Internship Report

Augmented Acoustic Cello

Lévy Benjamin

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ICSRiM - University of Leeds, UK

Supervisor : Dr Kia C. Ng

ENSEA
Ecole Nationale
Supérieure
de l'Electronique
et de ses Applications

Abstract

The aim of the Augmented Acoustic Cello's project is to provide the cello with additional possibilities to allow new expressions with technology. We focus our approach on the player's sonic control and use live audio to control the digital effects for the live audio. Using features extracted from the audio input we maintain the player's normal interactions with the instrument.

The system is developed in Max/MSP. It comprises analysis and processing modules that are mapped through virtual layers forming effects and it can be used for both live improvisation or compositional contexts.

This report presents the design and development of the audio-driven sonifications and effects. This report also discusses the musicality of the effects and pedagogical applications of the system.

Résumé

Le but du projet Augmented Acoustic Cello est de fournir des possibilités supplémentaires au violoncelle et permettre de nouvelles formes d'expressions grâce à l'utilisation de l'informatique. Nous concentrons notre approche sur le contrôle sonore du musicien et utilisons le flux audio pour contrôler les effets numériques appliqué à ce même flux audio. En utilisant des paramètres extraits du flux audio entrant, nous maintenons l'interaction normale entre le violoncelliste et son instrument.

Le système est programmé dans Max/MSP. Il comporte des modules d'analyse et de traitement audio reliés par différentes couches afin de former des effets et peut être utilisé aussi bien pour de la musique improvisée qu'écrite.

Ce rapport présente la conception et la programmation des effets et sonifications contrôlés par des paramètres audio. Ce rapport examine également l'intérêt musical des effets et des applications pédagogiques d'un tel système.

Acknowledgement

I would like to thank my supervisor Dr Kia C. Ng who welcomed me in his lab and gave me time and means to develop this project. I am sincerely grateful for his support and incentive throughout the whole project.
Many thanks to my colleagues in ICSRiM Lab 1, Oliver Larkin, Thijs Koerselman and Alexander Mikroyannidis who advised me patiently and showed me the working of things. Thanks also the every other researchers of ICSRiM, Bee Ong, Minh Thang Dang and the MSc Students.
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Contents

Chapter 1

Introduction

The application of computer technology to create music has introduced new possibilities to invent instruments that are detached from every physical constraints. Among several conferences and workshops in this research areas, the New Interface for Musical Expression (NIME, www.nime.org) stimulates the development of many new instruments. These developments have produced many new interfaces and computer based instruments to learn and master. At the same time, the progress in instrument design has generated questions about the quality, expressivity or consistency of an interface/instrument and comparisons with the acoustic instruments.

1.1 Motivations

The main interest of augmented instruments is to combine already established playing techniques and/or physical instruments with new computer technologies. Skilled musicians would like to be able to use their technique but extend the sonic possibilities of the instrument. Besides, augmented instruments are particularly interesting to study the questions previously mentioned about the quality and playability of a computer enhanced instrument and are also efficient to allow classical musicians and composers to explore new sonic possibilities.

The author plays the cello for 18 years and discovered the possibilities of computers for real-time performances few years ago. Since then he thought of using my cello and play music taking advantages of both acoustic and electronic sounds and richness. But the use of guitare effects pedals with either an electronic or an acoustic cello – as several cellists do – appeared as an unadapted solution to the specificities of the instrument. Considering the impossibility to perform alone both cello and computer as two separate instruments, augmenting the cello constitute an alternative.

1.2 Aim, Objectives & Requirements

The aim of this project is to develop a suite of audio-driven sonifications and effects for the augmentation of an acoustic cello.

Objectives include:

- a survey of the background and existing related works (state of art);
- design and develop of a prototype;
- test and evaluate the prototype system.

In this goal we had the following requirements :

- The effects and sonifications should be adapted to the cello in both technique and sonic result;
- The system is to be used in real-time by an unaided cellist;
- The effects need to be adapted to the cello and present a musical interest;
- The system has to be usable by a wide proportion of cellists.

1.3 Structure of the report

Following this introduction, this report consist of four chapters:

- Chapter 2 presents a survey on past and current research of the areas related to our project;
- Chapter 3 describes our approach and development. It includes justifications of our choices and technical details;
- Chapter 4 discusses the results, applications and evaluation of our system;
- Chapter 5 provides some conclusions and the future directions of this project.

Two appendices are included at the end of the report:

- Appendix A includes a paper presenting the Augmented Acoustic Cello project for the i-Maestro workshop which was co-located with NIME 2008 International Conference in June 2008;
- Appendix B presents the host, ICSRiM, where the Augmented Acoustic Cello has been developed.

Chapter 2

Related works

Augmented instrument as new instrument design raises a wide range questions related to fields from high level considerations such as expressivity and musicality to low level issues as audio feature extraction. Each of these domains have been investigate in past and current research. This chapter presents an overview of the related researches to the goals of this project.

2.1 Instrument Augmentation

In *Paradigms for the new string instrument: digital and materials technology* [15], Hugh Livingston proposed a taxonomy for the design of modified string instruments. Three directions are considered:

- using a *natural instrument*, that is the original instrument developed and improved over centuries;
- building a *representational instrument* i.e. an electronic controller which purpose is to retain only the basic gesture and playing technique of the orignal instrument while the sound source and playability rely on its electronics and computer based enhancements;
- programming a *virtual instrument*, computer based which focus on one aspect only of the player's interface.

In [15], the author considered in his research the advantages and drawbacks of each direction, concerning the interface (*upstream*) and the processing (*downstream*) necessary in each case (Figure 1).

The usage of a *virtual instrument* is not considered in this project as it has no physical instrument interface which allows a cellist to use her/his skills
We propose a fourth approach, *hybrid*, that can be added to the three paradigms as presented in [15]. This *hybrid* approach combines elements from the *natural* and the *representational instruments*. It uses the orignal instrument as well as captured movements of the player with motion capture systems or sensors (cf. [2, 22]). Two examples are studied in the survey: an *hybrid* violin [2] and a *representational* cello [9].

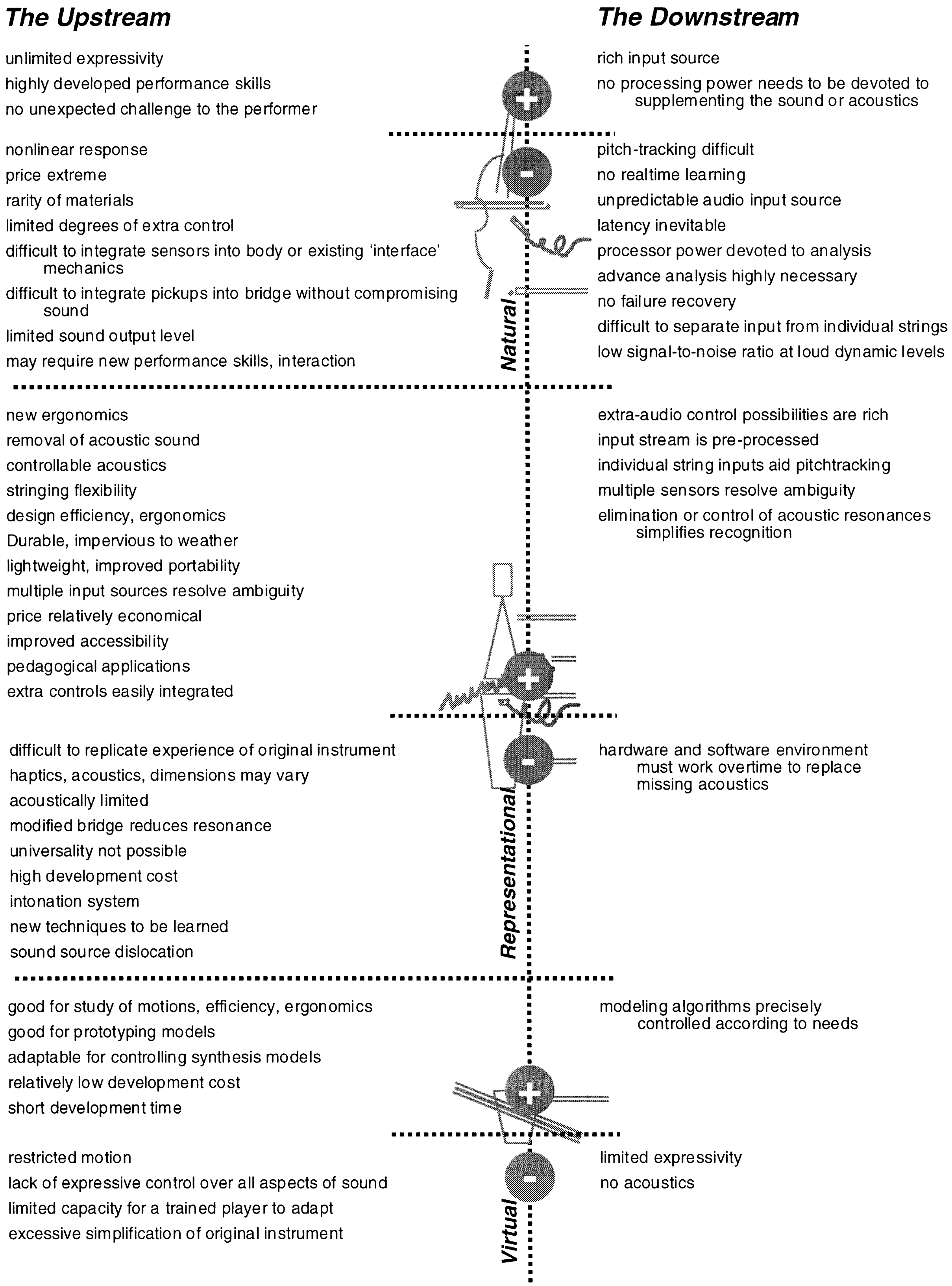


Figure 1: Evaluating the Instrument, from [15] p. 140

Figure 2: Prototype of the *Augmented violin*, from [8]

