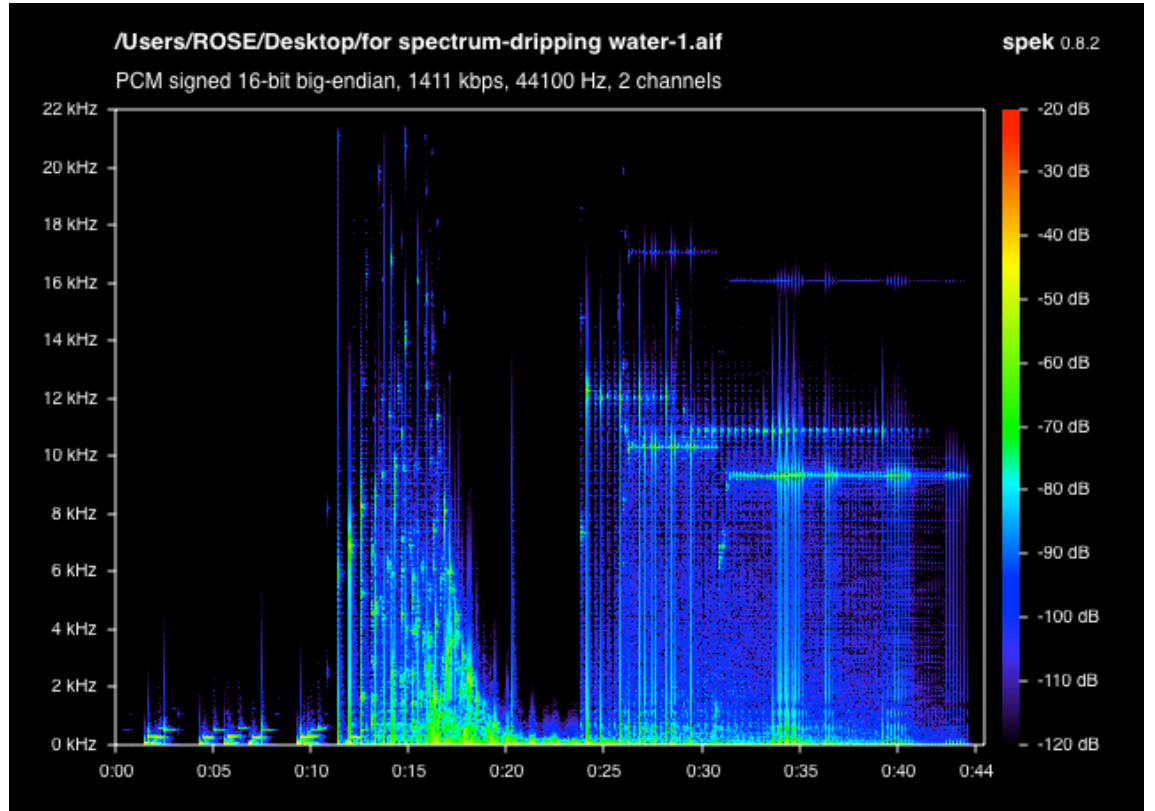


Figure 6.1: Transient state spectrum of a sonification excerpt using the *VOSIM* synthesiser.

### 6.2.1 Multi-channel Sonifications

As the model calculations run independently of the audio processes, the composer was able design sonifications using multi-channel synthesisers where all channels are modulated by only one model.

For instance, in the 4-channel AM-FM synthesiser all channels are modulated by the spring-mass-damper model, but mappings have slight numerical variations per channel. The composer used this sonification approach as a means for creating spatial textures and iterating motions of irregular fluctuations (variations of similar objects happen at different times in different channels). An example of

these variations and their spatial distribution is illustrated in Figure 6.2, where a fragment of the sonification is shown.

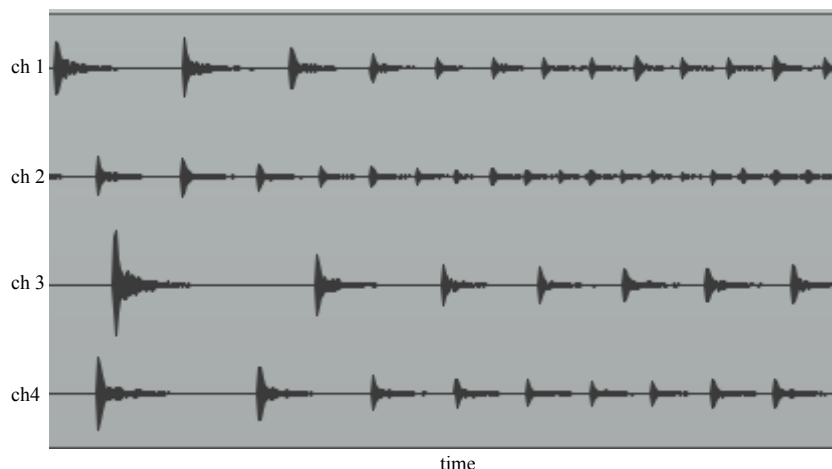


Figure 6.2: multi-channel sonification using the AM/FM synthesiser.

The mappings for the 8-channel *VOSIM* and the stereo FM synthesisers also follow the criteria of having numeric variations per channel<sup>82</sup> to explore the concept of spatial de-correlation and create textural and spatialisation effects. Sonifications based on FM and AM/FM synthesis are meant to provide more localised sound sources. Sometimes they are included in their original format, but they are also “expanded”, meaning that the stereo or 4-channel fragments are duplicated to fit bigger channel groups.

### 6.3 Structure/Language

*Synthetic Springs* has influences of David Tudor’s “Rainforest”. In this piece, he uses a set of amplified resonant objects, excited live, to produce an organic immersive space. Regarding this collection of objects Simon Emmerson highlights: “There was thus a kind of ‘orchestra of resonating objects’ ”<sup>83</sup>.

Instead of using physical oscillators, the composer uses the model to produce bouncing, undulating, continuous/discontinuous motion. Through the multi-channel mappings, the composer creates individual objects per channel. The latter are used to create immersive, texture motion and space, caused by the model’s behaviour but also by the composer’s real-time input to the model.

<sup>82</sup>For more details on these sonifications see: (Soria-Luz, “State-Space Models: Virtual World for Composition”).

<sup>83</sup>Simon Emmerson. *Living electronic music*. Aldershot, Hants, England ; Burlington, VT: Ashgate, 2007. ISBN: 978-0-7546-5546-6 978-0-7546-5548-0, p. 161.

The piece is divided in five sections and can be regarded as having a developmental structure<sup>84</sup>. There is no particular rule or relationship between the duration of the sections and sounds in the piece evolve organically from one section to the next. Figure 6.3 illustrates the piece’s structure and the materials used per section.

The input ranges for the model also define specific timbres and evolutions for each synthesiser; therefore the input ranges define the specific morphologies used for each section. To produce spatial depth the composer uses the recordings of the harmonics from the inside of the piano housing and creates the impression of being in a closed space. Pitched piano sounds are introduced as part of a multi-channel texture that defines the last section in the piece.

	section 1	section 2	section 3	section 4	section 5	
	0'0	2'53	4'02	5'45	6'52	9'00
4-ch AM/FM synthesiser	ch 1-2				ch 1-4 to 8-ch	
stereo FM synthesiser			to ch 7-8 & 1-4			
8-ch VOSIM synthesiser	8-ch & ch1- 4				splits + 8ch	
stereo piano strings recording						

Figure 6.3: *Synthetic Springs* - structure.

### Section 1 (0-2'53)

The piece opens with a slow continuous texture motion made of *VOSIM* and stereo reductions of AM/FM objects.

The composer caused abrupt changes to the model’s input to produce subtle gestures in *VOSIM* objects and briefly interrupt its continuous motion. These gestures are used as onsets for speed and timbre variations (1'12).

Arpeggio-like objects (*VOSIM*) are contrasted with the slow textural sounds (0'47). AM/FM objects introduce new timbres and discontinuous motion (1'32).

The piece enters in an accelerando-like state reaching a maximum speed point and then going back to the slow-motion state to end the section.

### Section 2 (2'53-4'02)

This section explores the creation of texture and undulating motion based on *VOSIM* objects. Sound departs from a collage of short fragments and slowly turns into a continuously evolving object.

<sup>84</sup> “More generally, these developmental structures proceed rather like some natural process in which the gestalt units at the lower level undergo perceptible changes also, as well as creating changing shapes at the higher level.” (James Tenney. *Form in 20th Century Music*. Online document. 1969-70. URL: <http://www.plainsound.org/pdfs/Form.pdf> [visited on 10/02/2016], p. 14)

To have faster evolving materials, the composer selected sonifications where the model was set to shorter sampling periods compared to the previous section. In those, the composer changed abruptly the model's input several times, while the model responded with smooth gestures; then the model was allowed to reach a steady state to produce a rather smooth continuous evolution.

The composer uses a sequence of 8-channel chord-like objects (3'08) as bonding elements that blend with the *VOSIM* objects gestures. The sequence is perceived as having a melodic contour.

As the section evolves, the fragmented elements in the sequence start an increasingly oscillatory behaviour, until they become a continuous elastic bouncing-like object (3'34), describing a streaming surrounding motion. The section closes with a motion deceleration that is interrupted by a gestural arpeggio object (3'52).

### **Section 3 (4'02-5'45)**

This section explores the idea of transferring and superimposing bouncing motion to different timbres and spectral layers. Continuous and discontinuous motions are also overlapped, to create texture motion.

The beginning retakes an element from the collage presented at the beginning of the previous section (the one at 2'55); this time enlarging it and enhancing the synthetic “drill-like” quality introducing discontinuous motion.

The composer creates a second layer through sequences of short high pitched grain-like objects that create an enveloping texture (4'22). This layer is based on time-stretched versions of a short excerpt of the “drill-like” element (only 1-channel) and it is used to broaden the spectrum towards upper mid-range frequencies (2 to 4kHz).

As the “drill-like” object reaches lower frequencies, an FM object slowly appears (4'40) to create contrast in timbre and to extend the spectrum towards the voice frequency ranges and lower. This material is located in the four rear channels to define a strong rear image. This continuous FM object takes up the bouncing role at (5'08) and slowly comes to repose.

The AM/FM synthesiser is re-introduced to take up the (discontinuous) bouncing role at (4'54) with its own characteristic percussive timbre. The FM synthesiser also complements this behaviour (5'07) in a lower frequency range. By the end of the section only the FM synthesiser is dominating, with a resemblance to human female voice. As the latter element fades out, the *VOSIM* synthesiser introduces a new timbre (5'37) creating small dripping-like gestures that create the transition towards the next section.

#### **Section 4 (5'45-6'52)**

Section 4 expands the dripping-like object created with the *VOSIM* synthesiser.

As mentioned earlier, this particular sonification is based on mappings with numerical variations per channel. The section explores the idea of creating texture, gesture and space out of these variations.

The section is mostly a long fragment from the experiments with running the model at very short sample periods (0.001 secs), so that it evolves faster. By producing several abrupt changes in the input, that is to say producing input gestures, the model enters in its transient state. This creates new timbre variations and irregular discontinuous motion resembling falling water or falling drops (spectrum shown earlier in Figure 6.1).

The percussive nature of the AM/FM synthesiser is used at the end of the section to complement the current texture. The introduction is subtle, as a fragment belonging to the same frequency range is superimposed to *VOSIM* objects. AM/FM objects evolve until their frequency and timbre stand out as contrasting element (6'52). This marks the end of the section and the beginning of the next.

#### **Section 5 (6'52-9'00)**

In this section the composer creates spatial textures and spectral layers using continuous/discontinuous AM/FM and piano objects.

At the beginning of the section the composer blends AM/FM objects with the sounds of a very high-note piano string. The composer slowly incorporates piano pitched notes, to create a counterpoint with the synthetic textural moving sounds (7'04).

The composer placed piano pitched notes deliberately in particular channels so that the notes are heard in specific places. The previous *VOSIM* “dripping-like” material from the previous section is kept to create textures with percussive timbre. The piano timbre becomes more distinctive as notes in lower registers are introduced and finally become melodic objects (7'28). The composer uses piano notes from its the lowest register to enrich the spectrum and evoke a sense of warmth.

The final moment of tension is created through agglomerations of FM and *VOSIM* objects (8'11). Some AM/FM discontinuous moving objects collapse and become a continuous granular object (8'16). The low frequency texture presented at the beginning of the piece is now used to close it.



## Chapter 7

### *Time Paradox*

This 8-channel fixed media piece takes inspiration from the concepts of time paradox and time travelling. The composer explores the concepts of elongation, contraction and motion as a metaphor for time travel. She also investigates the morphing of sound, from harmonic to inharmonic qualities, the creation of recession and approach effects and changes in timbre through sonification techniques.

The composer uses sonifications of a mass-spring-damper and inverted pendulum models, as well as recordings of a singing bowls' set. The language in the piece is based on a combination of objects created using the models and an instrumental approach introduced by the singing bowls.

#### 7.1 Sound Sources

##### 7.1.1 Singing Bowls

The composer recorded a set of 6 tibetan singing bowls of different sizes in the studio. The bowls were played using woolen and wooden mallets for singing bowls. A stereo recording set was located at about 1 meter away from the singing bowls, to have a panoramic stereo image of the whole set.

The singing bowls were played in different orders with alternating mallets. The smaller/higher pitched bowls were played using the wooden mallet, the bigger bowls were played with the woollen mallet to bring out more harmonics in the sound. The composer made additional recordings placing the microphones very close to the biggest and a medium sized bowl and playing them in soft dynamics to have a closer image. The composer also recorded them when they were being played around their upper outside rims using the wooden mallet to capture their resonance characteristics.

