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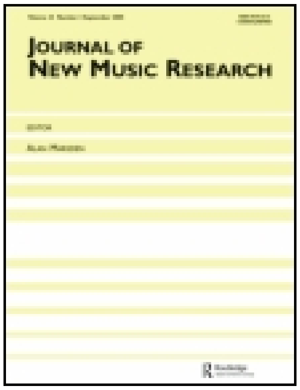
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The Chameleon Guitar—Guitar with a Replaceable Resonator

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The Chameleon Guitar—Guitar with a Replaceable Resonator

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Abstract

Each acoustic instrument is one of a kind. Its unique acoustic properties are transferred from the physical characteristics of its source materials and a handcrafted touch. In contrast, electronic and computer-based instruments lack this distinguishing trait. Though the technology support in musical instruments offers great flexibility, it tends to foster predictable and generic results, particularly with common use of easily-cloned digital presets. This paper presents a new approach to the design and fabrication of instruments that combine the advantage of acoustic and electric instruments—hybrid instruments—that exist simultaneously in both physical and digital environments. This approach exploits physical/acoustic properties via a replaceable physical object complemented by a simulated shape or other digital signal manipulation. The key concepts of this approach are presented through an example: *The Chameleon Guitar*, detailed in this paper along with evaluation from musicians and instrument makers. This work aims to demonstrate the possibility of maintaining the qualities found in real acoustic instruments, such as unique spectral and spatial behaviour of wooden soundboards, with the flexibility of digital processing.

1. Introduction

In this paper a new approach to the design of string instruments is presented, combining digital and the physical environments by allowing the player to seamlessly, simply, and simultaneously change both the instrument's acoustic resonator (a replaceable acoustic insert that function similar to acoustic guitar's sound board), and digital signal processing (DSP) characteristics. The main goal of the work is to merge traditional values and digital capabilities, while preserving both the resonator's spectral and spatial contribution to the overall timbre. This perspective is illustrated in the implementation of *The Chameleon Guitar* (see Figure 1). A deeper discussion about this project, along with the state of the guitar today, our conceptual motivation and influence on our work from other fields is presented in Zoran (2009). Sound examples and videos of *The Chameleon Guitar* are presented in www.thechameleonguitar.com.

In acoustic musical instruments, natural information embedded in wood can be extremely significant to the functionality of the instrument. Traditionally, the materials and craft qualities of acoustic instruments play an important role in defining the instrument's unique sound. It is difficult to find two acoustic instruments that sound and perform exactly the same, which leads to a strong personal connection and often a deep bond between the player and their instrument. At the same time, electronics are playing a huge and still growing role in creating and processing the instrument's sounds, due to the flexibility analog and digital processing techniques provided for sound control.

An acoustic guitar owes its sound quality primarily to its wooden chamber. The timbre and volume of a guitar depends on the shape of its chamber and the structure and properties of its material. The type of wood, its quality, the way it is prepared and its inhomogeneous structure all create a reality where no two guitars are the same; each guitar acts and sounds a little different. Wood can also change its acoustic behaviour over time and in different moisture conditions.

We implemented a new guitar that combines physical acoustic properties with digital processing abilities in an innovative design—a design that benefits from the distributed spatial-acoustic characteristics of an acoustic soundboard (unlike just sampling the surface vibration at

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Fig. 1. *The Chameleon Guitar* with four different resonators.

a single location). The concept of *The Chameleon Guitar* is to separate the chamber's shape from its material and craft quality. A physical resonator, a replaceable piece of matter that gives the guitar a distinguishing acoustic behaviour, is situated under the guitar bridge. *The Chameleon Guitar* allows the user to change the acoustic resonator without swapping the whole instrument (and requiring just slightly re-tuning), and the array of soundboard transducers enables a higher degree of information to be processed in the computer, relative to the typical pair or triad of magnetic string pickups or single contact pickup in common use on guitars today. Through this novel modular approach, sound flexibility and a high level of resonator personality are achieved.