IRCAM's augmented violin project

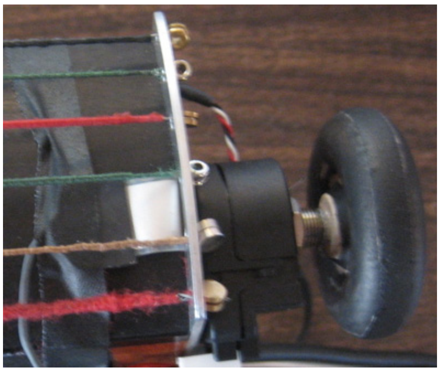
IRCAM developed an augmented violin since 2003 based on an acoustic violin with added sensing capabilities to measure the bow acceleration in realtime [2, 8]. The prototype uses accelerometers mounted on the bow and a capacitive receiver placed behind the bridge (Figure 2). Data is transmitted wirelessly to a computer where a real-time analysis of the bow stroke is performed. A bowing style recognition is used for a composition named *Bogenlied*.

In this augmented instrument, the raw sound of the violin is preserved and captured with a external microphone. The playing technique is kept and captured as well. Movements of the player are used to control the sound of the instrument – usual playing of the violin – and computer based augmentations. As a result, the violinist may feel an ambiguity in the playing gesture: whether focused on the sound of the instrument or on the augmentions (cf. 3.1). The bowing style recognition performed in this project allows us to assume that computer based augmentations are meant to come over the normal playing but not influence the bowing technique of the violinist.

CNMAT's Augmenting the Cello

Another example is given by a research from CNMAT. *Augmenting the Cello* [9] provide an electric 6-string cello with software and hardware enhancements. A new mechanical tuning device (Figure 3a), a new rotary sensor for bow interaction (Figure 3b) and other interface enhancements (Figure 3c) were designed to control a suite of polyphonic sound processing effects including double or triple stops.

(a) Cello heel with string tuning device



(b) Sensor wheel

(c) Cello body showing neck and body FSR

Figure 3: CNMAT Augmented Cello, from [9] pp. 410-411

This augmented instrument constitutes a clear prototype of *representational instrument* where the instrument is replaced by a new electric interface which provides new modalities but keeps the basic bowing and fingering gestures. The sound rendering depend on computer enhancements.
This augmented instrument requires a new style of playing to take advantage of the new interfaces possibilities.

Other augmented string instruments

In 2006, [18] presented a critical survey on past and current developments of augmented instruments in the violin family. A variety of instruments is sampled and experiences of string players are presented. Directions for future research in new violin-related interfaces are outlined, especially about the human interface, the sound generation and the mapping. A wide panel of other researches presents their own approach and direction to augment a string instrument [16, 28], most of these use a *representational instrument* model.

Augmented wind instruments

Augmented instruments with wind instruments (as saxophone, clarinet or tuba) is also very interesting to study. As the sound source rely on the mouth and breath, the players interface is controlled by both hands. Body movements are part of the sound creation, but are less directly related to the consistency of the sound which allows to use them as parameters as done in [22].
In [22] a review of the performer's gesture is done. These gestures are categorized in three functional levels : *instrumental gesture*, *ancillary gestures* and *sonic gestures*. This scheme is applied to the saxophone and the instrument is augmented with both new interfaces (push buttons, force sensing resistors, slide potentiometers, foot pedals) and usage of body movements (inclinometer, distance sensor, video tracking). Four audio features are extracted from the sound : *intensity level*, *attack detection*, *pitch estimation* and *zero crossing*. A care for unity in the playing and musical consistency is showed with a careful choice of mapping strategies.

Another example is given in [3] where the tuba is augmented. The *Self Contained Unified Bass Augmenter* make use of the same kind of new modalities (force sensing resistors, push buttons) without extracting parameters for the audio input. The sound of the instrument is captured then modified and output on speakers placed inside the bell to preserve the unity of the sonic source (Figure 4).

Figure 4: A tuba wearing the SCUBA, from [3] p. 38

2.2 Mapping

As highlighted in [12], the choice of gesture and mapping is a major concern in new instruments design. This is also valid when augmenting an existing instrument. Experiments carried in [12] show that different styles of mapping can radically change the playability of an interface. Volunteers who took part of this experiment proved the consistency of a complex mapping and claimed it as *rewarding* and *like an instrument*.
Therefore, a requirement for our augmented instrument is to allow complex and configurable mapping possibilities in order to provide a playable and consistent instrument and not to reduce the richness of the original instrument (cf. 3.4).

A higher point of view on mapping strategies is presented in [1] with three layers in the mapping chain: *from gesture data to gesture perceptual space*, *from sound perceptual space to synthesis model*, and *between the two perceptual spaces*. Both perceptual spaces are developed and depicted with their features. Technical as well as aesthetical aspects are studied and concrete musical examples are described. Such theoretic model of mapping strategies can be applied in many situations and allows to define sensitive and efficient mappings.

A mathematical analysis of the mapping problem has been developed in [10]. The mapping issue is considered here as an $\mathbf{R}^d \rightarrow \mathbf{R}^e$ continuous function which can be constructed with a geometrical approach. Controls vocabulary and input devices are reviewed then interpolations methods are developed. The problem of rate and loses of information is discussed. A geometrical point of view on the players possibilities is also developed (number of degrees of freedom). Such approach offers algorithmic solutions to enrich the mapping in instrument design.

Another important consideration in [6] is the *expressivity* in computer music instruments. [6] shows that sophisticated musical expression requires not only a good control interface but also virtuosic mastery of the instrument. Complex gesture-to-sound mappings taking advantage of established instrumental skills promote long-term dedicated practice. Visual, tactile and sonic feedbacks between the player and the instrument take also a non-negligible part in the expressive possibilities of the instrument.

2.3 Audio features & effects

Features

A features taxonomy is presented in [17] which differentiate global and instantaneous descriptors as well as temporal and spectral features. Each descriptor is described and Matlab scripts are given. Unfortunately only a few of these algorithms are possible for real-time processing and applications.

However objects such as these describe in [19, 13] allow real-time extraction of features form the audio stream with Max/MSP. The `fiddle~`object [19] performs a maximum-likelihood analysis on the discrete spectrum of its input to guess the fundamental frequencies. The "likelihood function" is based on the presence of peaks at or near multiples of the possible fondamental frequencies. This pitch tracking algorithm is particularly adapted to violin or cello harmonic spectra. The `noisiness~`object [13] estimates the spectral flatness of the sound with a bark-based analysis. These form the basis of some components in this project.

Other research focuses on complex behaviour of string instruments to get a better understanding of their characteristics. Coupling between the different strings, phenomena commonly used by cellist to tune and perform is discussed in [23]. Extending the theory of coupled horizontal and vertical wave of a vibrating string to a multiple strings system, a model for sympathetic resonance is sketch out. A model is given in [4]. Based on [23], piano synthesis method and infinite impulse response (IIR) synthesis method, this work attempts to automatically extract synthesis parameters with a neural-network and build an recurrent digital model to reproduce the coupling in the complex case of the piano. The phenomena is also considered when building a virtual model of a string instrument as in [11].

[24] studies body modes of acoustic instruments. Applied to the separate top and back plate of the instrument, a calculation method provide the modes of the plate. The overall modes of the instrument is also a parameter that a skilled cellist is capable to take into account without knowing the associated physics. For example, cellists are aware that a F# played on the third string (G) will produce a typically non-linear modulation due to the resonance frequency of the body of the instrument.