##### 7.1.2 Sonification and Synthetic Materials

The composer created most of the synthetic materials through sonifications of the spring-mass-damper model to allude to the concepts of elongation, contraction and motion. The inverted pendulum model, with a smooth non undulating behaviour (Figure 5.2(b)), was mainly used to transform the singing bowls recordings using wave-table synthesis in Max (*2d.wave* object).

The composer selected three synthesisers of different typologies and a delay line to sonify the spring-mass-damper model in SuperCollider. The sound parameters explored with each of them are shown in Table 7.1<sup>85</sup>.

Synthesiser	Music Parameter
8-ch FM	timbre/trajectory
4-ch pulse-wave	harmonicity/pitch
8-ch VOSIM+delay	closeness/distance/timbre
8-ch VOSIM	pulse length/frequency

Table 7.1: Synthesisers used to sonify the spring-mass-damper model for *Time Paradox*.

## 7.2 Compositional Methodology

To produce time-stretching effects and explore harmonicity, the composer used the “pulse-wave synth” and slowly changed the model’s sample period in real-time to slow down or speed up its response. Making very abrupt changes in the sample period also produced quick gestures.

The composer used the decaying characteristics of the model’s behaviour to control delay times in sound and create effects of recession and approach<sup>86</sup>.

The singing bowls became objects subject to transformation and, also, were themselves objects offering melodic, harmonic and textural characteristics.

The composer used several sonification materials as starting point and then went back and forth between Reaper and further sonification experiments. Some minor effects were applied to some of the selected materials including filtering, delay, channel-splitting and spatial relocation.

### 7.2.1 Spatialisation

The composer abandoned the idea of spatialisation based on stereo pairs and instead designed multi-channel sonifications to fit groups of 2, 4 or 8 channels. Only one model controls the sound produced for all channels, but the mappings for each channel have slight numerical differences, to produce spatial textures

<sup>85</sup>A more detailed explanation for the sonification process and implementation in SuperCollider is available at (Rosalia Soria-Luz. “Multichannel Composition Using Sonification and State-Space Models”. In: *Proceedings of SMC Conference*. 2015. URL: <http://smcnetwork.org/node/1929> [visited on 25/02/2016])

<sup>86</sup>The composer intuitively thought of this possibility based on the idea of the “spring-reverb”, “...an electromechanical device that uses a system of transducers and steel springs to simulate reflections”. See (Roey Izhaki. *Mixing Audio-Concepts, Practices and Tools*. 225 Wyman Street, Waltham, MA 02451, USA: Focal Press, 2012, p. 408).

and certain extent of de-correlation between channels. This offered possibilities of locating “sound families”<sup>87</sup> in different channel arrays to reinforce texture.

4-channel sonifications were placed simultaneously in the front and mid-front channels, or in the rear and side channels to reinforce texture (0’26). Another approach consisted of placing different sonification fragments on 8 channels (for instance one in the 4 front channels, one in the 4 rear channels) so they created an enveloping effect (1’52).

An opposite idea was using only specific channels from the original materials, for instance taking only 2 channels from an 8-channel sonification (5’04 ).

The singing bowls stereo recordings were useful to have as localized harmonic sources to contrast enveloping textures. These sounds also contained spatial information which the composer used to enrich spatial depth, due to their differences in the recording distance (0’13).

For the sonifications based on the FM synthesiser, the composer created a panning 8-channel effect by mapping gestures created with a finger on the computer’s trackpad to spatial locations. Figure 7.1 illustrates this idea and its corresponding time location in the piece<sup>88</sup>.

The composer uses the *VOSIM*+delay synthesiser to explore timbre. The model affects simultaneously two dimensions of the *VOSIM* object’s timbre, the spectral content and the delay time (affecting attack characteristics).

A third effect in the timbre is the perception of recession and approach as the delay time changes. Sounds without delay are originally sharp, as their attack is preserved. Delays of short durations affect the attack qualities (related to high frequency content), sound is perceived as “blurry” and therefore more distant<sup>89</sup> (2’12).

### 7.3 Structure

The piece’s structure can be described as developmental. It is divided in 2 main sections A and B; each of them subdivided in 2 subsections:  $a_1$  and  $a_2$  and  $b_1$  and  $b_2$  respectively. Section  $a_1$  is an introductory subsection, where all sound materials that will be used in the piece are presented. The remaining subsections extract

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<sup>87</sup>Sounds produced by the same synthesiser and with timbre variations between each channel, as an analogy to sound families in the orchestra.

<sup>88</sup>For more details about sonifications for this piece and the SuperCollider environment used see: Soria-Luz, “Multichannel Composition Using Sonification and State-Space Models”.

<sup>89</sup>“In one experiment timbre has been plotted in a two-dimensional space in which one dimension relates to the ‘bite’ in the attack, the other the placement of energy in the spectrum of the sound”. Wishart comments that these dimensions need to be expanded to include grain, noise characteristics, inharmonicity and various morphological characteristics. (Trevor Wishart. *On Sonic Art*. Ed. by Simon Emmerson. Vol. 12. Contemporary Music Studies. Emmapplein 5, 1075 Amsterdam, The Netherlands: Harwood Academic Publishers, 1996, pp. 78-80)

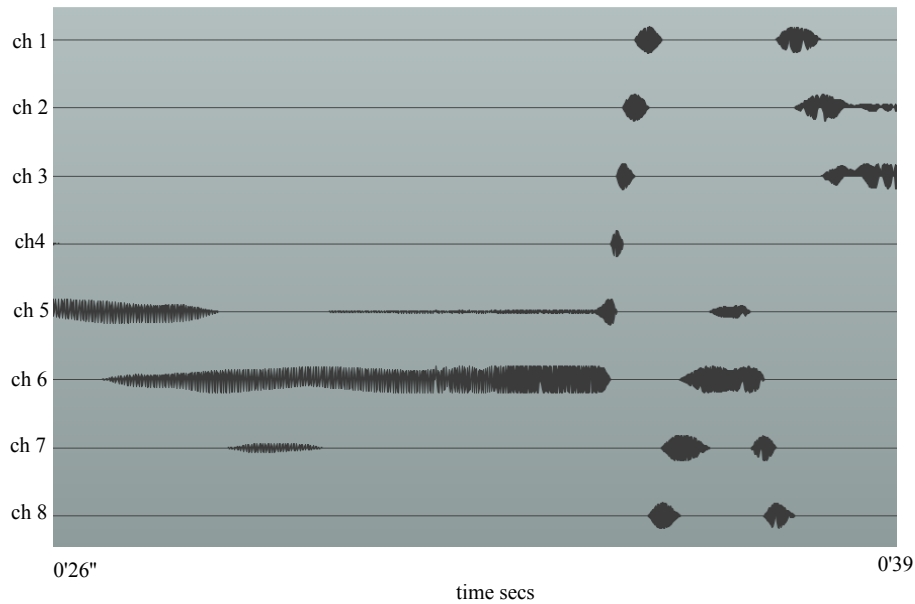


Figure 7.1: Spring-mass-damper FM sonification example used in *Time Paradox*.

specific elements from section  $a_1$  for further development. James Tenney refers to pieces where “the process seems to involve a kind of extractive variation”, as having a “kitchen sink type” developmental structure <sup>90</sup>.

The structure of *Time Paradox* as well as the materials used per section are depicted in Figure 7.2. Through the main two sections, the composer creates an arch form. In section A, motion tends to increase and materials accumulate, in section B, on the contrary, the motion’s speed decreases and sounds dissipate. Regarding harmonicity, section A departs from predominately harmonic-like qualities and becomes inharmonic towards the end; section B begins with inharmonic elements, returning to harmonicity to end the piece. A more detailed description of each section is presented in the following paragraphs.

## Section A

### $a_1$ (0-2’36’)

The composer creates an enveloping holistic textural space and at the same time explores the concepts of time-stretch, contraction and elongation.

The piece opens with an undulating motion texture made of “pulse-wave” objects, reinforced with shaped noise and the inverted pendulum sonifications. The “pulse-wave” objects come back and forth between harmonicity and inharmonicity

<sup>90</sup> “The Emerson movement of “The Concord Sonata”... seems to begin with everything at once, in a deliberately not-so-clear profusion – followed by a progressive clarification of this initial material, in which one after another of a set of four or five basic thematic ideas is singled out – extricated from the more complex fabric”. (James Tenney. *Form in 20th Century Music*. Online document. 1969-70. URL: <http://www.plainsound.org/pdfs/Form.pdf> [visited on 10/02/2016], pp. 14-15)

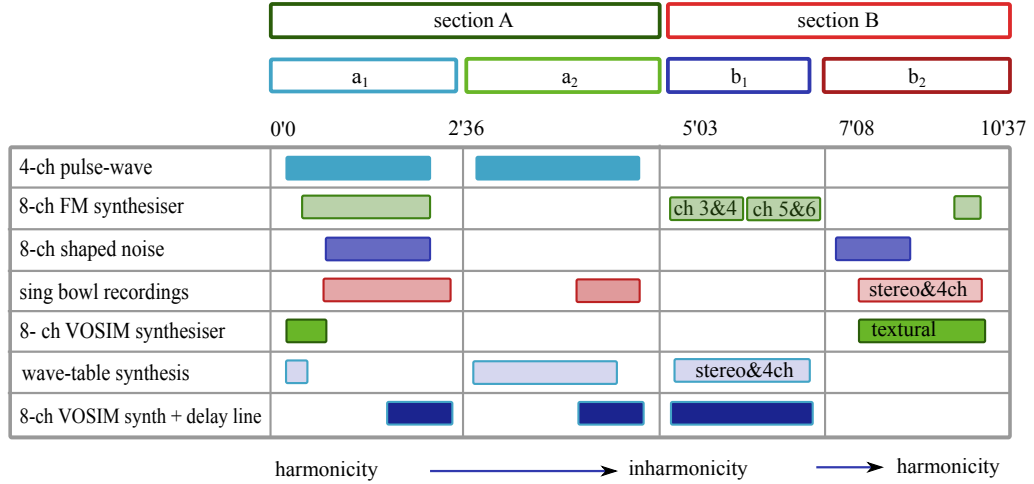


Figure 7.2: *Time Paradox* - structure

as a result of time-stretching effects (0'51).

The listener is introduced to single singing bowl objects as a contrast to the “pulse-wave” based texture (0'15). The composer regards these objects as reference points for listener. They are placed in fixed locations and offer strong harmonic qualities.

The composer creates elongation and contraction gestures using FM objects (0'26): sound starts in the rear with a low frequency sustained sound, then pitch rises and the sound spreads to create an 8-channel gestural panning effect.

Singing bowls, FM and “pulse-wave” objects, are slowly incorporated and superimposed to create a behavioural holistic circumspace.

The composer introduces “*VOSIM*/delay” objects (1'44) to explore the idea of elongation. These objects also define two spectral planes with alternating ascending and descending motion.

### a2 (2'36-5'03)

This section focuses on the creation of textures and agitation based on “pulse-wave” objects.

These 4-channel sounds are superposed in different channel groups (for instance 4 front+ 4 left) to create a subtle quiet texture, defining a fleeting tonal-pitch space (3'12). Variations in texture come back and forth between harmonic and inharmonic. They also create the illusion of closeness and distance (3'34).

The “pulse-wave” texture is complemented with a singing bowl note transformed with the inverted pendulum model, so that it imitates the rhythmic-pulse idea and complements its timbre. An untransformed singing bowl tone is integrated in soft dynamics to bring extra spectral components (4'05).

The composer slowly introduces “*VOSIM*+delay” objects as contrast in timbre,

first very quiet and distant (3'43), contributing the pulse idea. The element grows closer and louder turning into glissando-like elements of evolving timbre, creating an undulating descending motion. The harmonic-inharmonic idea in the section evolves until its inharmonicity dominates the end of the section.

## **Section B**

### **b1 (5'03-7'08)**

This section explores timbre possibilities and trajectories based on “*VOSIM* +delay objects” presenting mostly inharmonic morphologies.

These particular materials present simultaneous transformations of different dimensions in sound; it changes timbre, perceived source distance and perceived motion. The sonification process also explores the idea of sound de-correlation per channel.

The section begins with a time-stretched and down-shifted version of the FM object from section *a*<sub>1</sub>. The composer uses “*VOSIM*+delay” objects to create gestures and spatial immersive textures. The composer uses “transformed singing bowl” objects as a contrast in timbre (6'05), but also integrates them to the motion idea of the current textures. The section ends with a crescendo made of “noise-like” objects.

### **b2 (7'08-10'37)**

The last section begins the return to harmonic-based materials and creates several planes by agglomerating several close, distant, static and moving objects of different timbres.

The section starts with a singing bowl note, which creates a strong gesture to bring up harmonic materials.

The listener is gradually introduced to *VOSIM* objects (without delay). The composer creates texture through variations on pulse length (controlled with mass velocity) and variation in pitch (controlled by the mass displacement).

Three spectral planes are created by the pulses, low frequency FM objects and singing bowls. The singing bowls are integrated with an instrumental approach: without transformations, defining a tonal-pitch space with clear intervals (for instance 3rds, 9'32). The piece closes with an immersive space including untransformed singing bowl objects of different pitches, lengths and locations. A sequence of singing bowls objects create a dreamy melody that slowly fades out to end the piece.

## Chapter 8

### *The Silver Key*

*The Silver Key* is the portfolio's large scale piece. It takes inspiration from the story with the same name, by the American writer H. P. Lovecraft. The story is one of his "Dreamlands" series, in which he portrays an alternate dimension with vast cities and lands that can only be accessed via dreams. The piece is a metaphoric allusion to these dreamlands, conceived as abstract landscapes.

#### 8.1 Sound Sources

The main sound sources are the recordings of a koto and sonifications of four state-space models: a harmonic oscillator, a double mass-spring/damper, a spring-mass damper and an inverted pendulum.