2. Related work

Since the dawn of the synthesizer, significant effort was devoted to embed synthesizer capabilities into the guitar (Paradiso, 1997). Starting with envelope followers driving active filters and other effects (Thompson, 1997; Hughes, 2004) and continuing on to analog (then digital) pitch extraction that then can manipulate an entirely synthesized sound source, musicians and engineers tried to merge the world's most popular instrument with state-of-the-art technologies. Examples of this abound, coming from inventors and industry (see below), artists (ranging from Derek Bailey to Fred Frith, for example) and academics (e.g. Vanegas, 2007; Lähdeoja, 2008)—most high-end academic research has focused on bowed instruments as opposed to guitars (Machover, 1992; Jehan, Yound, Bell, & Lunn, 2005; Bevilacqua, Rasamimanana, Fléty, Lemouton, & Baschet, 2006).

One way to achieve sonic flexibility while preserving some degree of expressivity is to first detect pitch and the amplitude envelope of the acoustic signal, then applying synthetic timbres. In this way, an array of timbral possibilities is achieved via synthesized sound, and the sensitivity of the instrument is preserved

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through the amplitude and pitch channels. More sophisticated methods, based on articulation detection, can be used to expressively and dynamically control the timbre. In order to achieve this via audio analysis alone, high-level signal processing capabilities (and sometimes even artificial intelligence tools) are required. The most complicated part of the process is to model and extract the instrument's dynamic transient behaviour (at low latency) while preserving nuances in its expression and perhaps some aspects of its unique sound signature.

Guitar synthesizers from the early 1970s attempted this through analog signal processing or hardwired digital processing (e.g. the Arp Avatar or 360 Systems products), often using a separate set of processing electronics for each string. These devices were often unreliable, or required particular technique to play well. When MIDI first met the guitar in the early 1980s, an easier approach evolved where the guitar controllers sometimes did not even include strings (e.g. the Ztar controllers), or used the strings only as sensors for fingers and to determine fret position (e.g. the Yamaha G-10, Beetle Quantar, and devices mentioned below). The only similarity to the guitar was the way it was held, and sometimes the way it was fingered and perhaps plucked, but, although some interesting channels of articulation were invented, those instruments lacked much in the way of expressivity especially when compared to what guitars are capable of.

One popular example, the *SynthAxe*, invented by Bill Aitken (SynthAxe website, 2009), supported two sets of strings; one set, made from short-length strings running across the guitar's body, was used to detect picking, and another set ran down the fret board to determine pitch (lower cost controllers along similar lines were introduced by Casio and Suzuki). *Zeta Music* also made interesting hybrid guitars in their Mirror series (Paradiso, 1997) with a multimodal interface that featured a wired fret board for pitch detection, a capacitive touch detector on each string for determining the expected acoustic damping, hexphonic pickups for amplitude detection and pitch bend, accelerometers for measuring the instrument's rigid-body dynamics, and an instrumented whammy bar (and more).

In recent years, as signal processing capabilities have improved, there has been a shift away from the dedicated MIDI guitar controllers (described above) and back toward existing, standard electric guitar interfaces that identify playing features and dynamics by running real-time DSP algorithms on the guitar's audio stream, still generally exploiting hexaphonic pickups that derive separate audio from each string. The *Line 6 Variax* guitar, for example, maps the guitar player's input onto a variety of preset sounds (Line 6 website, 2009), from classic acoustic and electric tones to sitar and banjo. It allows the player to plug into a computer and customize a chosen timbre, while the hexaphonic piezoelectric pickup, located on the bridge, transfers the signal to a DSP unit located on the guitar. Expressive playing and sound flexibility are enhanced with these digital guitars. Another example is *Fender's VG Stratocaster*, a hybrid electric and digital guitar (Fender website, 2009). The *Gibson Robot Guitar* series also uses a DSP unit on the guitar to control the automatic string tuning mechanism (Gibson website, 2009). Modern high-end electric guitars often come equipped with a connector to transfer multichannel digital audio directly from the guitar to a computer network or dedicated processing electronics.

Some artisans still develop in the acoustic realm—for example, Ulrich Teuffel is a German designer who produces unique guitars. His Birdfish model is an electric guitar that allows the player to replace wooden supports (Teuffel website, 2009). The guitar has two metal structures connected by solid wood panels. By replacing the wood, the damping properties of the guitar change and modify the sound.