Rather than trying to model or reproduce these complex characteristics, we will try to use them as they are and allow the player to control the augmented instrument through these lower level features of the cello sound.

Effects

The DAFx conference, its proceedings and publications constitute a wide source of technical descriptions for a wide range of audio effects. In [30], a large review and technical classification of existing effects and their programming is reported. The type of algorithm and some examples are given, sorted by domain of processing and type of effects. The

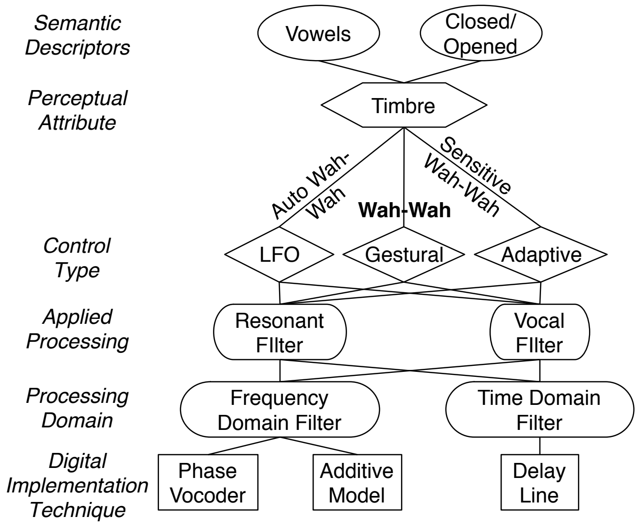


Figure 5: Transverse diagram for the wah-wah effect, from [26] p. 112

classification of audio effects which depends on their processing, perceptual, control or musical type is a complex task. [26] presents an interdisciplinary classification approach to link discipline-specific classifications into a single network containing various layers of descriptors from low-level to high-level features (Figure 5). This allows the programmer to consider the musical description of each effect and apprehend the result on a compositional point of view.

Interesting examples of adaptative digital effects are given in [25]. A selection of effects are classified according to the perceptive parameters they modify and new effects are presented. Effects on sound level, time duration, pitch, timbre and panoramisation are developed. Implementations and specific issues are highlighted especially concerning real-time or non real-time implementation and quantization. It shows that strategies of implementation depend on the effect itself. This work gives a good overview of the possible real-time implementation methods with their associated range of effects.

A specific strategie is given by [29] using real-time spectral analysis in improvised live electronical/instrumental context to explore spectral characteristics of the audio. A link is created between the spectral content of the sound and the timbral modifications by using FFT based analysis and effects mapped with a convergent scheme. We will try to combine this approach with a formant analysis to extend the possibilities of control by the musician.

Effects combining both time and frequency domain processing appeared to have consistent musical applications. An example of *spectral delay* is explained in [14]. By delaying individual bins of a Fourier transform, several musical applications are presented including the ability to create distinct spectral trajectories.

Chapter 3

Design & Development

This chapter presents our approach to augment the cello and the system developed. We decided to augment the acoustic cello with minimal sensors to minimize the obstruction to the normal playing. The system has been developed in a graphical programming environment using the Max/MSP software. The design is modular and flexible to support personalisation for different users (cellists).

3.1 Approach

Instrumental interface

As discussed in Section 2.1, several directions are possible when augmenting the cello. We considered the three possibilities: *natural*, *hybrid* and *representational* instruments, and examine in each cases the advantages and drawbacks with regards to our objectives:

- *natural instrument*: in this approach, the player can use her/his cello with a microphone or sound sensor. It does not provide any additional interaction modality to the player who cannot be at the same time playing the instrument and control directly the computer (cf. Fig 6). However, the acoustic cello, developed over centuries constitute a refined and subtle interface that produces a rich and complex sound. The interaction with the instrument is non linear and provide an unlimited expressivity depending on the skills of the player. The computer based enhancement requires robust algorithms to be reliable and adaptable to the sound source.

- *hybrid instrument*: in this case, the player uses also the cello as a rich interface and sound source. To provide physical gesture data to the system, an electronic enhancement is needed. It can be mount on the cello and the bow as position/speed/acceleration sensors or rely on a motion capture system. Both require to add some devices either on the instrument or on the players body which can be obstructive by their weight or location. An external motion capture system is very expensive and requires a permanent installation which eliminate the possibility of nomad usage by any cellist. Depending on the level of feature to be extracted from the movement data stream, the computer enhancement may be simpler than in the previous approach.

- *representational instrument*: in this latter direction, an long-term and expensive hardware development is need to built the new electronic interface. This interface though, can be adapted to the computer augmentations and designed to add new playing gestures to the normal cello playing. This allow more interactions between the player and the augmentation through buttons, sensors and other electronic devices placed on the interface but exclude the ability of any cellist to play with the system without learning the new gestures and modalities of the instrument.

The scope of developing a *representational instrument* appeared beyond our possibilities for this project, therefore we decided to compare more in depth the two first directions.

Gesture Control

Coming to the playability of the system, Figure 6 represents the interaction between the player and the instrument in both case of the *hybrid* and *natural* approach. Using both the original instrument as interface and sound source, we examined the interactions between the player and the whole system in terms of control and feedback which are two important parameters to be able to play the instrument.

In the *hybrid* (Figure 6, physical gesture driven) approach, we can notice a duality in the players control of the system. The captured movement are used at the same time to create and modulate the sound of the instrument – normal technique of playing – and to feed the computer based enhancement and interact with it. From the instrumental point of view, this duality of each movement tend to void its efficiency in both purposes. It reduces the possibilities of finely control the augmented instrument as a whole. A choice from the player is then required to decide which of the acoustic or electronic part of the instrument she/he focuses on while playing.

In the second case (*natural instrument*, Figure 6, audio gesture driven), the usual gestural control and feedback loop is preserved. A second sound feedback is only added compared to the normal situation of playing an acoustic instrument. We believe any cellist is used to this multiple audio feedback as it is close to the duet or chamber music situation where the player is to listen to the sound of every other musician. This control-audio feedback loop is also the most important tool in learning an instrument. Maintaining this process allows the augmented instrument to be handle and learnt exactly the same way as the original instrument.

Concerned by the consistency and the playability of the augmented instrument as a whole, we finally chose the *natural instrument* approach and tried to preserved the integrity of the playing.