The koto was recorded in the studio, where the composer captured in close detail different articulations and sound characteristics of the instrument. The performer was asked to play several arpeggios and single notes in different registers and durations. She also performed several fragments from traditional koto repertoire, this with the aim of having recordings of various dynamics and articulations in the instruments' own language, with the performer being fluent in performing traditional koto repertoire.

The composer used additional materials such a sampled cello and recordings of an electric bass guitar to enhance textures.

##### 8.1.1 Sonification

The composer explored different music parameters through multi-channel sonification approaches using the real-time tools implemented in Max and SuperCollider, as shown in Table 8.1.

To illustrate their nature, the behaviours of the harmonic oscillator and the double-mass-spring models's are briefly explained now.

The harmonic oscillator consists of a mechanical system of a mass attached to a spring<sup>91</sup>. Its state-space is depicted in Figure 8.1, where an constant oscillatory behaviour can be observed.

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<sup>91</sup> "A harmonic oscillator is an ideal oscillator that never stops" (Debora M. Katz. *Physics for Scientists and Engineers: Foundations and Connections*. Vol. 1. 20 Channel Center Street, Boston, MA 02210, USA: CENGAGE Learning, 2015, p. 473)

The Silver Key		
State-Space Model	Music Parameter	Environment
Mass-spring-damper	Oscillatory Motion/Timbre	SuperCollider
Double mass-spring/damper	Trajectory/Timbre	SuperCollider
Harmonic Oscillator	Pitch/Timbre	SuperCollider
Inverted Pendulum	Sound Transformation	Max
Inverted Pendulum	Sound Transformation	SuperCollider
Inverted Pendulum	Timbre	SuperCollider

Table 8.1: State-Space Models used for *The Silver Key*.

The double-mass-spring/damper consists of a mechanical array of a damper attached to a series of two mass-spring elements<sup>92</sup>. This system presents bouncing behaviours as a product of the damper and the effects of the two mass-spring pair on each other. Figure 8.2 shows the model's state-space and behaviour, the states are: the mass1's speed and velocity and mass2's speed and velocity.

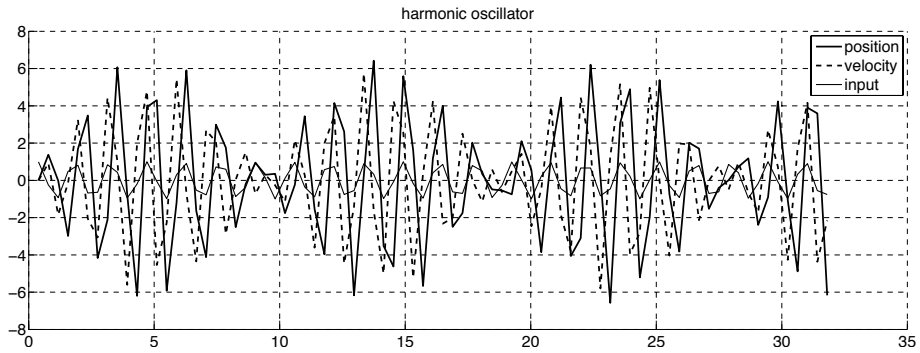


Figure 8.1: Harmonic oscillator's state space simulated in MatLab with a sine-wave input.

The composer chose this set of models because they offer variations in oscillatory behaviours and present different steady states. Their sonifications were based on pairs of model-synthesiser or model-sound-transformation as shown in Table 8.2. The composer achieved multi-channel approaches using SuperCollider. Max was mostly used for sound transformations of stereo sources.

The composer selected the synthesisers with the criteria of having different sound typologies to represent the models' behaviours.

## 8.2 Space

The composer uses a 16-channel system to reinforce spatial depth and create landscapes based on textures with de-correlation characteristics. The piece presents

<sup>92</sup>Robert L. Williams and Douglas A. Lawrence. *Linear State Space Control Systems*. Hoboken NJ: John Wiley and Sons, Feb. 2007, p. 10.



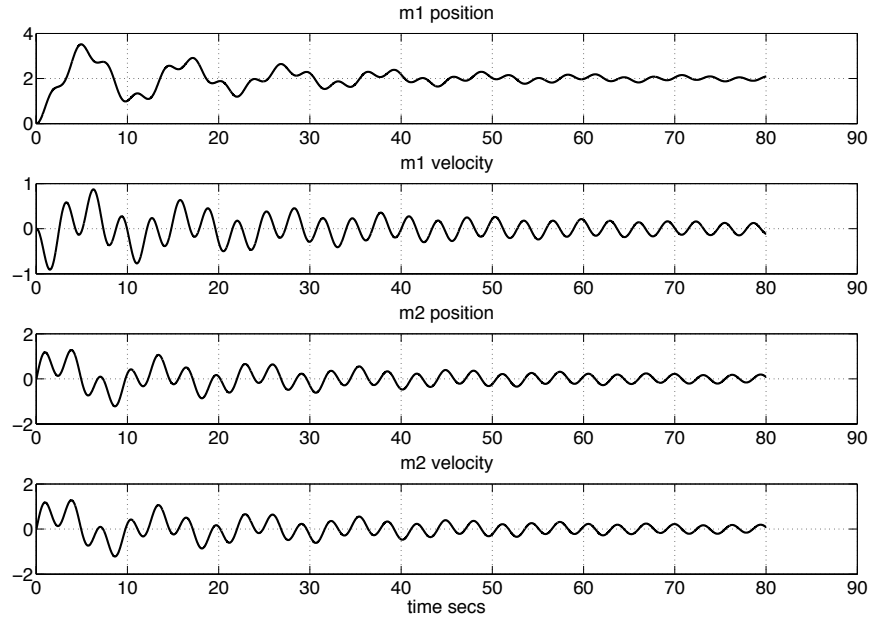


Figure 8.2: Double-spring-mass/damper’s state space simulated in MatLab with a step input.

Sonification Pairs	
State-Space Model	Synthesiser/Transformation
Double mass-spring-damper	8-channel GrainFM synthesiser
Harmonic Oscillator	8-channel ring modulator
Inverted Pendulum	8-channel granulator
Inverted Pendulum	Stereo wave-table
Inverted Pendulum	4-channel ring modulator
Mass Spring Damper	4-channel wave-shaper

Table 8.2: Sonification Pairs used for *The Silver Key*.

the listener with different spaces, some closer (0’12), some more distant (11’42) and others rather more holistic (22’10). At the same time, processes of recession and approach can be perceived throughout the piece (for instance at 5’55).

To reinforce spatial depth, the composer chose three main layers. The intimate space is defined by the close loudspeakers, normally a set of 4 loudspeakers placed in the middle of the audience and in the middle of the concert hall. The next layer is the close space, defined by the main ring of eight and constitutes the main aural space. The distant space is defined by loudspeakers placed further away from the main ring of eight. In the composition space this was achieved by placing only 4 distant (diffuse) loudspeakers (placed on the floor, facing the wall)<sup>93</sup>. In large

<sup>93</sup> “Very Distant speakers facing away from the audience and reflecting off the wall can be effective, the high frequency attenuation and general reduction in source location delivering

performance spaces, the distant space can be reinforced using eight loudspeakers. The distant space was also emphasised through low-pass filtering<sup>94</sup>.

The composer also sent the audio signal from the distant channels to the main eight, with quieter dynamics and delayed, to emulate early reflections and to provide some sharpness to sounds<sup>95</sup> and link the main channels with the distant channels.

The composer designed sonifications that fitted in groups of 2, 4 and 8 channel groups and with slight numerical deviations between channels. Sound materials were then placed and/or overlapped in the intimate, close or distant spaces to create texture and experiment with spatial perception<sup>96</sup>. In the last section of the piece, the tool “ReaSurround”, from Reaper, was used in very brief moments (21’46) to create contrast in the spatial language, for instance to create space through panning rather than de-correlation.

### 8.3 Structure

The piece is divided in five sections where the composer explores the creation of abstract landscapes<sup>97</sup> through superpositions of different sonifications, or better said, “different behaviours”.

This idea was influenced by Bernard Parmegiani’s “Matières Induites”, where he creates landscapes by developing a “surrealistic approach to recognisable sources” using superposition of “unrelated” images<sup>98</sup>. Also, according to Trevor Wishart, when we present “acoustic virtual spaces” ... “they need not to be real and we may in fact play with the listener’s perception of landscape”<sup>99</sup>.

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remarkably well the sensation of distance. (Dr Jonty Harrison. *CEC — eContact! 2.4 — Diffusion: theories and practices, with particular reference to the BEAST system by Dr Jonty Harrison*. URL: [http://econtact.ca/2\\_4/Beast.htm](http://econtact.ca/2_4/Beast.htm) [visited on 07/23/2016]).

<sup>94</sup>“Signals with strong parts around 1 kHz lead to auditory events that sound rather diffuse in space and sometimes even sound as if they are coming from behind the listener” (Jens Blauert. “Hearing of Music in Three Spatial Dimensions”. In: *Systemic Musicology* [2007], pp. 103–12. URL: <http://www.uni-koeln.de/phil-fak/muwi/fricke/103blauert.pdf> [visited on 02/10/2016], p. 106).

<sup>95</sup>“The early lateral reflections not only create the desired spatial effect but also make a positive contribution to the sharpness of articulation and clarity.” (Blauert, “Hearing of Music in Three Spatial Dimensions”, p. 110)

<sup>96</sup>“When the correlation of the radiated sound signals decreases, the spatial expansion of the auditory event increases. With several uncorrelated radiated signals there are mostly several distinct auditory events”. (Blauert, “Hearing of Music in Three Spatial Dimensions”, p. 107).

<sup>97</sup>Wishart defines landscape “as the source from which we *imagine* the sounds to come”. (Wishart, *On Sonic Art*, p. 136)

<sup>98</sup>Simon Emmerson says that Parmegiani “...has used such devices as duality (recognisable/abstract), perspective (near/far) and the juxta –or superposition of unrelated images to achieve an effect of surrealist paintings). As cited in (Wishart, *On Sonic Art*, pp. 136-137).

<sup>99</sup>Trevor Wishart. *On Sonic Art*. Ed. by Simon Emmerson. Vol. 12. Contemporary Music Studies. Emmapplein 5, 1075 Amsterdam, The Netherlands: Harwood Academic Publishers, 1996, p. 136.

The composer uses the recordings of the koto to explore the concept of duality (recognisable versus abstract). The piece presents different identities of the koto by introducing it untransformed (17'20); transformed but still recognisable (15'45); and transformed, so it becomes an abstract object (2'54, front channels). However, as most of its transformations are based on models, these abstract objects present mixed typologies of the koto and models' behaviours in several degrees of relation (for instance at 2'58).

Figure 8.3 shows the sound sources and state-space models used in *The Silver Key*. The materials for each section are shown in different colours and kept the same in the following sections to illustrate their morphological distribution along the piece. Shades of blue represent sound materials with the koto's morphologies.

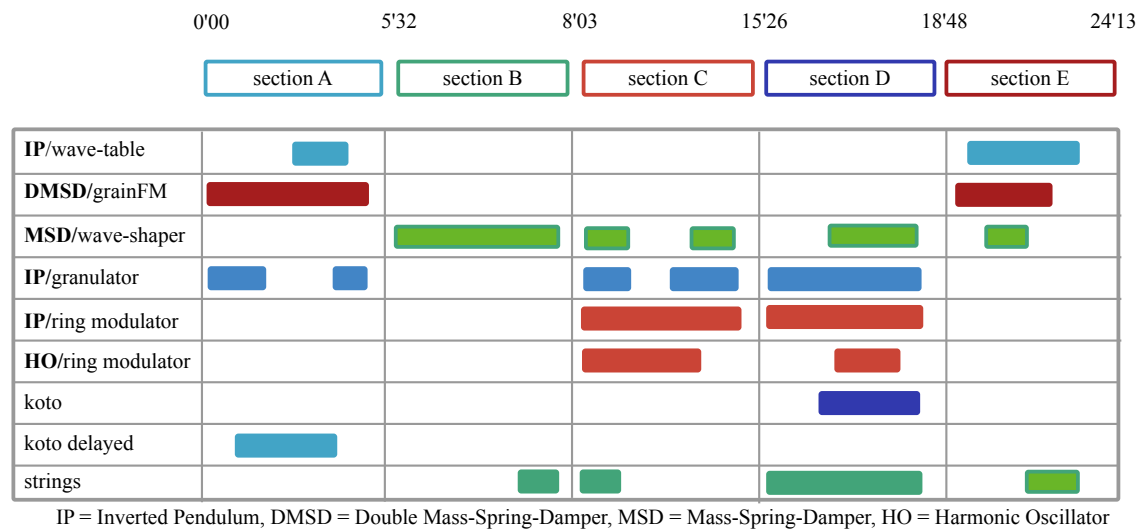


Figure 8.3: *The Silver Key* - sections and material's distribution.