The haptic feedback from the musical instrument, as well as the tactile qualities of the experience, was the focus of many projects. Several projects applied a similar concept in musical instrument design, such as in The Sound of Touch (Merrill & Raffle, 2007), or with the Cicada's Rapid Sequential Buckling Mechanism (Smyth & Smith, 2002). In the work of Cadoz, Luciani, Florens, and Castagné (2003), a vibrating device with sensing forces and displacements at its manipulation stick was able to produce a force-feedback, and allowed one to highlight an inter-sensory phenomenon. Howard and Rimell (2003) describe a physical modelling music synthesis system known that enables virtual instruments to be controlled in real-time via a force-feedback joystick and a force-feedback mouse.

3. Motivation and vision

The Chameleon Guitar design preserves the unique properties of the wood used to craft guitars, yet through its modular construction, also offers an instrument that musicians can use to customize and modify the guitar's intrinsic timbre and acoustic 'personality'. Traditionally, acoustic guitars cannot be modified once they are made; it is not part of the player's experience to 'tamper with' the structure of the instrument. Acoustic guitars are highly crafted and offer acoustic integrity, but they offer no flexibility for sound design control. An exception is perhaps seen in the work of certain artists who modify and extend their guitars (e.g. Derek Bailey, Fred Frith, Elliot Sharp, Paolo Tofani), but these tend to be one-off creations that stay in a particular timbral space.

Under our concept, a musician can still be involved in creating and modifying the guitar's acoustic timbre, as well as sharing designs with the guitar community, using

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online blogs and websites for example. This combines the values of an electrical (analog or digital) guitar with the uniqueness of a wooden acoustic guitar's tone. By doing so, we can achieve expressive playability through a unique tool that also enables the player to design a desired sound under a coordinated acoustic and signal processing approach.

The design of *The Chameleon Guitar* focuses on the influences of the chamber on the guitar's sound. The chamber's main acoustically-relevant parameters are its shape and material. As different chambers can be separately identified when they are inserted into the guitar body, the digital processor will know what chamber is installed, and a customized suite of digital processing effects can be presented that are well suited to the current resonator—in some sense, we can consider this to be a digital part of the particular physical chamber that is being played. Accordingly, we have realized an interchangeable 'hybrid chamber': part of it is physical (the guitar's resonator) and part of it is virtual (the span of digital effects and processing that are suited to that resonator).

All resonators are small soundboards with an arch-top guitar bridge. The strings are tied to a conventional tailpiece. The resonator can be very easily swapped by opening an aluminum tray in the back of the guitar. The resonators have four piezoelectric sensors located in different places on its surface to capture different mixtures and phases of the eigenmodes. The signal-processing unit is located at the back of the guitar; it merges the signals into one (or, for example, a stereo pair) and acoustically compensates the output to imitate the sound of a full acoustic guitar of an average size, using filter banks. The signal processor is also capable of introducing a variety of other effects, such as phase modulation, frequency modulation, and distortion. Several different kinds of resonators were made and experimented with in order to explore their difference—a change in resonator structure leads immediately to a change in output timbre.

The Chameleon Guitar presents a three-element instrument: the body, the resonator and the digital signal processing unit. The body is essentially a skeleton of a standard guitar that holds the two other elements; it is the guitar's player interface. Underneath the guitar interface, there are two customizable parts: the programmable DSP and the replaceable resonator.

By combining digital with physical in this fashion, we believe we can merge both values. The replaceable resonator can play an important role in continuing the traditional connection between players and their unique instruments while at the same time allowing a coarse span of intrinsic timbral characteristics; the digital part can be finely controlled, and augments the acoustic experience within the virtual domain.

4. Technical background

In his thesis work, Ra Inta explained and analysed the physics of the acoustic guitar (Inta, 2007), and Fletcher and Rossing (1990) gave a classic physical overview on the subject, including acoustic background.