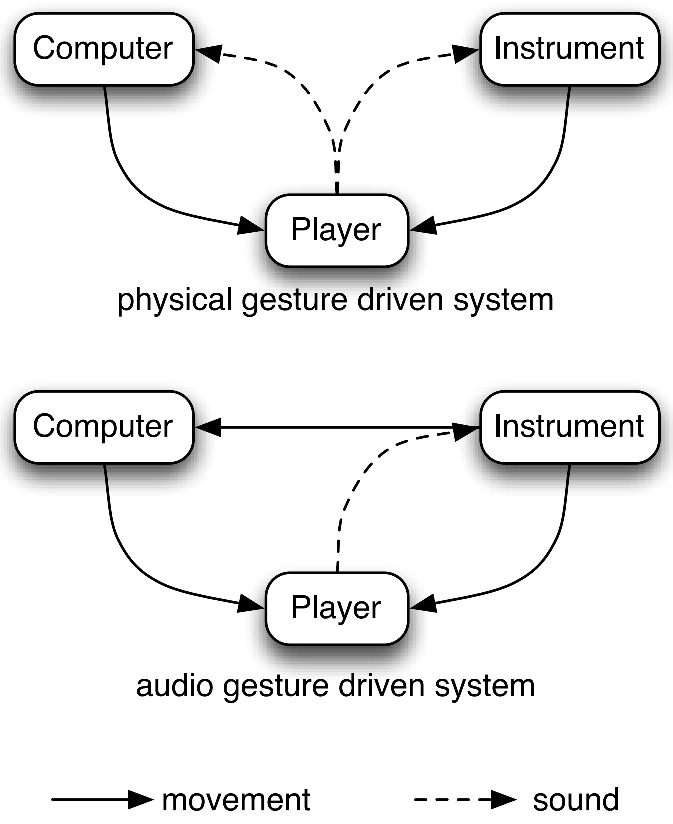


Figure 6: Functional diagram of the control

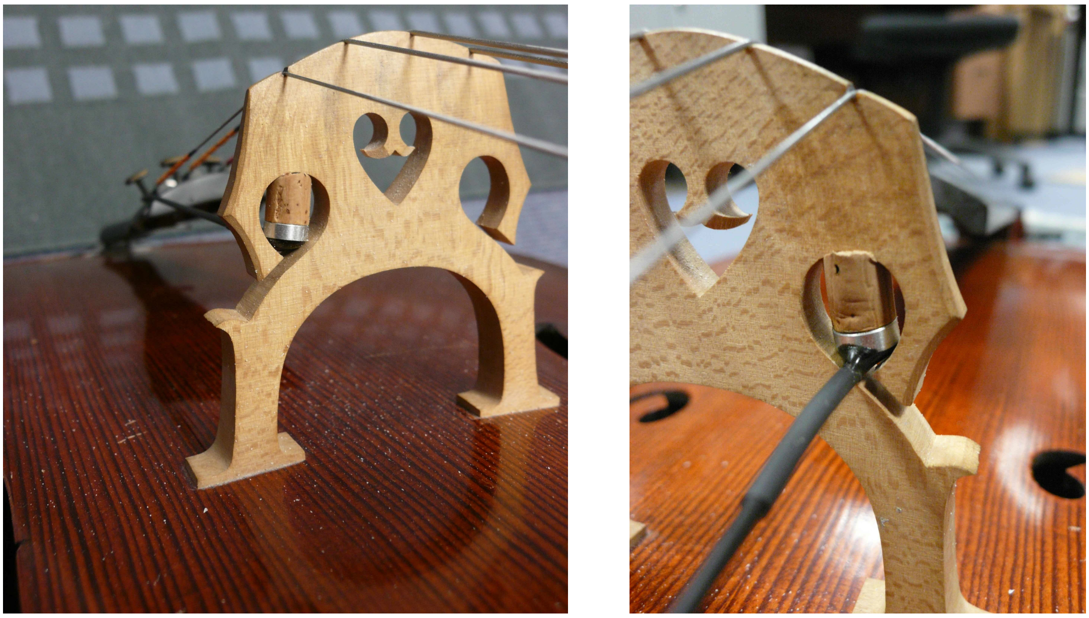


Figure 7: Stat-C mic on the bridge of cello

Audio gesture

Sound sensor

The *natural instrument* augmentation uses the audio output of the acoustic instrument as the input of the computer based enhancements. A microphone or a sensor is then required to capture as precisely as possible the richness of the sound. Two microphones/pickups are renowned for the acoustic cello without any alteration of either the instrument or the bridge: Schertler Stat-C bridge microphone [21], using a patented static microphone technology and Fishman C-100 cello pickup [7] relying on the piezo technology. Both are placed on the bridge. The Fishman recommend a impedance matching amplification while Schertler sells the sensor with its own amplification system. Both are sold around 320€ (≈ £250, including amplifier).

After trying with low cost piezo sensors on the body and the bridge of the instrument, it appeared that the reversible character of the piezo phenomena increase the feedback (larsen) effect between the speakers and the cello by sustaining the physical vibration. The piezo sound rendering is also amplifying more the higher frequencies than the lower which in the case of the cello result in a whiny output. Therefore we chose the Schertler Stat-C microphone (cf. Fig 7 and 8).

Figure 8: A Stat-C system on a cello

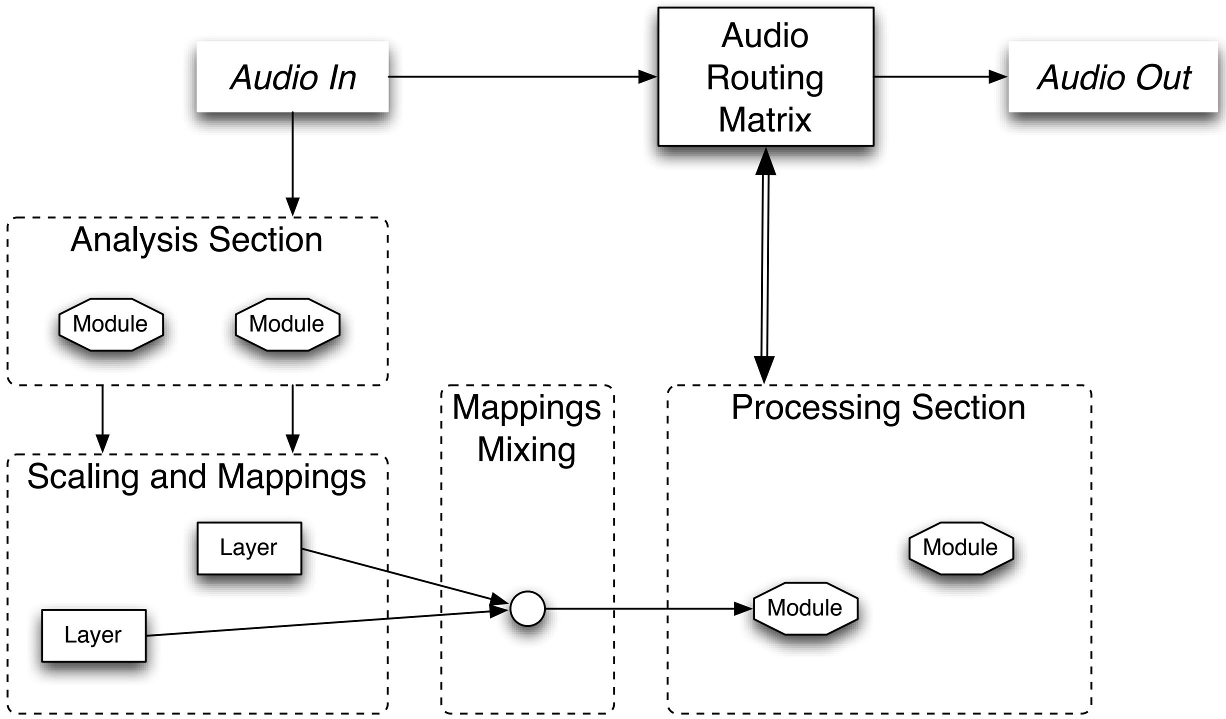


Figure 9: Architecture of the system

3.2 Structure

The overall design of our development is presented Figure 9. The audio input is routed to every module of the analysis section as well as to a routing matrix allowing to program the path through the different modules of the processing section. Modules from the analysis section i.e. performing feature extraction from the audio stream, output these features as parameters to be scaled and mapped to control the modules of the processing section performing some audio effects.

This modular structure allows to add easily additional analysis and effects modules. It is embedded in a single main Max/MSP patch with reduced interfaces for every processing module and a preset and configuration system. The routing matrix also appear in the main patch as shown in Figure 10.

3.3 Modules

As previously explained, we developed two types of modules : analysis and processing modules. Each module perfoms a specific algorithm on the audio stream. Processing modules can have more than one audio input. The audio connections are made as direct as possible to reduce latency. Modules can also have some float stream inputs for example feature coming from an analysis module. These float stream are sent using the OSC protocol [5].