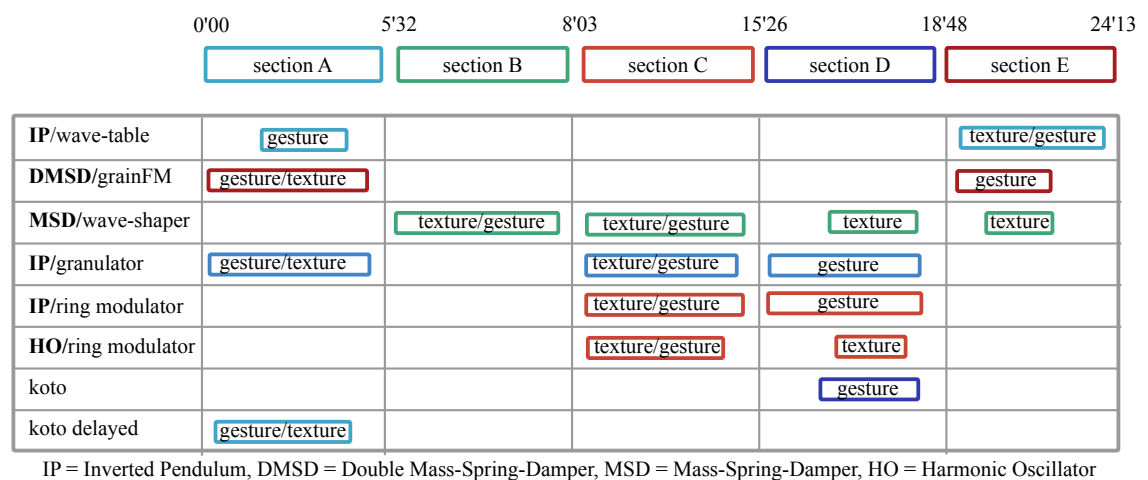


Figure 8.4: *The Silver Key* - gesture and texture.

Figure 8.4 illustrates the sound material distribution regarding gesture and texture. The composer used the same sonification pairs to create either texture

or gesture. For instance, the inverted pendulum model (wave-table) is used to create gestures in section A and texture and gesture in section E. The mass-spring damper is used to create both gesture and texture in section B.

Figure 8.5 summarises the piece’s structure. The piece can be thought of having a polymorphic structure<sup>100</sup>, as the composer uses different combinations of a set of predefined materials to create each section. At the same time, the piece can be thought of as having a “windowed” structure<sup>101</sup>, as each section has distinctive morphological characteristics and a self-contained beginning and end. Each section defines an abstract landscape to correspond with the metaphor of dreamlands.

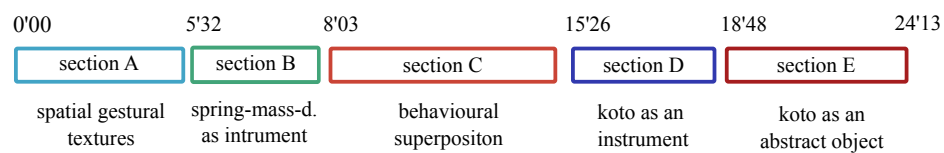


Figure 8.5: *The Silver Key* - general structure.

The following paragraphs explain each section in more detail.

### Section A (0'0-5'32)

To include materials with koto’s morphology, the composer used a koto melody excerpt and transformed it using wave-table synthesis in Max. The composer set very short sampling periods (around 30-60 ms) for the model to create quick gestures. The composer also took a koto monophonic arpeggio and transformed it using an 8-channel granulator. The sonification was designed to produce different grain sizes and diverse playback rates per-channel when varying the model’s input. A third transformation was performed in Reaper, applying a delay chain with low-shelf filtering on a melodic fragment.

The double mass-spring-damper model was represented by a *GrainFM* synthesiser. The composer changed the model’s input and the sampling period simultaneously to produce variations in the model’s response. These variations, in combination with the mappings, create gestural sounds with different grain sizes and dynamics per channel (0'12).

The composer explores the idea of onset and continuation using scattered sounds. The piece opens with synthetic chords combined with gestural granulated objects. The chords have a low frequency component to create strong onsets. The

<sup>100</sup> “variable ordering of a fixed set of “basic shapes”. (James Tenney. *Form in 20th Century Music*. Online document. 1969-70. URL: <http://www.plainsound.org/pdfs/Form.pdf> [visited on 10/02/2016], p. 20).

<sup>101</sup> “...the effect here is as though looking at a landscape through an open window – the perceptual boundaries are defined “arbitrarily” (by the window frame), rather than being inherent or “intrinsic” to the process (“landscape”) itself” . (Tenney, *Form in 20th Century Music*, p. 11)

continuation elements are based on granular flocking textures scattered in the circumspace, slowly dissolving and spreading from the close to the distant space (0'23).

“Delayed koto” objects (of melodic qualities) appear as continuation elements with contrast in timbre(1'08). To play with the idea of emergence and disappearance, recession and approach, the composer masked or interrupted these objects using short gestures or low frequency notes (1'08). They also disappear from the close space and reappear rather in more distant spaces (1'19) and vice-versa.

Towards the second part of the section, the melodic material connects with “floating” koto arpeggio-like objects (wave-table) to create a gesture-carried atmosphere (1'50). The listener is gradually introduced to a more inharmonic section, where short harmonic gestures and inharmonic objects define a vectorial space based on behaviours of the double mass-spring-damper and inverted pendulum (2'54). The section culminates with an increase of energy and motion in the close space, arriving again to “delayed koto” and granular objects (4'40) this time presented in louder dynamics.

### **Section B (5'32-8'03)**

This section was constructed using synthetic materials only. It is based on behaviours of the mass-spring-damper model. The model is sonified using a “wave-shaper synth”. Sound is more oscillatory when the model is in its transient state and becomes more textural in its steady state (see Figure 2.4).

One single model modulates the 4-channel wave-shaper, but scaling values are slightly different per channel to cause the effect of having one model per channel (de-correlation). These 4-channel sonifications are assigned to different 4-loudspeaker groups. In the main ring of eight, the composer overlaps them, for instance, 4 of the front with 4 of the left (or 4 of the back with 4 of the right) to enrich texture (6'54).

The composer creates a synthetic holistic space, regarding the model as an “instrument”, with a virtual mass-spring-damper (mechanic) system in its core and 16-channel loudspeakers as its “voices”<sup>102</sup>. At the loudest points (6'13), there is no defined “sweet spot”, as virtually a mass-spring-model is present on each loudspeaker and sound is scattered in three spatial planes simultaneously. The model’s dynamics also imply the creation of a behavioural space, where a collection of oscillating objects emerge, disappear or fade out in the close and distant spaces.

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<sup>102</sup>This notion inspired by David Tudor’s rainforest. The composer says: “One of the ideas in my Rainforest series is that loudspeakers should be individuals, they should be instruments. So if you need a hundred of them to fill a hall, each one should have its own individual voice ...” (Emmerson, *Living electronic music*, p. 161)

The composer enhances the closer space by increasing volume and enhancing high frequency components for a brighter spectrum.

### **Section C (8'03-15-26)**

In this section the composer superimposes the behaviours of three models: a harmonic oscillator, a mass-spring-damper and inverted pendulum. The harmonic oscillator provides a constant oscillatory behaviour, the inverted pendulum provides smoother oscillations and constant steady states, the spring-mass-damper provides a mix of both. The composer superimposes the variations of these behaviours to create contrasting objects and timbres in the section.

The landscape in this section describes several arches and perspectival spaces (for instance from 8'03 to 9-13). With regard to the overall piece's structure, this section develops mostly with slow evolutions, quiet dynamics and higher dynamic ranges.

The composer creates tension and release moments through gestures caused by the models' behaviours and recession and approach gestures.

The section opens with a layered texture that builds up by adding sonifications of the three models. Sounds are presented in a quiet distant tonal-pitched space and gradually, they close in.

The inverted pendulum provides a slow oscillating motion (9'00)<sup>103</sup>; the spring-mass-damper adds an undulating layer in the intimate space (9'04); and the harmonic oscillator (in its transient state) causes agitation and randomness in the close/egocentric space (9'26). Agitation eventually dissolves to initiate transfer processes between "models" (9'50) with an onset based on one model and continuation based on another.

The harmonic oscillator is also used to create a descending motion texture, to introduce the listener to a distant oscillating sound (10'21). The composer creates a transparent distant space by sonifying the harmonic oscillator when it goes back and forth from its transient to steady state. Its sound describes undulating behaviours and several harmonic contours. The composer adds subtle gestures in the intimate space to define a fleeting perspectival space.

The accumulation process restarts at (12'10), broadening and contracting the spectral content and increasing and dissipating energy.

Towards the end of the section, the inverted pendulum's sonifications based on granular synthesis re-introduce the koto's morphology. Several gravitation layers emerge and fade out until the koto and sonifications of the mass-spring damper model converge in an elongation gesture (14'53) to finalise the section.

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<sup>103</sup>The 4-channel ring modulator is duplicated to cover 8 channels and also extended to the distant space to create the illusion of a bigger space.

## **Section D (15'26-18'48)**

This section creates an holistic space, enhancing the koto's morphology and presenting it as an augmented instrument. The sound materials are sonifications of the inverted pendulum (granular synthesis and ring modulator) and the harmonic oscillator.

The section is built upon granular transformations of melodic fragments of the koto. Through the model, the composer changes the grain sizes and playback rates, so different sound qualities are scattered in the close circumspace (15'30). The composer uses transfer processes between the transformed koto and synthetic elements (16'53) to create a transition towards a holistic space based on an untransformed koto and synthetic sounds.

A koto melodic object is finally fixed to the front (17'20), inhabiting a space defined by agitation textures generated with the harmonic oscillator. To close the section, the impression of harmonic tension between the koto and synthetic sounds is dissolved and sound slowly fades out in the distance.

## **Section E (18'48-24'13)**

The final section consists of textural developments based on sonifications of the inverted pendulum (Max) and a stereo reduction of sonifications of the double mass-spring-damper (*GrainFM*).

With regard to the overall piece's structure, this section presents a contrast in timbre. As opposed to previous sections, this is composed using mainly transformed koto materials. The unity with the whole piece is kept by the model's behaviours. Regarding space, the first part in this section explores recession and approach processes with stereo sources, gradually evolving into a holistic immersive space (21'12) towards the end.

The composer uses the inverted pendulum model to “freeze” gestures played by the koto, or to get metallic percussive morphologies based on koto sounds. The spatial image is entirely constructed using stereo materials, located and/or expanded in stereo or quadraphonic channel groups.

The section opens with subtle inharmonic gestures in the distant space (18'51). Frozen koto notes emerge also in the distance to blend with the inharmonic content. Gradually, textures become more articulated and harmonic, while slowly approaching to the close and intimate spaces (19'41). The composer creates motion through *GrainFM* objects, describing vectors in the close space (20'53). A low frequency sound creates cohesion and defines a low-frequency spectral layer. The composer adds textures based on down-pitched koto (transformed) objects to bring a warmer broader spectrum. As the section evolves, textural materials become more gestural to finally create localised oscillating objects and vectors (22'20). To

create the moment of tension, agglomerations of gestural materials bring the piece to a full spectrum (23'12). The accumulated layers gradually fade out to end the piece.



## Chapter 9

### Conclusion

In this portfolio of compositions the composer explored ways of adapting the concept of state-space models to an electroacoustic composition context.

In all the pieces, the models have been used as a means to transform recordings or create synthetic sound via sonification techniques. Each model offers unique behaviours and characteristics that the composer translated to gestures, textures, timbres and spaces. The pieces in the portfolio explore some of the vast possibilities and means for translating the model's behaviours into music.

The models were chosen because of their behaviour: the mass-spring-damper, harmonic oscillator and double mass-spring damper all offer oscillatory characteristics. The inverted pendulum was chosen because it offers a smooth behaviour and is less oscillatory compared to the systems that involve springs. The abstract model and DC motor model offered less complex behaviours, which made them suitable as a starting point for developing personal sonification techniques. That allowed the composer to investigate the musical impact of sonification techniques in the first two portfolio pieces.

All models offer organicity because they represent physical systems. This organicity is transferred to sound through sonification techniques, affecting directly the musical language. Also, the models become alive as software tools, allowing the creation of sound with diverse qualities, such as sounds being close, distant, harmonic, inharmonic, granulated.

*4 Dreams* presents the very first attempts to integrate state-space model's sonifications in the compositional process. In spite of being non-real-time, a DC motor model introduced the composer to the world of sonification techniques, revealing an organic quality in sound evolution. The model's behaviour was represented by a fixed data set that the composer used to create music objects of different typologies.

The composer created different holistic spaces within the same piece, by combining concrete sources with sonification materials that define contours, resonances and illusions of motion.

In *Superposition of Two Opposites* the composer developed further sonification techniques using an abstract model. The composer created several data sets representing the same model's behaviour and created a collection of sound objects

to create the piece. She also realised the potential for creating naturally evolving timbres when mapping two states simultaneously into the same synthesiser.

*Wake Up* and *Holly* opened new avenues for experimentation with real-time state-space models. Rather than being restricted with fixed data sets, the composer was able to generate the behaviours in real-time. In both pieces, the tape was created using a real-time inverted pendulum's model. The model is regarded as an additional force; a new instrument to complement or contrast the instrumental sounds, extending the instrumental timbres into the electroacoustic world.

*Fuzzbox* explores the possibilities of using real-time state-space model's sonifications in a live-electronics context. As the composer had discovered that each model has a strong identity, she experimented with the idea of thinking of the model as performer with whom a bass-guitar performer is encouraged to interact in an improvisatory way.

*Synthetic Springs* was composed mostly using a real-time state-space model of a spring-mass-damper system. The composer explored ways of creating timbres, gesture, spatial textures and motion illusions through the individual mappings per-channel in several multi-channel sonifications (de-correlation). The composer used synthesisers of different typologies to sonify the same model. Very long fragments of recorded sonifications defined an entire section in the piece, as they were musically engaging while still representing the model's behaviour.

*Time Paradox* combined sonifications of the spring-mass-damper and the inverted pendulum's models. The composer experimented with sound envelopes and delays to create effects of proximity, distance and timbral variations. The piece presented the challenge of integrating the model's language with a more instrumental approach presented by a set of singing bowls.

*The Silver Key* is a large scale piece incorporating sonifications of four state-space models and recordings of a koto. The flexibility of a real-time system allowed the composer to experiment with the creation of landscapes by superimposing sounds of different behaviours in a 16-channel system. The composer also created spatial illusions through the effects of de-correlation in sound by setting numerical deviations per channel in the sonification process.