The main parts of the modern flat-top acoustic guitar are the neck and the body, which contains an air cavity. The most important part of the body is the soundboard (the top plate), usually made from spruce or cedar wood, in which a round hole is placed just near the end of the fret board. The neck itself is usually made of a harder (but flexible) wood that resists the string tension. The guitar strings are tight between the bridge and the tuners on the headstock (the end of the neck). When the strings vibrate, they transfer vibrations via the bridge to the soundboard, which then starts to sympathetically vibrate. The soundboard in turn drives the air, which is the sound we hear. Although all the guitar parts vibrate, and there really isn't a fixed part in the guitar, the sound we hear is mostly emitted from the soundboard and the chamber's hole. The shape and dimensions of the soundboard, chamber and hole, as well as the soundboard material, are the most significant elements to affect the sound. The back and sides of the chamber are usually made from hard woods, in order to prevent acoustic energy from being damped there.

In the arch-top guitar family, unlike the flat-top, the soundboard (top plate) is curved and usually carved from a bigger wooden block, similar to the violin. The strings are tied to the head of the guitar and the tailpiece, and they are pushing the bridge (located in the top arch of the curved soundboard) down into the soundboard.

When a string vibrates, it excites the bridge. The bridge then drives the soundboard. However, not all the harmonics are actually transferred to the soundboard; this depends on the eigenmodes (modes of vibration) of the guitar's body, which is a coupled vibrating element constructed from the soundboard itself (similar to a plate behaviour) and the Helmholtz resonator made by the hole.

The tension in the strings tends to rotate the bridge and deform the soundboard. To make the instrument relatively loud, the soundboard must be thin yet span a relatively large area, hence a structural reinforcement is required to balance the force introduced from the string tension. This is usually in the form of wooden braces behind the soundboard. This bracing system plays an important role in sound production. By adding more mass to the soundboard, as well as adding stiffness to specific locations on the plate, the braces influence the eigenmodes (natural frequencies and spatial patterns). The art of bracing the top plate of the guitar is highly important to the sound of the guitar—different guitar styles usually have different bracing designs, yielding varying acoustic characteristics. The expertise of a

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guitar-maker depends on his ability to control the sound through delicate bracing craftsmanship (Siminoff, 2007).

The low frequencies of the guitar depend on the guitar's chamber; the Helmholtz resonance and the soundboard size are critical to the first and second modes of vibration (Fletcher & Rossing, 1990). The soundboard's material qualities and braces are usually responsible for the midrange and higher eigenmodes. One of the important jobs of the luthier is to select and prepare the wood, especially for the soundboard.

All of the above suggests that guitar design is highly dependent upon a luthier's design and craftsmanship (M. Coppiardi, 2008, videos, personal and e-mail interviews; K. Parker, 5 February 2009, public talk in the MFA, personal and e-mail interview). From the player's perspective, the guitar is a highly expressive instrument that can be controlled by using different excitation methods, e.g. using a pick or fingers to pluck the strings, plucking them at different locations, damping or bending strings with fretting fingers, etc. Friction and mechanical properties of the finger or pick, as well as the plucking direction, are most influential on the interaction between the string and the guitar body. The strings or the body can be excited or damped in many other ways, giving rise to a large range in native timbre and a multitude of playing techniques. Together with the structural–acoustic characteristics of the wood, the player maintains a unique relationship with the instrument that contributes to the musical style that it fosters and sound being created.

5. Fabrication and implementation

The Chameleon Guitar merges acoustic qualities and digital processing into a new guitar platform. This new platform was designed in several stages that will be presented here. *The Chameleon Guitar*'s signal path was the first element of the project to be defined (see Figure 2). The string vibrates the resonator's bridge, similar to an arch-top guitar, and then the bridge drives the soundboard. Unlike a normal acoustic guitar, here the soundboard is too small to drive loud acoustic waves (especially at low frequencies; for instance, the modes influenced by the Helmholtz resonance in an acoustic guitar). An array of sensors captures the structural–acoustic behaviour of the resonator (the multipoint displacement of its surface), while a computer simulation processes the signal through a transform derived from a programmable (virtual) shape, or any other digital sound effect: four piezoelectric sensors, located in different places on the resonator, capture different combinations of the eigenmodes. The four sensors' signals are buffered and amplified by the analog circuit on the *resonator PCB* (printed circuit board), and then, using an electronic connection, transferred to a digital signal processing unit (*SP unit*) located on the guitar. The signal output is then re-assembled from the four inputs, imitating different guitar chamber sizes along the way (by changing the properties of the filter bank presented in Section 5.6), or implementing other appropriate digital audio effects. The resultant signal is transferred to the output jack, and then sent to an acoustic guitar amplifier. After a preliminary prototype was built to validate the basic concepts and the signal path was defined, the digital version of *The Chameleon Guitar* was designed.