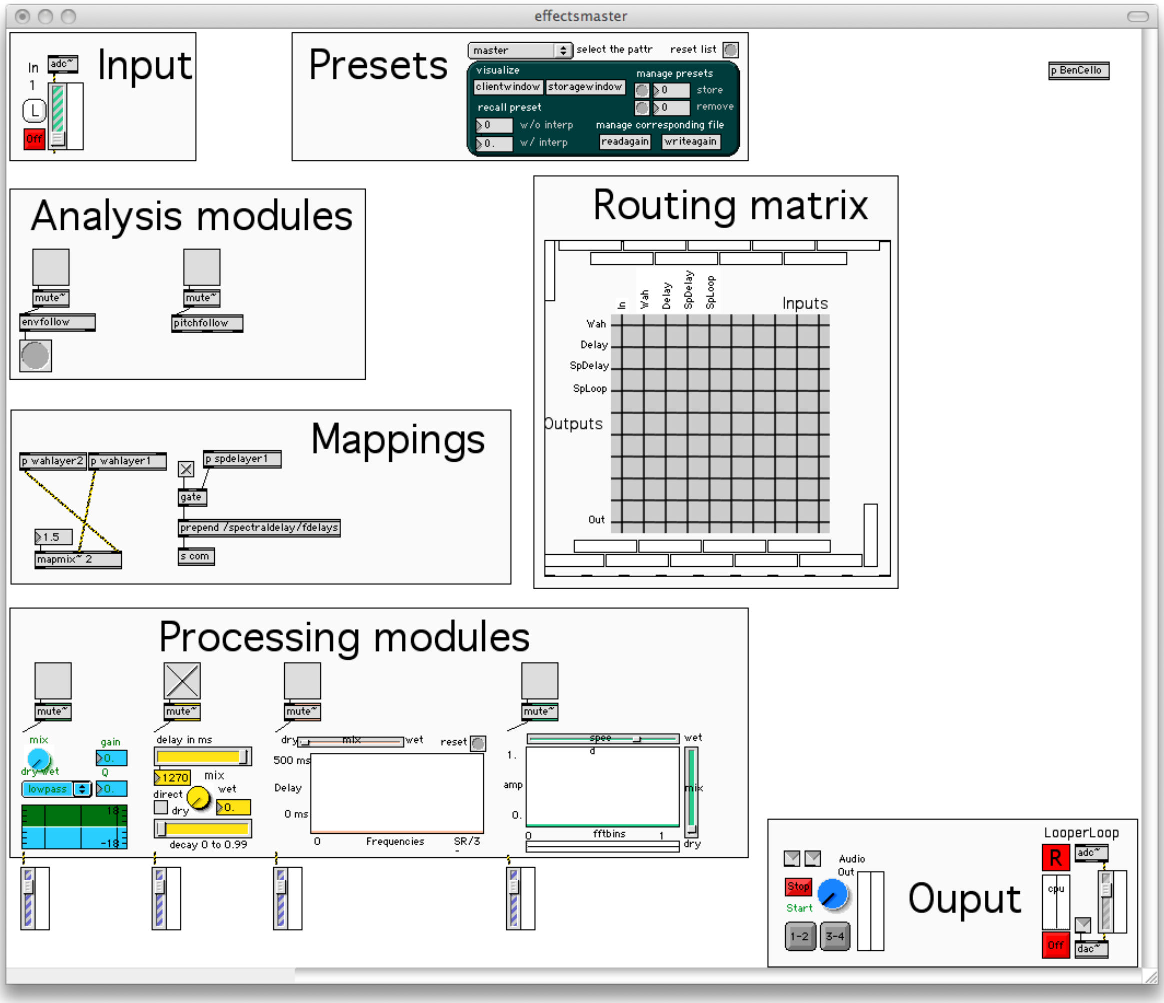


Figure 10: Main interface of the system

Analysis section

The analysis modules receive direct sound input from the cello microphone and output their extracted features either as float stream or an audio stream. The following modules have been implemented.

Pitch tracking

Based on the `fiddle~` object [19], this module outputs the current MIDI pitch detected in the audio stream. Originally, this object was developed for the violin, it allows polyphonic detections. We adapt the object with a larger window size to be able to detect more precisely the lower pitches of the cello and adjust the other parameters as number of partials to consider based on experimentations. The pitch tracking module outputs a continuous stream of float.

Envelope following & Attack detection

Filtering by a first order IIR digital filter the absolute value of the audio input, we can follow the overall amplitude of the audio (see Equation 1 where $x[n]$ is the input sample n, $y[n]$ the output sample n and *slide* an adjustable parameter).

$$y[n] = y[n-1] + ((x[n] - y[n-1])/slide) \tag{1}$$

This creates a simple but efficient envelope follower. Using this envelope with a second filtering and a dynamic threshold based on the average amplitude allows us to detect the attacks and re-attacks.

Processing section

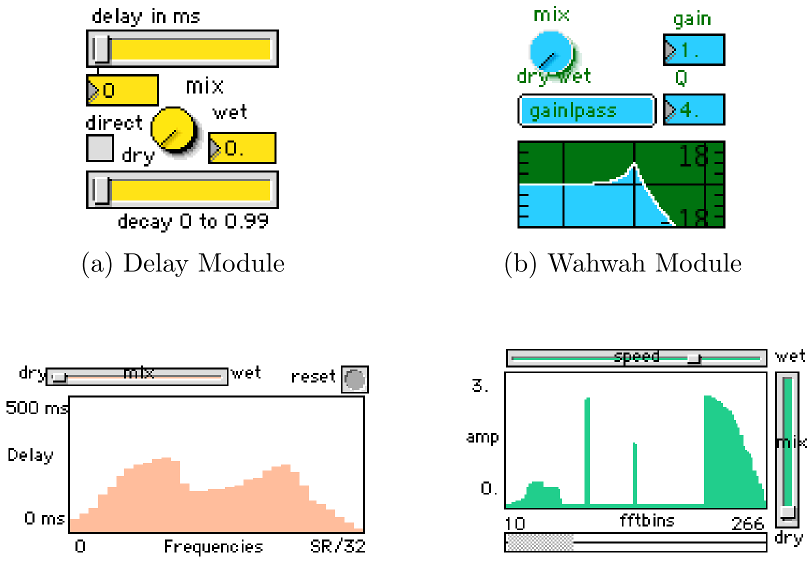
Modules of the processing section receive both audio and float streams as input from the mappings mixing layer. Each processing module possess a condense graphical interface (Figure 10) which appears in the main patch to allow the player to monitor if needed, the functioning and parameters of the module. A mixing between the "clean" sound (*dry*) and the processed (*wet*) is also provided. The following modules are currently available.

Delay line

The classical delay effect is implement using `tapin~`/`tapout~` pairs which work writing and reading in a common buffer. A fixed delay time is a classical effect which allows us to validate the working of the structure. Used with a variable delay, this effects can produce interesting musical rendering in particular with doppler effect for pitch shifting or an approach of granulation effect. Figure 11a shows the interface of the delay module.

Wah-wah effect

The wah-wah effect is particularly interesting on the cello because of the similarities between voice and cello spectra. The cellos spectrum present 2 formants of 3 to 6 harmonics around the fondamental frequency then around 1800Hz. Therefore a second order low-pass or a bandpass filter (Equation 2) with a shifted cutoff frequency through time is very



(a) Delay Module

(b) Wahwah Module

(c) Spectral Delay Module

(d) Spectral Vibrato Modules

Figure 10: Modules Interfaces

efficient. Our wah-wha module allows to chose the type of filtre and adjust the gain and Q factor (Figure 11b). The cutoff frequency being controlled by an internal parameter of the system (opposed to a foot pedal often use by guitarists), this effect is sometimes named autowah or adaptative-wah.

$$y[n] = a_0 * x[n] + a_1 * x[n-1] + a_2 * x[n-2] - b1 * y[n-1] - b_2 * y[n-2] \quad (2)$$

Spectral delay

Based on [14] we implemented a *spectral delay*. This effect consist of delaying differently each bin in the running FFT of the audio input. FFT frames are stored in a circular buffer. The running index of the current FFT bin is used to access another buffer where the delay time for each bin is stored. This delay time which is expressed in millisecond is converted into a number of FFT frame then used to retrieve the correct past bin. We focused this effect on the first 16th of the FFT bins (lower frequencies) to allow the player to control precisely the meaningful and audible frequencies of the spectrum. The interface (Figure 10c) allow the user to draw the delay profile along the frequencies.

Spectral vibrato

Extending the principle of working on running FFTs, we programmed what we named a *spectral vibrato*. It applies a periodically shifted amplitude profile to the FFT bins. The amplitude profile is drawn by the user and written in a buffer. This buffer is read to scale each FFT bin and shifted with at a controllable rate (towards higher or lower frequencies). Same as the *spectral delay*, the interface show the amplitude profile along frequencies (see Figure 10d). The scope of amplification is scalable from a factor 1 to 10 and the span of FFT bins amplified is controllable by the user.

3.4 Layers & Mapping

Following the conclusion of Section 2.2, we took a careful attention to design a flexible mapping system to allow a wide range of possibilities. Each parameter output from an analysis module is scaled in a layer to fit to a particular parameter in a processing module. Non linear scaling are supported to obtain a musically consistent controls. For each processing parameter (either audio or float stream), the possible controls are gathered and mixed to create a wide range of combinations which are adjustable to allow different expression of the playing. In this way, we provide adjustable possibilities from triggered to continuous controls depending on the chosen mix of mappings.

3.5 Routing

To route the audio signal through audio effects and obtain a whole chain of effects, we use a signal matrix (`matrix~` object in Max/MSP). Inputs of the matrix are the direct sound from the cello and the outputs of the each processing modules while outputs of the matrix are the inputs of the processing modules and the sound output of the whole system. An eleven state amount (multiplication from 0. to 1.1) is provided for each possible connection in the matrix.Thus we provide a very flexible tool to design audio paths through effects. Parallel or joining paths are possible. Feedbacks are also supported. Figure 11 shows an example where the audio is simply routed from one effect to another in the order: *input, wah-wah, delay, spectral delay, spectral vibrato, output.* For each input and output, a signal level meter is shown on the top (inputs) and the bottom (outputs) of the interface.

3.6 Presets & Configuration

Based on the `pattr` objects family, we built a system to store and retrieve parameters at two different levels. Data conditioning is applied whereby each modules parameters can be accessed directly (including the routing matrix and mapping mixing) and stored in *presets* (cf. Figure 13a showing 2 presets stored for the wah-wah effect). These presets can then be utilized to built *configurations* of the whole system storable and accessible through the same system (under the name *master*, cf. Figure 13b showing 9 configurations). Every stored preset/configuration can be written in xml file linked to the module or the main patch. Once two presets/configurations are stored, the `pattr` system allows interpolation between these two presets/configurations either linearly or following other scheme (power curve, threshold…). The interface to manage presets and configurations is displayed in the main patch (Figure 12).