It was possible, for instance, to create a spatial illusion of a room "full of springs" as the loudspeaker system was regarded as a 16-channel instrument having a spring-mass-damper model as a core element. The composer superposed behaviours of different models to create landscapes. The composer discovered that each model "imprints" its own identity into sounds and the sound itself evolves in organic ways. The composer used this behaviour to create gesture, texture, evolving behaviours and behavioural spaces.

The composer also plays with the koto's identity by transforming it through the model's, creating mixtures between koto's and model's typologies.

### Methodology

Through the compositions of the portfolio, the composer developed a methodology for the compositional process. It always started with observing different model's behaviours and thinking in meaningful ways of mapping the state-space into music parameters and at the same time thinking of a musical concept/idea to explore with the sonifications.

The sonification techniques can be summarised as follows: Each state in the model controls one or more music parameters through (simultaneous) amplitude and frequency modulations, granular synthesis and wave-table synthesis. Additionally, mappings for multi-channel approaches involve slight numerical variations per channel, to create de-correlation effects to enriched spatial textural sounds.

An experimenting stage was always involved, as not all sonifications were as engaging or musical as desired. The selection criteria were based mostly on timbral qualities: the sound should have some evolution in timbre and not just simply change perceived (fundamental) frequencies/pitches. The timbres could be of harmonic or inharmonic character, but the composer preferred sonifications where sounds organically go from one to the other (as in *Time Paradox*). If timbre was fixed, the composer preferred mapping behaviours to pulse duration or amplitude to create spatial texture (as in *Synthetic Springs* AM/FM synthesis). In some cases these also provoked changes in timbre as shortening and collapsing sound events created continuous sound with changes in timbre.

As the real-time models offer continuous evolutions, the composer made decisions on how to represent a continuously changing model with either short/interrupted, long or indefinitely evolving sounds. The evolution implies changes in timbre, length and dynamic range. As the model's behaviours are predictable, so is the sound, meaning that one of the affordances of the models is the power to predict sound behaviours, evolutions and arrival points when designing sonifications.

A further step was the selection of sonification experiments materials to start a second composition stage in the DAW, where sounds get reorganised, not only in time, but also spatially and also combined with other sound sources different from the sonification materials.

The composer realised that the sonification possibilities for each model are vast. As shown in this portfolio, the very same model can bring different timbres or sound qualities depending on which musical parameters are affected and which sonification techniques are used (sound transformation or sound synthesis).

## **A Software Tool**

An important research outcome is the creation of a software tool. The composer implemented objects in Max and SuperCollider, to be able to interact with state-space models in real-time.

The implementation of these real-time tools had a strong impact; rather than working with fixed data sets, the composer could afford exciting the models, generate behaviours and use them to transform sound in real-time. The composer realised that creating sound this way was not necessarily sonification, but could rather be regarded as a hybrid sound synthesis technique that combines physical modelling and abstract sound synthesis. This also influences the electroacoustic language because ways of representing these behaviours can be thought from the electroacoustic perspective to affect space, timbre, or sound evolution, disembodying the models. The composer considers the real-time models as “virtual instruments” that evolve according to the composer’s input and sonification skills.

## **Future Work**

The models used for this portfolio are very well known in the world of control engineering. New models representing other physical or abstract systems are yet to be explored and are considered as future work for this research. Further research could explore the application of these models in the context of live electronics and mixed media pieces.

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# Appendix A

## State-Space Models Implementation for Composition

In order to represent and sonify state-space models in a music creation environment, the composer designed several implementations in SuperCollider and Max. The following subsections describe briefly the implementation process.

### A.1 MatLab

All models used for the research were first simulated in MatLab to guarantee the models' stability and to test/validate their behaviours.

After the first sonification experiments, the composer decided implementing the models in Max and Supercollider, to be able to design sonifications in a more straightforward way and allow real-time interactions. The particular cases are discussed in the following sections.

### A.2 Max

The composer chose Max 6 for the first implementations (dc motor model and inverted pendulum). These were achieved in two ways: an abstraction model, and a JavaScript object

The first consists of an abstraction per model, based on IRCAM FTM objects which handle the linear algebra operations<sup>104</sup>. Each abstraction contains the particular matrixes for a system. The abstraction receives the user's input, and provides the systems' output in real time using a sample period  $T_s$  as a time base in milliseconds. If  $T_s$ , for instance, has a value of 10, each sample is calculated every 10 milliseconds. The second implementation consists of a JavaScript object to handle linear algebra operations with the same functionality as the first implementation<sup>105</sup>. Both, the abstraction based and JavaScript objects can be used as control/modulating signals for sonifications designed using any other Max/MSP objects. The composer developed the JavaScript implementation to improve performance, with respect to the FTM based implementation.

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<sup>104</sup>IRCAM IMTR. *A brief introduction to FTM*. URL: [http://ftm.ircam.fr/index.php/A\\_brief\\_introduction\\_to\\_FTM](http://ftm.ircam.fr/index.php/A_brief_introduction_to_FTM) (visited on 08/09/2015).

<sup>105</sup>For the implementation details see: Rosalia Soria-Luz. "State-Space Models: Virtual World for Composition". In: International Computer Music Association, 2015, pp. 178–181. URL: <http://hdl.handle.net/2027/spo.bbp2372.2015.035> (visited on 10/02/2016)

The behaviours of several models can be combined, as in the example shown in Figure A.2. To implement other systems, only the values in the matrixes have to be changed.

Additionally these objects work independently of audio processes, so that the models run even if the audio is off<sup>106</sup>. As the approach is to use the states as control signals for audio processes, it is not necessary that they run in audio rates and they also do not need to be sample accurate with respect to audio processing.

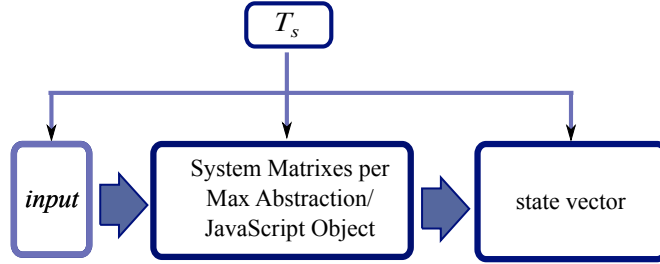


Figure A.1: State-space implementation in Max/MSP.

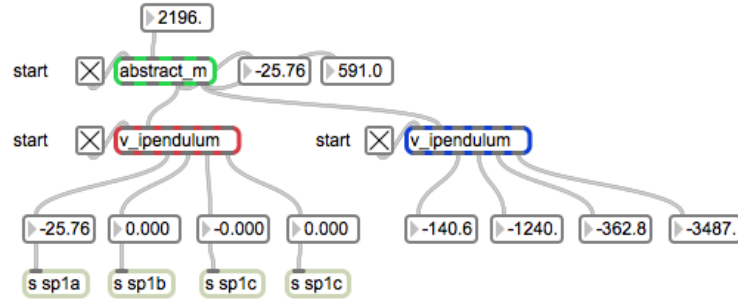


Figure A.2: State-space implementation in Max.

### A.3 SuperCollider

This implementation was achieved by creating a class to handle linear algebra matrix operations in real-time. A schematic diagram of the implementation is shown in figure A.3. The class arguments are the models' matrixes, and the user's input  $u$ . The class outputs the models' state vector. This vector updates in real-time according to the sampling period  $T_s$  which defines the time between each sample.  $T_s$  can also be modified in real time, the bigger this time the slower the system evolves and vice-versa<sup>107</sup>.

<sup>106</sup>For more details see (Rosalia Soria-Luz. "State-Space Models: Virtual World for Composition". In: International Computer Music Association, 2015, pp. 178–181. URL: <http://hdl.handle.net/2027/spo.bbp2372.2015.035> [visited on 10/02/2016])

<sup>107</sup>For details on the SuperCollider implementation see: Rosalia Soria-Luz. "Multichannel Composition Using Sonification and State-Space Models". In: *Proceedings of SMC Conference*. 2015. URL: <http://smcnetwork.org/node/1929> (visited on 25/02/2016)

The class allows the models to be independent from the audio signals, making the real-time interactions more efficient as they run at control rates rather than audio rates. The model's outputs can be used as modulating signals for any synthesiser or sound transformation process running in SuperCollider.

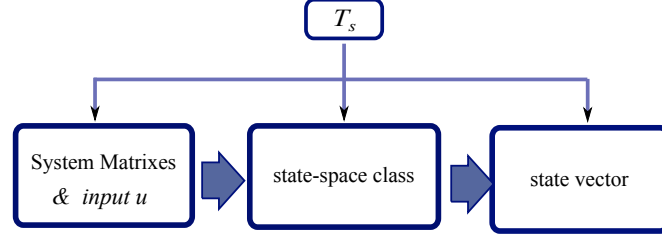


Figure A.3: State-space implementation in Supercollider.

Figure A.4 shows the state-space implementation in SuperCollider. The parameters in the synthesisers change according to the composer's mappings for the models. In general, the user interacts with the models by changing the inputs  $uc$ ,  $uc1$  and  $uc2$ . The sampling period is modified changing the value in  $t1$ . The preset buttons in the figure are meant run specific sonification routines that the composer designed for her compositions.

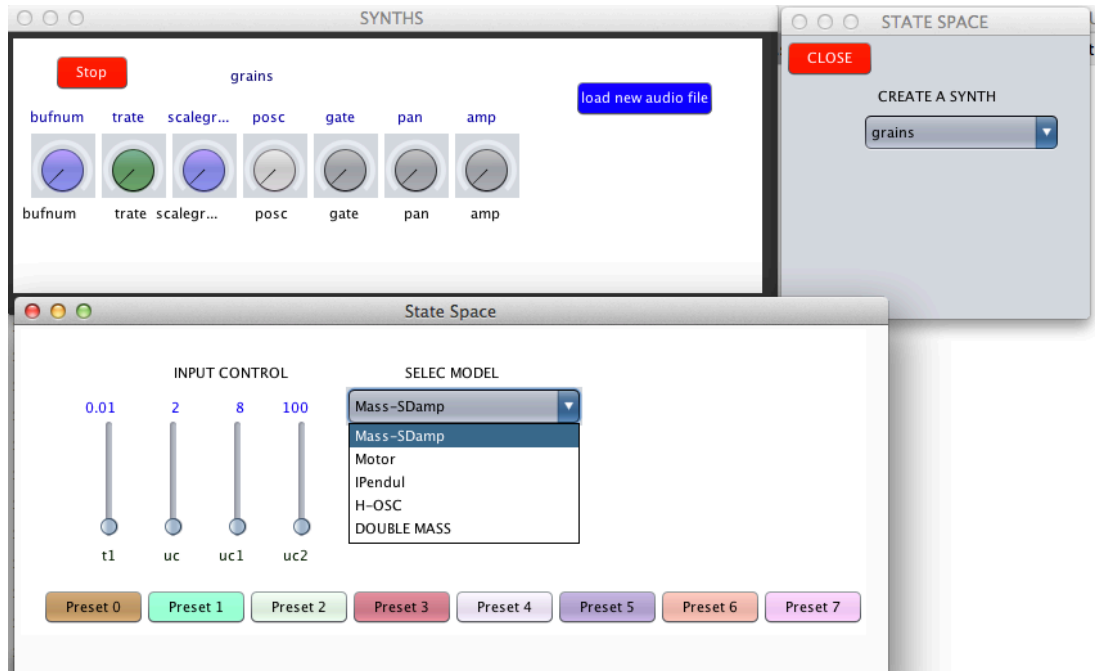


Figure A.4: Screen shot of state-space models environment implemented in SuperCollider.

# Appendix B

## Programme Notes and Performances

### **4 *Dreams*** (2013)

Format: 5.1

Duration: 12'16

The piece portrays four episodes of a daydream, going from behavioural spaces to a very peaceful enveloping space through the phrase “ergo sum”. The composer transforms recordings or to creates synthetic sounds based on the sonifications of an electrical motor’s state-space model. The piece presents textures and spaces built upon this sonifications. The composer combines this materials with the recordings of an oud, crotales, a plastic bracelet, and voice. Each of them defines a specific episode in the dream.

#### Performances

*4 Dreams* was premiered on the 26<sup>th</sup> of October 2013 at the MANTIS Fall Festival. The John Thaw Studio Theatre, Martin Harris Centre, Manchester.

### ***Superposition of two opposites*** (2013)

Format: 8-channel

Duration: 8'36

This piece is originally inspired by the image “Superposition of two opposite ‘twisting’ light modes”, from the laboratories of quantum scientists at the University of Vienna. The composer explores the superposition of several textures based on string and vocal sounds; and oscillating synthetic objects produced by an abstract state-space model. These textures are also contrasted with concrete objects to create three different spaces that evoke movement, tension, and calm environments.

#### Performances

*Superposition of two opposites* was premiered on the 2<sup>nd</sup> of March 2014, at the MANTIS Spring Festival, at The John Thaw Studio Theatre, Martin Harris Centre, Manchester.

A short stereo version was released online in October 2013<sup>108</sup>.

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<sup>108</sup> *Exhibition: Physik & Musik: Superposition of two different “twisting” light modes (Soria Luz)*. URL: [http://call4sounds.neuesatelier.org/2013/09/superposition-of-two-different-twisting\\_12.html](http://call4sounds.neuesatelier.org/2013/09/superposition-of-two-different-twisting_12.html) (visited on 03/31/2016).

### ***Wake Up*** (2014)

For two violins and stereo tape.

Duration: 8:34

The piece is inspired on ideas from Jean-Paul Sartre's novel "La nausée", where its protagonist has trouble defining himself.

The composer explores timbral possibilities based on combinations of strings, synthetic sounds and transformations of recorded strings. The tape was composed using an inverted pendulum and DC motor state space models. The composer regards the models as sound transformation agents and as additional forces integrating with the violin duo. Sound transformations expand the violin's timbre in to the electroacoustic world and are not necessarily meant to complement or expand the violin's capabilities.

#### Performances

*Wake Up* was premiered on the 7<sup>th</sup> of June 2014, at the "Chapelle de Monty" in Liege, Belgium.

### ***Synthetic Springs*** (2014)

Format: 8-channel

Duration: 10'38

This piece is a metaphor for my favourite season in England. It portrays days in spring, sunrises and life blossoming after the cold winter.

The piece is composed using synthetic sounds mostly, some are percussive, and other are rather textural. They were created through different sonifications of real-time mass-spring-damper state-space model. In both senses, the piece is a very particular representation of synthetic springs.

#### Performances

*Synthetic Springs* was premiered on the 25<sup>th</sup> of October 2014 at the "Sines and Squares Festival" at The John Thaw Studio Theatre, Martin Harris Centre, Manchester.

### ***Holly*** (2015)

For Flute, piano, hyoshigi, bass drum and stereo tape.

Duration: 5'06

This piece is inspired on the character “Holly Short”, from Eoin Colfer’s *Artemis Fowl* books. I combined the sounds played by the performers with synthetic sounds I created through sonifications of a spring-mass-damper model. The synthetic sounds have a distinctive personality, and are meant to represent an artificial character, contrasted to the natural timbre of the instruments.

Instruments and synthetic sounds represent Holly’s sparkling and emotional character, specially depicted by the flute.

#### Performances

*Holly* was premiered by the ensemble Psappha, on the 6<sup>th</sup> of March 2015, at the Cosmo Rodewald Concert Hall at the Martin Harris Centre for Music and Drama Manchester.

### ***Time Paradox*** (2015)

Format: 8-channel

Duration: 10'38

*Time Paradox* takes inspiration on the concept of time paradox, and the idea of time travelling. It explores the concepts of motion, elongation, and contraction through sound. For this piece I created synthetic sounds which evolve from harmonic to inharmonic characteristics. I also use sounds of evolving timbres that play with the idea of closeness and distance. I created spaces and textures by combining synthetic sounds, with recordings of a set of tibetan singing bowls. Their harmonic characteristics and their resonances are used as a contrast to the moving, evolving synthetic sounds.

#### Performances

*Time Paradox* was premiered on the 28<sup>th</sup> of February 2015, at the MAN-TIS Spring Festival, at The John Thaw Studio Theatre, Martin Harris Centre, Manchester.

***Fuzzbox*** (2015)

Electric bass and live electronics. Duration: 9:58

This piece presents the idea of a performer on stage performing together with a mathematical model that creates sound transformations. The composer pre-decides the trajectories the model should follow in order to transform the electric bass in real-time. The performer plays some materials, and then the model reacts with certain transformations.

***The Silver Key*** (2015/2016)

Format: 16-channel

Duration: 24'12

*The Silver Key* is a large-scale 16-channel piece, inspired on the story “The Silver Key” by the American writer H. P. Lovecraft. The story is one of his “Dreamlands” series, where he portrays an alternate dimension with vast cities and lands that can only be accessed via dreams. The music consists on five sections as a metaphoric allusion to these dreamlands, conceived as abstract landscapes. The source materials include recordings of a koto and synthetic sounds created using several state-space models. Sound transformations, timbres, behaviours and trajectories are based on sonifications of these models.

Performances

*The Silver Key* was premiered on the 5<sup>th</sup> of March 2016, at the MANTIS Spring Festival, at The John Thaw Studio Theatre, Martin Harris Centre, Manchester.

# Appendix C

## Papers

### State-Space Models: Virtual World for Composition

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#### ABSTRACT

*This paper presents sonifications of linear state-space mathematical models commonly used in control engineering as a source for electroacoustic music composition. These models can represent dynamical physical systems with the advantage of providing a states vector. In this paper the contents of that vector is generated and sonified in real time. This allows the composer to experiment with timbre, gesture and texture through manipulating the models input. The paper presents two specific systems implemented in Max/MSP and SuperCollider: an inverted pendulum and a spring-mass-damper. Examples of their use in multichannel sound synthesis and composition are provided.*

#### 1. INTRODUCTION

Auditory displays and sonifications have gained attention as alternatives for representing data and information. The accuracy and simplicity of aural representations is of great significance, but the aesthetic aspect has also become more and more important [1]. And in recent years sonifications have been intentionally used as sound sources for composition [2].

State-space models are commonly used in control engineering for system modeling, controller design and simulation, as they provide a compact way for representing and monitoring physical systems. These models can be adapted to represent variables of interest. Applying the same mathematical principles, they can be used to shape and control sound. The paper presents the implementation of two state-space models in Max/MSP and SuperCollider: an inverted pendulum, and a spring-mass-damper system, as well as their use as an interactive tool for sonification and electroacoustic composition.

##### 1.1 General Description

State-space models describe physical systems through  $n$  differences equations grouped in a vector-matrix equation. The model consists of a set of inputs, outputs and state variables expressed as vectors. The dynamics of the system can be described as a function of the state vector and the input signal. In other words, it is possible to determine the behavior and

evolution of a system at any time  $t > 0$  if the value of the state vector and the input at that time are known [3].

A general state-space representation of a continuous linear time-invariant system with  $m$  inputs,  $p$  outputs and  $n$  state variables is written in the form:

$$\begin{aligned}\dot{x}(t) &= Ax(t) + Bu(t) \\ y(t) &= Cx(t) + Du(t)\end{aligned}\quad (1)$$

Where  $x(t) \in R^n$  is the  $n$ -dimensional state vector,  $u(t) \in R^m$  is the  $m$ -dimensional input vector, and  $y(t) \in R^p$  is the  $p$ -dimensional output vector [4].  $A$ ,  $B$ ,  $C$  and  $D$ , are constant matrixes defined by the system parameters. A digital version of the continuous representation is obtained by sampling the system (1) and has the form:

$$\begin{aligned}x(k+1) &= \Phi x(k) + \Gamma u(k) \\ y(k) &= Cx(k) + Du(k)\end{aligned}\quad (2)$$

Where  $\Phi = e^{AT_s}$  and  $\int_0^{T_s} e^{As} ds$  are obtained by considering a zero order sample and hold circuit with a sampling period  $T_s$  [5].

#### 2. IMPLEMENTATION

The implemented models have the form (2). For SuperCollider the class "States" was written to handle linear algebra operations; it takes as arguments any  $\Phi$ ,  $\Gamma$ ,  $C$ ,  $D$ , and  $u$ . The output is the states vector, which is updated in real time according to the input value  $u$ , and a sample period  $T_s$ . For Max/MSP, different JavaScript objects were developed. Each object contains the specific matrixes  $\Phi$ ,  $\Gamma$ ,  $C$ , and  $D$  for a model. They can take any numerical Max/MSP signal as input. The output state vector is updated in real time according to the input  $u$  and the sample period  $T_s$ .

##### 2.1 Inverted Pendulum

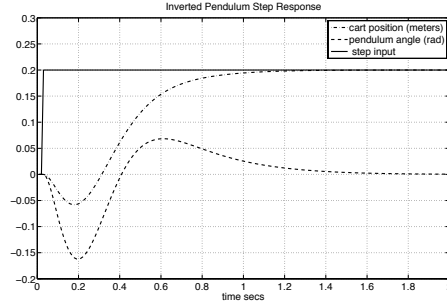
The system consists of an inverted pendulum coupled to the top of mobile cart as depicted in [6]. The input represents a desired new position for the cart. The aim is that the inverted pendulum reaches the vertical position once the cart arrives to the new position [7].

To validate the model the step response is used. This means applying a signal from 0 to a constant amplitude, to test the response to an abrupt change. The system outputs are cart position and pendulum angle. Figure 1(a) shows the step response

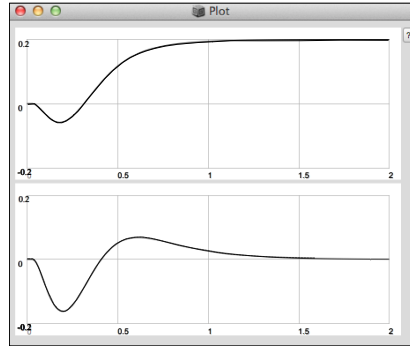
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of the inverted pendulum simulated in MATLAB when applying a step input of 0.2 amplitude<sup>1</sup>. Figure 1(b) shows the step response of the model implemented in SuperCollider. In both figures, the cart arrives to the desired position and the angle is 0, which means pendulum has reached the vertical position. The same validation for this model was applied to the implementations for Max/MSP although for simplicity it is not shown in this paper.



(a)



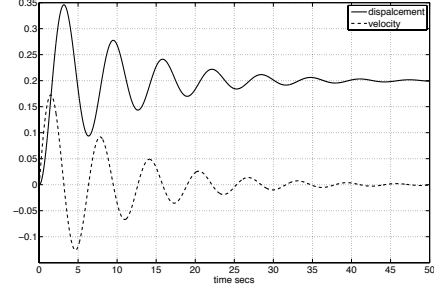
(b)

**Figure 1.** Inverted pendulum step response. (a) MATLAB Simulation, (b) SuperCollider implementation.

## 2.2 Spring-Mass-Damper

The implementation follows the system described in [8], with mass  $m = 1\text{ kg}$ ,  $k = 1\text{ N/m}$ , and  $b = 0.2\text{ Ns/m}$ . The continuous system is sampled using a sampling period  $T_s = 0.1$  seconds. The model outputs represent the mass position and mass speed. When a force is applied to the mass it will generate an oscillatory movement exponentially decaying in amplitude. If the input remains static the mass will eventually reach a stationary position. Figure 2 shows the system step response simulated in MATLAB.

<sup>1</sup> Meaning a change in position from 0 to 20 cm.

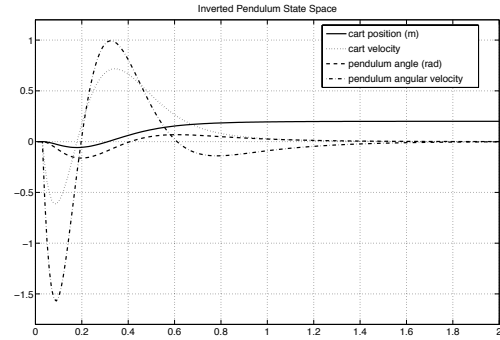


**Figure 2.** Mass-spring-damper step response (MATLAB).

## 3. SSM AND SONIFICATION

State-space models provide a states vector. The variables in this vector represent the state-space of the system. For instance, the state-space of the inverted pendulum consists on the variables cart position, cart velocity, pendulum angle, and pendulums angular velocity. These four variables will evolve over time accordingly when an input is applied.

Figure 3 shows the evolution of the state variables for the inverted pendulum for the step input of 0.2 amplitude. If the input remains static, the states eventually reach a stationary state. If sonification is used to represent the system states



**Figure 3.** Inverted pendulum state-space.

instead of a graph, it is possible to have up to 4 variables to be mapped simultaneously into sound parameters in real time. The aim of the sonification is to find musical meaningful mappings rather than merely representing the models behaviour. The states can be mapped either into oscillators control rate parameters to generate sound synthesis, or sound transformation parameters such as time delay, granular synthesis, etc. The models can be excited in real time, slowed down, accelerated or frozen by manipulating the sample period  $T_s$ . This implies that certain timbres can be frozen if desired. Slowly changing the input  $u$  can create textures, mak-

ing abrupt changes in the input signal can generate gestures<sup>2</sup>, and simply letting the models arrive to their stationary state can create smooth musical transitions.

#### 4. STATE-SPACE MODELS IN COMPOSITION

##### 4.1 Sonifying SSM

Following are a few examples about possible ways of sonifying state-space models and their use in composition.

##### 4.2 Inverted pendulum

Once the output vector states are available in real time and dependant on an input signal, it is possible to make sonifications in real time. For example, a two dimensional wave object in Max/MSP is used to create synthesis. The 4 output states of a virtual pendulum are mapped simultaneously into 4 input parameters of the 2d.wave object as shown in Table (1). The composition process then consists on choosing meaningful scaling values for the system states and planing the sonic outcome depending on these values and the system behaviour.

State	scaled output	2dwave Parameter
position	150 - 3750	start point
velocity	0.01 - 40	y phase
angle	1-8	x phase
angular velocity	25 - 200	No. rows

Table 1. Inverted pendulum sonification using Max/MSP.

The selected input range includes values between -4000 and 4000. The system input  $u$  can be manipulated either by typing values, using a slider object and/or using a midi controller. As the input changes, different timbre transformations can be heard and also, when the pendulum reaches its stationary state<sup>3</sup>, the sound quality stops changing. If the input is constantly changing, the stationary state is not reached and the transformations continue. It is important noticing that the cart's position determines the reading start point in the 2d.wave's buffer. In other words reading start point is directly related to the the system input  $u$ . A recording of this sonification using a crotale recording as sound source can be found at<sup>4</sup>.

A stereo sonification using SuperCollider and AM/FM modulation is presented in Figure 4. The system input  $u$  can be manipulated either by typing values and/or using a midi controller. Position is mapped to the parameter  $f1$ , which is scaled and used as the frequency of the sawtooth wave. Velocity is mapped to the parameter  $f2$ , scaled and used as a frequency for a sine wave. To give variety to the sound the scaling factors are different per channel.

<sup>2</sup> "A gesture is therefore an energy – motion trajectory which excites the sounding body [...]" [9].

<sup>3</sup> A new position has been reached and the pendulum has returned to the vertical position.