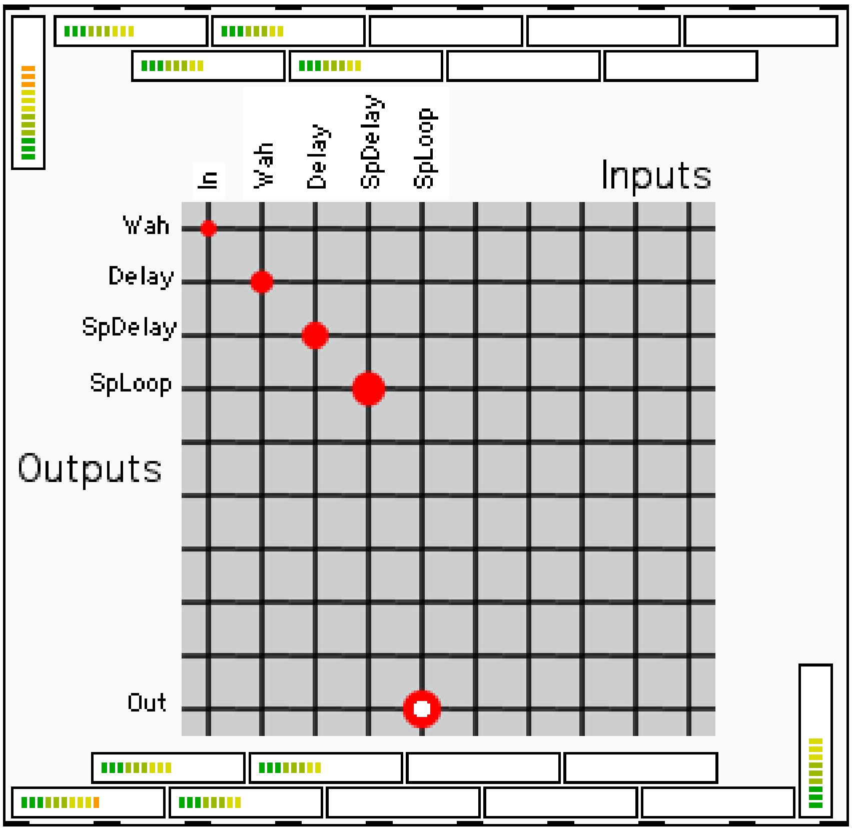


Figure 11: Routing Matrix Interface

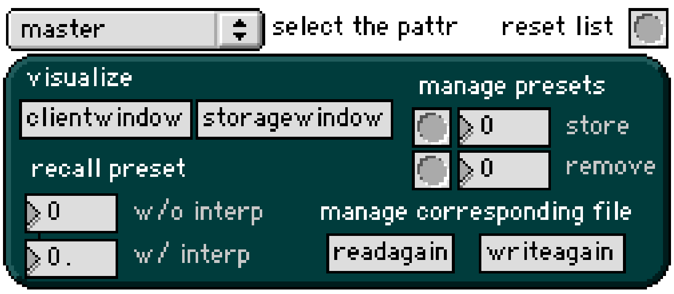
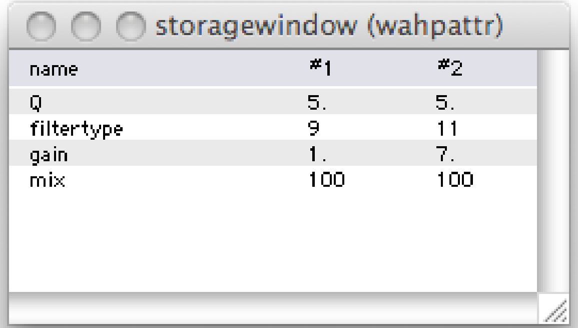


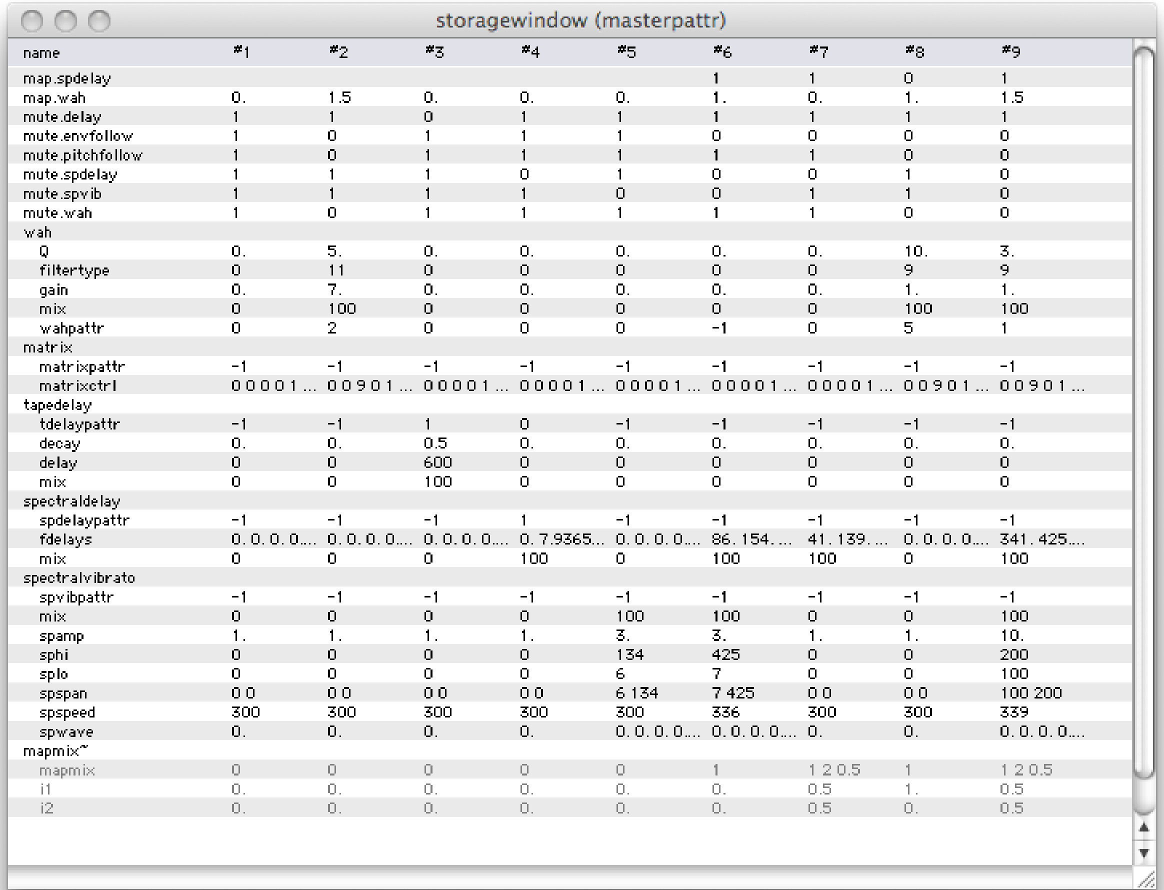
Figure 12: Preset and Configurations Management Tool



storagewindow (wahpattr)

name	#1	#2
Q	5.	5.
filtertype	9	11
gain	1.	7.
mix	100	100

(a) Wah-wah Presets



storagewindow (masterpattr)

name	#1	#2	#3	#4	#5	#6	#7	#8	#9
map.spdelay						1	1	0	1
map.wah	0.	1.5	0.	0.	0.	1.	0.	1.	1.5
mute.delay	1	1	0	1	1	1	1	1	1
mute.envfollow	1	0	1	1	1	0	0	0	0
mute.pitchfollow	1	0	1	1	1	1	1	0	0
mute.spdelay	1	1	1	0	1	0	0	1	0
mute.spvib	1	1	1	1	0	0	1	1	0
mute.wah	1	0	1	1	1	1	1	0	0
wah									
Q	0.	5.	0.	0.	0.	0.	0.	10.	3.
filtertype	0	11	0	0	0	0	0	9	9
gain	0.	7.	0.	0.	0.	0.	0.	1.	1.
mix	0	100	0	0	0	0	0	100	100
wahpattr	0	2	0	0	0	-1	0	5	1
matrix									
matrixpattr	-1	-1	-1	-1	-1	-1	-1	-1	-1
matrixctrl	0 0 0 0 1 ...	0 0 9 0 1 ...	0 0 0 0 1 ...	0 0 0 0 1 ...	0 0 0 0 1 ...	0 0 0 0 1 ...	0 0 0 0 1 ...	0 0 9 0 1 ...	0 0 9 0 1 ...
tapedelay									
tdelaypattr	-1	-1	1	0	-1	-1	-1	-1	-1
decay	0.	0.	0.5	0.	0.	0.	0.	0.	0.
delay	0	0	600	0	0	0	0	0	0
mix	0	0	100	0	0	0	0	0	0
spectraldelay									
spdelaypattr	-1	-1	-1	1	-1	-1	-1	-1	-1
fdelays	0. 0. 0. 0....	0. 0. 0. 0....	0. 0. 0. 0....	0. 7.9365...	0. 0. 0. 0....	86. 154. ...	41. 139. ...	0. 0. 0. 0....	341. 425....
mix	0	0	0	100	0	100	100	0	100
spectralvibrato									
spvibpattr	-1	-1	-1	-1	-1	-1	-1	-1	-1
mix	0	0	0	0	100	100	0	0	100
spamp	1.	1.	1.	1.	3.	3.	1.	1.	10.
sphi	0	0	0	0	134	425	0	0	200
splo	0	0	0	0	6	7	0	0	100
spspan	0 0	0 0	0 0	0 0	6 134	7 425	0 0	0 0	100 200
spspeed	300	300	300	300	300	336	300	300	339
spwave	0.	0.	0.	0.	0. 0. 0. 0....	0. 0. 0. 0....	0.	0.	0. 0. 0. 0....
mapmix~									
mapmix	0	0	0	0	0	1	1 2 0.5	1	1 2 0.5
i1	0.	0.	0.	0.	0.	0.	0.5	1.	0.5
i2	0.	0.	0.	0.	0.	0.	0.5	0.	0.5