<sup>4</sup> <https://www.escholar.manchester.ac.uk/uk-ac-man-scw:264499>

The cart position determines the frequency (pitch quality) of the sound, whereas the velocity determines the timbre quality. When the scaled velocity is less than 20, the sound has a more percussive rhythmic character, more evident when close to 0. For higher velocity values the timbre changes and is no longer percussive like. Therefore if we desire a percussive rhythmic quality, we have to let the pendulum arrive to the equilibrium position. The sound's pitch will be proportionally related to the position value – the bigger this value, the higher the pitch. If we are not interested in rhythm then we should vary the input values and freeze the system when a satisfactory timbre is reached. In addition, sound evolves more or less smoothly between timbres depending on the value of  $T_s$ . A recording of this sonification can be found at<sup>5</sup>.

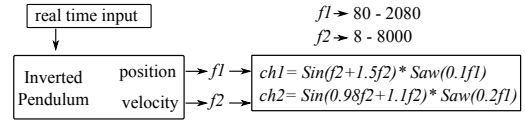


Figure 4. Inverted pendulum stereo sonification example.

##### 4.3 Mass-spring-damper

A sonification for the mass-spring damper system using a vosim synthesiser is shown in Figure 5. It consists of 8 carriers, one per channel. Each carrier is modulated by the same states, so the resulting sounds are related per channel. Each carrier, however, is slightly different from each other due to the scaling factors. The model is excited by freely choosing dynamic input values between 0.2 and 15000. More gestural sounds are obtained when the input jumps between extreme input values, with  $T_s$  of approximately 0.02 seconds, and more textural when the input varies smoothly.

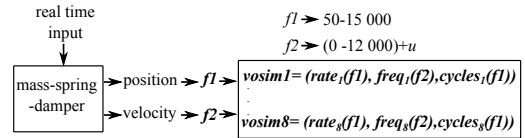


Figure 5. Mass-spring-damper 8-ch sonification example.

As the model is excited with different values, different timbres are generated, more rhythmical for input signals below 100, and more textural for inputs above 400. In most cases it is possible to recognise the behaviour of the system itself; i.e. when applying a force, the mass bounces until finally reaching a stationary point. A short recording of this sonification can be found at<sup>6</sup>.

<sup>5</sup> <https://www.escholar.manchester.ac.uk/uk-ac-man-scw:264513>

<sup>6</sup> <https://www.escholar.manchester.ac.uk/uk-ac-man-scw:264532>

## 5. MUSIC EXAMPLE

Synthetic Springs is a fixed media 8 channel piece based on the sonified mass-spring-damper system model implemented in SuperCollider. The sound sources are derived from the vosim based sonification presented in Figure 4; a 4 channel expansion of the synthesiser of Figure 5 controlled with the mass spring damper system; a stereo FM sonification, and a stereo recording of piano string.

The composition process consisted on experimenting with the model sonifications to find satisfactory sound characteristics, recording and making selections to include in the piece. Figure 6 presents the sound material distribution in the piece. The 8 channel vosim sonification textural quality was used (1'10", 3' to 4'45"), and also its gestural behaviour (5'35" to 6'50"). The 4 channel AM/FM sonification provides a rhythmic quality (1'40" to 3'), and transitions between rhythmic quality and texture (6'50" to 8'46"). The stereo FM sonification and piano recording are more localised sound sources used to provide contrast in timbre.

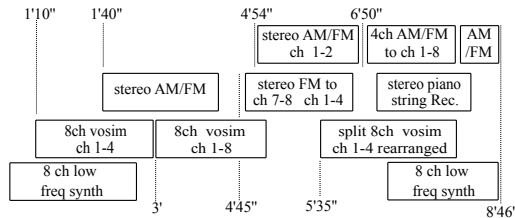


Figure 6. *Synthetic Springs* sound material diagram.

For some sections specific channels were selected, i.e. stems of only 4 channels of the vosim synthesiser, or stereo pair of the 4 channel AM/FM synthesiser. Additionally, some sounds were spatially relocated or expanded following musical ideas. The piece also includes sounds not generated using model sonifications such as a 8 channel low frequency synthesiser that can work as cohesive material. A stereo reduction of this piece can be found at <sup>7</sup>.

### 5.1 State-space models as interactive tool

SSM are suitable for interaction not only with SuperCollider or Max/MSP objects, but also external controllers such as midi, OSC or any kind of sensors. They can be excited and sonified in real time. As tested implementations are valid for models up to 4th order (4 states), any dynamic system with these characteristics can be represented in SuperCollider and Max/MSP, provided that matrixes  $\Phi$ ,  $\Gamma$ ,  $C$  and  $D$  are known.

## 6. CONCLUSIONS

State-space models used in composition are a very powerful tool for creating sound synthesis and transformations. This implies that part of the compositional process relies on the

meaningful mapping of state-space vectors. So, when these states are all mapped simultaneously into sound parameters, particular characters and behaviours are generated that would be difficult to obtain otherwise. One important aspect is the creation of multichannel sonifications, which explore textural and rhythmic effects involving the spatial factor. SSM can be seen as customisable instruments that can be played in real time. SSM not only represent physical systems, but also chemical, economical, etc., which means a great variety of objects that can be used and virtually connected to create new sonifications. Future work includes experimenting with multi-input and non-linear state-space representations.

### Acknowledgments

The author thanks The University of Manchester PDS awards organisation for funding this research.

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<sup>7</sup> <https://soundcloud.com/rosalia-soria/synthetic-springs-stereo>.

# MULTICHANNEL COMPOSITION USING STATE SPACE MODELS AND SONIFICATION

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## ABSTRACT

This paper investigates the use state space models and real time sonification as a tool for electroacoustic composition. State Space models provide mathematical representations of physical systems, making possible to virtually capture a real life system behaviour in a matrix-vector equation. This representation provides a vector containing the so called states of the system describing how a system evolves over time. This paper shows different sonifications for state space models and ways of using them in multichannel electroacoustic composition. Even though conventional sound synthesis techniques are used for sonification, very peculiar timbres and effects can be generated when sonifying state space models. The paper presents an inverted pendulum, a mass-spring-damper system, and a harmonic oscillator, implemented in Supercollider, and different real time multichannel sonification approaches, as well as ways of using them in electroacoustic composition.

## 1. INTRODUCTION

Sonification has become a very important tool to convey information and represent/analyse data using sound. In recent years a musical interest has developed as a result of the aesthetic awareness on the different ways of representing data in meaningful ways [1] [2] [3]. This paper investigates the uses of real time sonification as a source for electroacoustic composition. A motivation to use state space sonifications in composition is finding ways to produce synthetic sound which evolves in an organic way.

Sonifying State Space models can be described as a parametric model based interactive sonification [4]. It is based on the implementation of physical systems, as mathematical models in their State Space form, and the possibility of exciting and sonifying them in real time. The advantage of the State Space form is that a vector containing the states of system can be available in real time, making simultaneously available several variables from the same system. The aim in these sonifications is not necessary accurately representing the system's behaviour, but rather looking for interesting sound timbres, or behaviours when simultaneously mapping all system variables into sound generation,

or sound transformation parameters. A multichannel approach is used to add an spatial element in the composition process.

## 2. STATE SPACE REPRESENTATIONS

State Space mathematical models are a useful tool to represent dynamical physical system's behaviour in a compact way. Provided the system is linear and time invariant, it is possible to formulate a matrix equation that describes the systems behaviour. The matrix representation is called the State Space representation of a continuous system dynamics and can be written as follows:

$$\begin{aligned}\dot{x}(t) &= Ax(t) + Bu(t) \\ y(t) &= Cx(t) + Du(t)\end{aligned}\quad (1)$$

Where  $x(t) \in R^n$  is the n-dimensional state vector,  $u(t) \in R^m$  is the m-dimensional input vector, and  $y(t) \in R^p$  is the p-dimensional output vector. A and B are constant matrixes, containing information about the characteristics defining the system. C determines which states are the model outputs, and D is a feedback matrix connecting directly the output to the input [5].

The SSpace representations used for this paper consist of one input and  $n$  outputs, depending of the nature of the system. The implemented models are sampled digital representations of the continuous systems.

The sampled version of (1) with sampling period  $T_s$  can be represented as follows:

$$\begin{aligned}x(k+1) &= \Phi x(k) + \Gamma u(k) \\ y(k) &= Cx(k) + Du(k)\end{aligned}\quad (2)$$

Where  $\Phi = e^{AT_s}$  and  $\int_0^{T_s} e^{As} ds$  are obtained by considering a zero order sample and hold circuit, and the simplified notation  $k$  refers to a general time  $t_k \in \{t_0, t_1 \dots t_N\}$  [6].

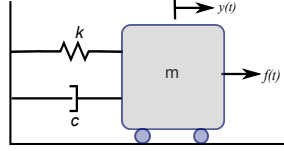
## 3. SYSTEM DESCRIPTION AND IMPLEMENTATION

The three specific systems are described briefly to understand the physical nature of their behaviour. Although the description shows the continuous systems, the implemented ones are digital representations of them, and in the state space form (2).

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### 3.1 Mass-Spring-Damper

The mass-spring-damper system is depicted in Figure 1. The input to the system is the force  $f(t)$  applied to the mass. The system outputs  $y(t)$  are the mass position (displacement) and velocity [7].



**Figure 1.** Implemented Mass Spring Damper system illustration.

When a force is applied to the mass, it will start a unidimensional movement in the direction of the applied force. This movement has an oscillatory elastic nature due to the action of the spring( $k$ ), and will be dampen due to the action of the damper( $c$ ). The movement will eventually stop if no further force is applied.

The implemented sampled version of this system with  $m = 1kg$ ,  $k = 1N/m$ ,  $c = 0.2Ns/m$ , sampling period  $T_s=0.1s$ , and in the form (2) has the following system matrixes:

$$\Phi = \begin{bmatrix} 0.99503 & 0.09884 \\ -0.09884 & 0.97526 \end{bmatrix}, \Gamma = \begin{bmatrix} 0.00496 \\ 0.09884 \end{bmatrix}, \quad (3)$$

$$C = [1, 1], \quad D = 0$$

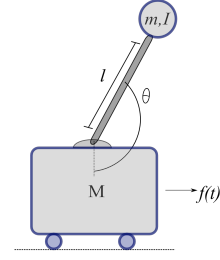
### 3.2 Inverted Pendulum

The inverted pendulum system is depicted in Fig 2. The system consists of an inverted pendulum mounted on a mobile cart. If the system is not controlled, the pendulum will fall over when an input force is applied to the cart. For this reason a controlled system was implemented [8]. The aim of the controller is that when the cart is displaced to a desired position, the pendulum is able to come back to equilibrium vertical position. The input of the system is a number representing a desired position for the cart (meters). The outputs are the cart's displacement (meters), cart's velocity, the pendulum angle (radians) and pendulum angular velocity.

The inverted pendulum with  $M = 0.5$ ,  $m = 0.2$ ,  $I = 0.006$ ,  $l = 0.3$  and a sampling period  $T_s = 0.02$  secs is represented by the following matrixes:

$$\Phi = \begin{bmatrix} 1.0056 & 0.0130 & -0.0085 & -0.0017 \\ 1.1263 & 1.6069 & -1.7003 & -0.3420 \\ 0.0141 & 0.0076 & 0.9800 & 0.0057 \\ 2.8168 & 1.5178 & -4.0073 & 0.1460 \end{bmatrix}, \quad (4)$$

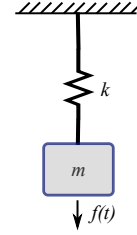
$$\Gamma = \begin{bmatrix} -0.0056 \\ -1.1263 \\ -0.0141 \\ -2.8168 \end{bmatrix}, C = [1, 1, 1, 1], \quad D = 0$$



**Figure 2.** Implemented Inverted Pendulum physical representation.

### 3.3 Harmonic Oscillator

A harmonic oscillator system representation is depicted in Figure 3. It consists of a mass attached to a spring and connected to a rigid wall in a non friction environment. If no force is applied, the mass remains in its equilibrium state. If a force is applied to the mass, an elastic force due to the spring will try to restore the equilibrium state, producing a periodic movement. The system input is therefore a force applied to the mass, and the outputs are the mass unidimensional position, and velocity [9] [10].



**Figure 3.** Harmonic Oscillator physical representation.

The digital implemented system with  $\sqrt{k/m} = 133$  and  $T_s = \pi/32$ , is represented by the following matrixes:

$$\Phi = \begin{bmatrix} 0.8819 & 0.4714 \\ -0.4714 & 0.8819 \end{bmatrix}, \Gamma = \begin{bmatrix} 0.1181 \\ 0.4714 \end{bmatrix}, \quad (5)$$

$$C = [1, 1], \quad D = 0$$

### 3.4 SuperCollider Implementation

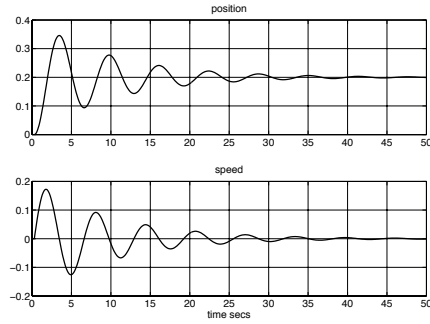
The implementation in Supercollider was achieved by creating a class to handle linear algebra matrix operations. The class arguments are the matrixes  $\Phi, \Gamma, C, D$ ; and the numeric input  $u$ . The class outputs are systems state vector  $x$ . State variables update in in real time according to the sampling time parameter  $T_s$ , which can also be modified in real time.

The implemented systems work according to the following criteria: (1) All systems require only one numeric input; (2) the systems state space is the set of variables in the vector  $x(k)$  describing the systems behaviour (i.e. position and velocity in the mass-spring damper system); (3)

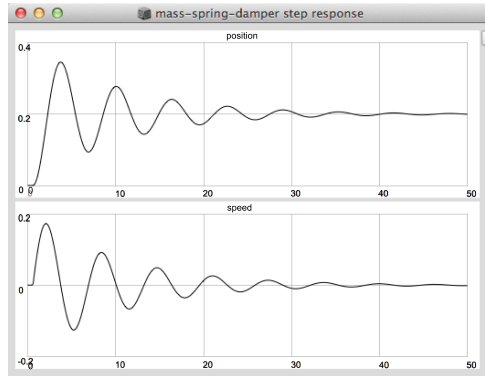
the output vector depends on the matrix  $C$ , the elements in this vector represent physical variables of the system; (4) the system's current output depends on the current input value, a previous input value, the current state and a previous state; (5) the system's output vector updates according to a sample period time parameter; (6) the numeric input  $u$ , and sample period  $T_s$  can be changed in real time: the output state vector updates accordingly to this values.

### 3.5 Validation

A way of validating the implemented models is obtaining the step response. For simplicity in this paper, only the mass-spring-damper system step response is shown, although a similar process was applied to the inverted pendulum and harmonic oscillator models. Figure 4 shows the mass-spring-damper system step response simulated in Matlab, and the implemented system response in supercollider. The step response represents how the system variables behave when a force of 0.2N is applied.



(a) Step Response: Matlab



(b) Step Response: Supercollider

**Figure 4.** Mass-spring-damper system step response. (a) Matlab Simulation, (b) Supercollider Implementation.

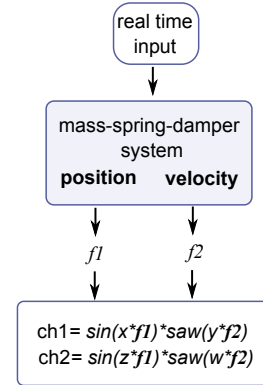
## 4. SONIFICATION AND SSPACE MODELS

### 4.1 Sound Synthesis

A first sonification approach is generating sound synthesis. This can be done by simultaneously mapping all outputs from a chosen system into different parameters of the same synthesiser. Even though AM and FM techniques are used to create these sonifications, sound becomes part of the model dynamics and evolves in an organic way as the modulating signals come from the same system.

As an example, a combination of AM/FM sound synthesiser was used to sonify the mass-spring-damper system. As the model behaviour is available in real time, it is possible, to "virtually play it" by applying numerical inputs in real time.

Having in mind that the output variables represent position and velocity, it is possible to design a synthesiser to sonify them. Figure 5 shows the stereo sonification process schematic diagram. The position is mapped into the  $f1$  parameter, it is scaled and used to modulate in frequency a sine wave. The velocity is also mapped into a  $f2$  parameter, after scaling, it modulates in frequency a saw tooth wave. However the scaling factors are different between channels, this is represented by the coefficients  $x, y, z$ , and  $w$  in the schematic diagram. This gives more diversity to the sound although both channels are related as both are sonifications of the same model.



**Figure 5.** Mass-Spring-Damper system stereo sonification example.

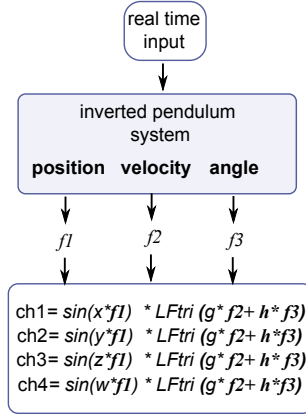
Once the synthesiser is set-up, the numerical input can be changed in real time and the sound will evolve in time according to the system. What is expected is behaviour as depicted in Figure 4, sinusoidal oscillations exponentially decaying. This means that if the input doesn't change, the output states will reach a stationary state with almost no oscillations. A recording of this sonification process can be found at [11].

Using the same synthesiser it is also possible to sonify the harmonic oscillator. This system is also oscillatory, but as it doesn't have any damping or elastic elements, it will continue oscillating without decaying with an amplitude proportional to the input force applied. Even though the same

synthesiser is used, the sound has a different behaviour, making it possible to have variations of the same timbre. This fact can be heard at [12].

#### 4.2 Multichannel approach

It is also possible to expand the stereo sonification idea to a multichannel approach. This can be achieved by creating multichannel synthesisers all driven simultaneously by the same model. As an example, a 4 channel sonification for the inverted pendulum is depicted. The 4ch synthesiser is designed to have three control variables. Three output variables of the inverted pendulum are therefore mapped to simultaneously control this variables. The cart position is scaled and mapped so it modulates in frequency a sine wave, however the scaling factor is different for each channel. This is represented by the letters  $x$ ,  $y$ ,  $z$  and  $w$  in Figure 6. The cart velocity is scaled by the same factor for all channels, this is represented by letter  $g$  in Figure 6, and a similar process is applied for the pendulums angle. The velocity and angle modulate in frequency a low frequency triangle wave.



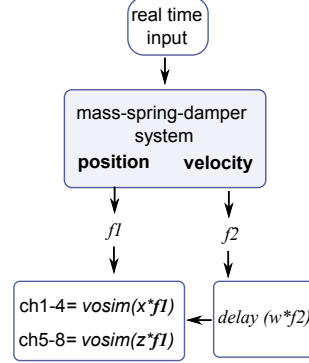
**Figure 6.** Inverted Pendulum system. 4-ch sonification example.

The expected behaviour is an oscillating movement that will settle when it reaches the desired position according to the numeric input. Velocity will settle at 0 when the final position is reached, and the same will happen for the angle, as the pendulum has to end up in a vertical position. This means that after a change in the input, sound will vary according to changes in position, velocity and angle; if the input doesn't change, the sound will reach an stationary state. A recording of this sonification example can be found at [13].

#### 4.3 Sound transformation

Sonification can also be achieved by transforming sound. As an example, a vosim oscillator is used to sonify the spring-mass-damper system. The position is scaled and mapped into frequency parameters whereas the velocity is also scaled and used to modify a time delay parameter that

affects the vosim oscillator. Figure 7 shows a schematic diagram for this example. A fragment of this sonification can be found at [14].



**Figure 7.** Inverted Pendulum system. Sound synthesis and sound transformation 8-ch sonification example.

### 5. COMPOSING WITH SSPACE MODELS

#### 5.1 Sonifications and Sound Synthesis

As the models behaviour is available in real time, a combination synthesiser-sonification can be seen as an instrument that can be played in real time. Depending on the mapping and synthesiser complexity, it is possible to generate different gestures, textures [15] and timbres.

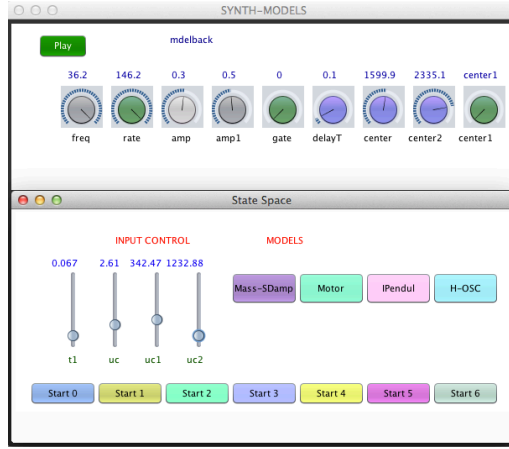
This implies that the composition process includes a sound synthesis design step which involves choosing a model to sonify; awareness of the model's behaviour to achieve meaningful mappings of the different parameters (knowing numeric range of the outputs for different inputs and consider this when scaling variables); and experimenting with pairs model - synthesiser to explore behaviour and timbre possibilities for different inputs.

So far only the input-output aspect of the models has been discussed. However, there is a third factor included in the implementation and that is the sample period  $T_s$ . This parameter controls how often the output states update according to the input. Even though this parameter could remain fixed, it is possible to change it in real time to virtually "time stretch" or expand the systems behaviour, or even more, to freeze the system time evolution, making it possible to time stretch, expand, or freeze timbres.

Figure 8 shows an interface created in Supercollider to interact with sonification synthesisers and model parameters in real time.

The state space input window allows the user to interact with the models by changing the input parameters according to Table 1.

The total input to the model is  $U = uc + uc1 + uc2$ ; this combination is useful to have different input resolutions. The buttons labeled as start 0 to start 6 trigger the models real time evolution, for different customized sonifications. When active, the chosen model updates in real



**Figure 8.** Supercollider interface to interact in real time with state space models and sonification synthesisers.

Symbol	Parameter
t1	Sampling period value in secs (0.01-1)
uc	Model input value 0 -10
uc1	Model input value 0 -100
uc2	Model input value 0 -1000

**Table 1.** Interface parameter to interact in real time with state space models.

time; if not active, the model remains in the latest updated state. The interface also allows switching between models by pressing the desired button, allowing different models to be sonified by the same synthesiser.

The start/stop buttons, as stated earlier, update the models outputs in real time. However, if inactive, the selected model is frozen, meaning the current state is frozen, therefore timbre is frozen. In this condition it is also possible to manually change the synthesiser parameters. For example in Figure 8, "freq", "rate", etc. That means manually manipulating the timbre once the model has brought the synthesiser to a particular timbre.

## 5.2 Sonic Outcomes

Even though stereo sonifications can create interesting timbres, the multichannel sonification approach allows experimenting with timbre and space in a wider sense.

One possibility is the creation of sound families by placing numerically related sounds, a different one per speaker, but all controlled by the same model. An example of this is the sonification depicted in Figure 6. In this case timbre also includes the spatial factor.

A second option is multichannel gesture and texture generation. This can be controlled by manipulating the sampling period parameter  $T_s$  in the model input: if short, the models arrive faster to a stationary state, creating gesture; if  $T_s$  is larger, sound evolves slowly creating smooth transitions and texture.

In addition of different panning effects in selected groups of speakers by controlling this parameter with state space models.

## 5.3 Composition Possibilities

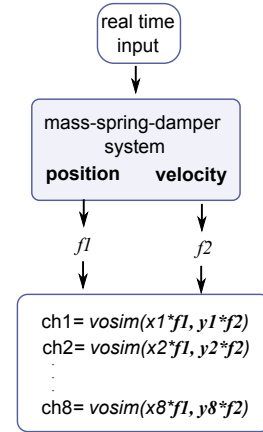
Once a satisfactory sonification is achieved, real time interactions can be recorded and used in fixed media or mixed media compositions. Some possibilities are including directly recorded sonification excerpts, they may be as long as desired; splitting multichannel sonification recordings; spatially rearranging them or using only selected audio channels; applying further sound transformations to any of the above.

## 5.4 Example: Time Paradox

### 5.4.1 Sonifications and Structure

Time Paradox (2015) is an 8 channel fixed media piece composed using sonifications of the mass-spring damper system and singing bowls stereo recordings. The sonifications were designed to fit in stems of 4 or 8 channels. This offers the possibilities of locating sound families in different spatial locations when using 4ch sonifications, and to create more atmospheric textures of related sounds when using 8 ch synthesisers.

The sonifications are based on an 4ch pulse wave synthesiser, 8 ch FM granular synthesiser (details not shown in this paper), the synthesiser depicted in Figure 7, and 8ch vosim synthesiser depicted in Figure 9.



**Figure 9.** Time paradox mass-spring-damper sonification.

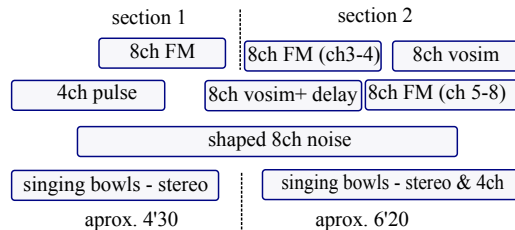
The synthetic sound materials were created using the interface shown in Figure 8.

Regarding sound materials, the piece consists of two sections. Figure 10 shows the sound material structure per section. Section 1 includes direct recordings of sonification fragments, such as FM, Pulse, vosim+ delay and fragments of singing bowls. Section 2 consists on split versions of the FM synthesiser, this means using different pairs of selected channels and relocating them spatially; unmodi-



fied recording of 8ch vosim fragments, and stereo and 4ch expansion of singing bowls.

However, it was necessary to create transitions between sections and musical ideas. These transitions were not necessarily created using the state-space models, they rather obey musical ideas. A shaped 8ch noise synthesiser was used as transition material and it is not a sonification of the system. A stereo version of Time Paradox can be found at [16].



**Figure 10.** Time paradox sound material structure.

## 6. CONCLUSION

The paper illustrates the use of state space models in composition. Sonified State Space models offer new possibilities for creating multichannel sound materials for electroacoustic composition. As the physical systems behaviour is available in real time, a sonified state space model can be seen as virtual instrument that can be played and recorded in real time.

They also present the possibility of creating very peculiar timbres as sound "obeys" the systems behaviour. This is particularly interesting when mapping simultaneously to sound parameters all variables of a system. The spatial element is also important, as multichannel sonifications can be designed fitting stems of mono, stereo or any number up to 8 channels.

One of the main advantages of using sonified models, is that sound evolves in a more organic way, as the models obey laws of physics, preventing them for abrupt changes. However, it is also possible to slow down, speed up or freeze the time evolution, or to "virtually" apply input forces that would not be possible in real life, providing interesting possibilities in timbre and sound evolution, such as gesture, texture, or smooth variations.

Regarding the composition process, untransformed recordings can be included as part of fixed media or mixed media pieces, but also further sound transformations can be applied as well as multichannel split or spatial rearrangements.

As a state space framework has been developed in Supercollider, additional physical systems can be easily implemented, offering new sonification-composition possibilities for electroacoustic composition.

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