(b) Overall Configurations Log

Figure 13: Presets and Configurations

Chapter 4

Results, Application & Evaluation

This section discusses the results and applications of this project, with evaluation criteria and approaches.

4.1 Results

While building the framework and adding the modules one by one, we tested the system for overall working and particular functionalities at every intergration cycle. As a result, the system, although not presenting a large diversity of effects yet, is fully integrated and usable. Every integrated module offers multiple possibilities that the player is able to choose for different contexts. Each parameter can be either fixed or dynamically set in real-time. Chaining possibilities between effects through the matrix allow various rendering with the four effects that are included in the current system.

4.2 Pedagogical applications

Trying out the possibilities of our system it appeared that the analysis and processing can be use for pedagogical purposes. Since this augmented instrument has been designed not to modify the normal interaction between the player and the instrument, a student who is learning the cello can use the effects to highlight some characteristic of her/his sound and work to control them more precisely with the system. Likewise, a teacher can use it to show and make a student listen to a particular feature by simply connecting the cello and load a prepared preset. To explore these possibilities, we developed the two following simple scenarios:

Scenario I

To acquire control over the consistency of the sound, a player usually trains with long and regular bow strokes and tries to focus on the evenness of the sound. However, the human ear is far less accurate in sound level than in sound frequency. If we link this consistency to a frequency parameter, then the player is able to monitor precisely this parameter.

Objective

Acquire precise control over the consistency of the sound by training in long and regular bow stokes (such as in scales).

Tools

Use the volume envelope follower and route its output to the frequency of the wah-wah effects set to a narrow bandpass filter.

Result

Instead of slight fluctuations in the overall consistency of the sound, the player hears magnified shift in the frequency of the filtered sound and the player is able to control the evenness of these fluctuations more easily while not being disturb in the playing technique.

Scenario II

One cannot expect every music performance student to appreciate the physic of the sound and the harmonic structure of notes. When trying to explain the sympathetic resonance phenomena, for example, which is particularly useful in string instruments music teachers can use this system to improve students awareness of the partial sequence that constitutes the sound they produce.

Objective

Raise awareness to the harmonic organisation of the sound.

Tools

Use the *spectral vibrato* in the range of FFT bins where cellos harmonic frequencies are and periodically amplify a single bin to sweep through the different sounding harmonics.

Result

While playing (long bow strokes for example) the student hears precisely the sequence of harmonic frequencies and she/he can compare this sequence or the level of each harmonic for each different tone color e.g. same pitch but produced differently with different strings and/or different playing techniques.

4.3 Evaluations

Our augmented instrument requires to be evaluated both as a technical realisation and as a music instrument. Therefore we need two separated types of criteria. The technical evaluation can be done with a single cello and without any musician. The musical evaluation needs to consider different musical contexts, different cellists and eventually different cello to be augmented and possibly some composers and other musicians. With the limited time available for this project, we only focused on the evaluation criteria in this report. Musical evaluation has been performed with a single cello and a player.

Technical Evaluation Criteria

The technical evaluation for such a real-time system includes the following criteria:

- Measure of the overall latency between an event in the input and the the resulting effect in the output. This evaluation needs to be performed for a range of different configurations (e.g. with different mappings but same effect chain or different effect chains). Measuring this latency can be done with simply the system time stamp of the input audio stream and the begining of the effects;
- Measure of the latency of each module. The efficiency and optimisation for each module is not the same and this evaluation can bring out different level of performance measure for different module;
- Measure of jitter of each module, especially analysis modules which parameters are used to control processing modules, and the overall system.

Musical Evaluation Criteria

The musical evaluation can consider a wide range of contexts and to collect feedback of different musicians, cellist and/or composers. The following contexts are proposed:

- the augmented cello to be played by a group cellist, with specific musical passages and predetermined effects;
- With a short training (prerecorded video screen shot) on the GUI, the player can be asked to adjust/personalise the effects and build an effect chain;
- the augmented cello is played in a chamber context with other instruments;
- the augmented cello presented and played to an audience of composers.

In these evaluations, the player view on musical factors can be evaluated using a questionnaire to grade each of the following criteria:

- ease of use;
- interface design;
- balance of the effects (dry/wet/mix);

- control of the effects;
- sufficiency of the sonic space provided by the effect chain;
- balance and harmony between instrument (in chamber context);
- responsiveness of the system;
- accuracy of the analysis modules;
- consistency of the effects for their musical purposes;

A separate thread of evaluation has been performed in parallel of the technical development. The author being himself a cellist has been using the augmented instrument for his own musical purposes. Interested in electroacoustic improvisation, possibly with other musicians, his set up includes an acoustic cello connected to a laptop running the system with an external audio card (M-Audio® Fast Track Pro®) and a pedal to record and playback loops (Digitech® JamMan®).
The following feedbacks have been collected :

- the system is easy to use but still requires to switch often between the cello and the computer to adjust parameters;
- the routing matrix is very efficient but difficult to use at first and sometimes confusing;
- the analysis modules are good but more analysis modules need to be added to extend the mapping capabilities;
- the mixing between mapping offers consistent configurations;

Chapter 5

Conclusion & Future directions

From the literature survey, it was noticed that relatively few research adopt the *natural instrument* approach in comparison to *representational* or *hybrid* approaches with sensor and/or new interfaces. In this report, we presented the augmented cello project which aims to extend the sonic possibilities of an acoustic instrument. Working in this directions allowed us to reached the following goals:

- This system provides an effective solution to allow a cellist to extend his possibilities preserving the normal interaction with the instrument.
- The musician her/himself is able to control the augmentation through control of the sonic output of the instrument.
- The system is easy to use, with no new gesture to learn.

However such a system presents the following limitations:

- High level features are difficult to extract in real-time from the audio stream.
- Complex analysis and processing may increase latency of the system
- The sonic output of the augmented instrument remains split between the acoustic sound of the instrument and the effects output through speakers. This may be resolved with embodying the speaker in the instrument as in [3]. However, it goes against the design criteria with minimal changes to the instrument.

To extend the system, the next step is to add more analysis and processing modules. Integration and extension is straight forward thanks to the modular design of the overall system. A spectral/formant analysis module based on [29, 27] and a bow segmentation based on the noisiness [13] of the bowing are currently being fine tuned. New processing including overdrive or phasing effects are also being adapted to the cello characteristics and to our structure to be implemented in the system. An extensive evaluation, both technical and musical remains to be done. Usage and feedbacks will influence our further directions.

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Appendices

Appendix A

Publication

This project has been presented at the 4th i-Maestro Workshop on Technology-Enhanced Music Education co-located with NIME 2008 International Conference, Casa Paganini, InfoMus Lab, Università degli Studi di Genova (Italy) the 4th June 2008. The following paper about the project has been submitted and accepted by the committee. A 20 minute talk relating the content of the project and its pedagogical applications followed by questions took place during the workshop.

B. Lévy, K. Ng, *Audio-driven Augmentations for the Cello*, in Proceedings of the 4th i-Maestro Workshop on Technology-Enhanced Music Education, pp. 49-51, University of Leeds - ICSRiM, 2008, ISBN 978 0 85316 269 8

Audio-driven Augmentations for the Cello

Benjamin Lévy and Kia Ng
ICSRiM – University of Leeds
School of Music & School of Computing, Leeds LS2 9JT, UK
info@icsrim.org.uk, www.icsrim.org.uk

Abstract

This paper presents the design and development of a suite of audio-driven sonifications and effects for the acoustic cello. Starting with a survey of existing augmented string instruments, we discuss our approach of augmenting the cello, with particular focus on the player's gestural control. Using features extracted from the audio input we maintain the player's normal interactions with the instrument and aim to provide additional possibilities to allow new expressions with technology. The system is developed in Max/MSP. It comprises analysis and processing modules that are mapped through virtual layers forming effects for either live improvisation or composition. The paper considers the musicality of the effects and pedagogical applications of the system.

1. Introduction

This project aims to extend the sonic possibilities of a cello with minimal physical obstruction through exploiting the normal interaction between the player and the instrument. The main objective is to augment the cello with audio effects; extending the sonic possibilities of the instrument without interfering with the playing. We make use audio gestures/features that are extracted from the sound generated by the playing to control real-time parameters for the effects.

The system is designed to be modular, easy to use, and adaptable to the player's needs, as if it were a collection of hardware effects pedals. The system can be used for both improvisation and written music.

2. Related works

A survey on different strategies to augment a string instrument can be found in [1]. It distinguishes three types of augmented instruments: *natural instrument, representational instrument* and *virtual instrument.*

Systems such as [2, 3] use representational instruments i.e. an electronic instrument/interface especially designed to retain only the basic gesture and playing technique of the original instrument, while the sound source and controllability rely on electronic interface and processing. This strategy typically modifies the link between the gesture and the sound production.

A *hybrid* approach between *natural* and *representational instrument,* chosen in [4, 5], captures the movements of the player with sensors and/or motion tracking devices. The physical movements detected by the sensor/motion devices are used to control the sound production (cf. 3.2 and Figure 1).

As the name implies, *virtual instrument* does not utilise physical interfaces and hence it is not considered for this project.

For this project, we aim to preserve the inner relation between the player and the resonant instrument whist providing new audio possibilities as an intimate augmentation of the cello. Hence, this project can be categorised under the *natural instrument* strategy.

3. Approach and realization

3.1. Acoustic cello

The design of the acoustic instrument was developed and improved over the centuries together with playing techniques and styles. In this section, we detail some of the key considerations and factors for the design of this project:

- *sound source*: The richness and complexity of the acoustic sound includes several physical parameters such as body modes, string coupling and bow noises that a skilled player is able to take into account.

- *interface*: Over years of practice a player acquires intuitive understanding/feeling with her/his instrument with a level of instinctive perception. We take advantage of this control mostly based on the direct feeling of the vibrating strings and body of the instrument.
- *feedback and learnability*: The feedback between movements and sound excitation constitute a basis for the learning process of an acoustic instrument. Hence, preserving this direct feedback can offer a natural feel to the control of our system as well as using this loop for pedagogical applications. Precise controls over the effects can be acquired without adding any new movement to be learnt.

3.2. Audio gesture control

There is a wide range of research that focuses on extracting and analysing audio features [6, 7, 8]. We utilise some of these algorithms, especially those available in real time (cf. 3.3.1) to produce control parameters.

Figure 1 illustrates a more concentrated link between the player and instrument to offer a better focus and closer feedback-loop between playing and sound. This is precisely what a teacher would like a student to do during practicing.

3.3. Setup

A cello is connected to a computer through a pickup or microphone. We use Schertler Stat-C ® bridge microphone [11] to minimize feedback and other environment noises. Figure 2 shows an overview of the system.

Modules, performing analysis or modification on the input, are connected through scaling stage and mapping layers. The audio routing is controlled by an input/output matrix.

To improve the responsiveness the audio connections are made as direct as possible while float-streams are sent using the OSC protocol.

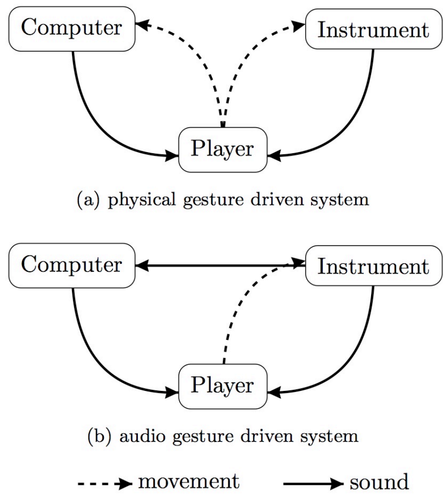

Figure 1. Functional diagram of the control

3.3.1. Modules. Each module implements a specific algorithm. Currently, the analysis section comprises a pitch follower [9], an envelope follower, an attack detector and a bow segmentation algorithm. The processing section includes effects such as a two-pole frequency-shifted filter (*wahwah* effect), delay, spectral delay, spectral looper and others.

3.3.2. Layers. Layers encapsulate scaling and mapping of the analysis modules with the output to be routed to the processing modules (cf. Figure 2). As highlighted in [10], the importance of mapping should not be underestimated. The implementation includes a switching and mixing system between the different mappings to achieve a rich control of the effects.

3.3.3. Routing matrix. Effects are routed one to another over a reprogrammable matrix. Parallel routings among the effects are possible to layer various augmentations at once. Real-time changes do not provoke any break in the audio chain allowing more flexibility whilst performing.

3.3.4. Configuration and presets. Every module, the main patch and the routing matrix embed a preset management system based on the Max/MSP *pattrstorage* object. Controlled by a specific interface, the presets can be stored, recalled and interpolated either separately for each effect or globally.

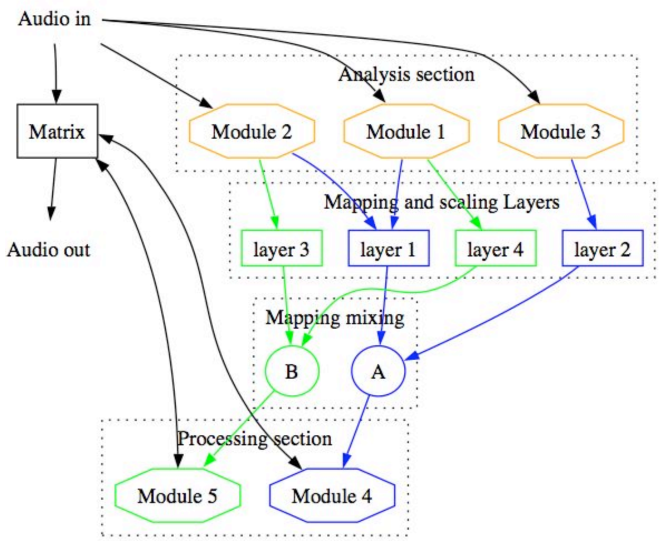

Figure 2. An overview of the system

4. Pedagogical applications

The analysis and processing sections can offer "*sonic highlight*" possibilities that can be used for educational purposes. For example:

- A player who wants to acquire more awareness of the regularity of her/his bow can set the *autowah* effect to be controlled by the envelope of the sound. Whilst playing normally (e.g. on a music passage with regular note duration such as a scale), the filtered output of the system, modulated in real-time, highlights the fluctuations of the bow strike with a shift in frequency. With the highlighted fluctuations, the student and hear the inconsistencies clearly
- A teacher who wants to bring to the attention of a student the harmonic organisation of the sound can use the *spectral looper*. This feature will periodically amplify the different harmonic so that the student is then able to hear in real-time the sequence of partials which shape the sound of each note being played.

5. Conclusion and next steps

In this paper, we presented the augmented cello to extend the sonic possibilities of the *natural instrument* with real-time effects.

The system can easily be extended to add more effects with additional modules. By default, it is designed for real-time improvisation. In the case of a composition, the presets can also be controlled by a simple timeline system. Additional external control parameters (e.g. from other sensor/motion capture system) can be fed in to allow further interaction or collaborative creations.

Currently, the prototype is being tested and optimised while more effects and analysis modules are also being added.

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Appendix B

About the Host - ICSRiM

In 1987, the school of Music of the University of Leeds established an Electronic Studio to provide undergraduate and postgraduate programmes in electronic- and computer-music courses and research. Research and development in this area has been steadily increasing in the University, leading to direct collaboration between artists and scientists within and outside the School. This formed the basis of the Interdisciplinary Center for Scientific Research in Music (ICSRiM), which was founded in 1999.

ICSRiM currently involves members of the School of Computing, School of Music, Electronic and Electrical Engineering, Mathematics, Psychology, and Physics & Astronomy, with external members from other academic institutions, freelance artists and industrial collaborators.

A new physical center was completed in the Music School building in January 2003, with major funding support from the HEFCE (Higher Education Funding Council of England), SRIF (Science Research Investment Fund) and the University.

Research Themes

ICSRiM provides a venue for research and development in a wide range of interdisciplinary research areas, including:

- Analysis, encoding and transcription of the musical information
- Creative Human-Computer Interactions, Interactive Gesture Music, Virtual and Augmented instruments,
- Music Psychology and its technological applications
- Technology enhanced Music Education