5.1 The reference guitar and impulse response tests

A *Yamaha FG330* acoustic guitar was used as a reference. The actual timbre of an acoustic guitar depends on the acoustic properties of the surrounding environment. The reference acoustic guitar was recorded with a single *MXL USB.008* microphone in a recording studio room, located 50 cm in front of the guitar bridge, while the instrument was placed on the floor of the studio and damped with soft foam.

A linear system's behaviour can be analysed by its response to an impulse input. Although a guitar is not a linear system, its behaviour at low amplitudes is very

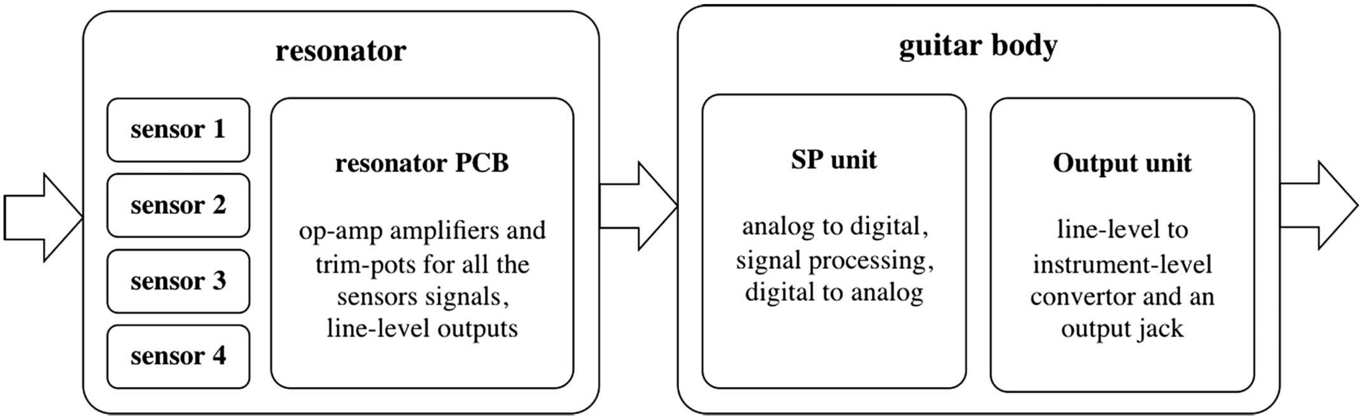

Fig. 2. *The Chameleon Guitar* signal path.

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similar to one. Inta (2007) used the method of impulse response to analyse and model a guitar's behaviour. In this research, impulse response was imitated by hitting the top-centre of the guitar's bridge with a plastic-coated, hand-held metal stick. Several iterations were recorded, and the most similar three recordings were averaged to create the system response.

5.2 Acoustic principles and resonator design

The goal of the basic signal processing that we perform is to modify the resonator's sound so the output will sound like a full size guitar without damaging its intrinsic audio features; the output sound will still represent the resonator's main acoustic properties that relate to the material and the fashion from which it is made, while the properties that relate primarily to the vibrating system's shape (the chamber's dimensions) will be modified.

An acoustic guitar's behaviour depends on its shape and material properties. However, at lower frequencies, when the frequency is much lower than the rate of changes in materials (changes in stiffness, density, supportive braces, etc.), these properties can be calculated as an average. In other words, the lower eigenmodes, depend more on shape than on wood patterns, especially those influenced by the Helmholtz resonance, (usually around 100 Hz) and the one related to the soundboard's lowest eigenmode (usually around 200 Hz, mostly dependent on soundboard size). However, as the frequencies get higher, their dependence on material pattern and brace structure becomes more significant.

Based on the above, *The Chameleon Guitar*'s intrinsic processing should modify the lower formants (based on the lower resonator's eigenmodes) and keep the higher ones as natural as possible, in order to achieve the design principle of preserving the wood's authenticity but modelling the output signal to sound like an acoustic guitar (with a controllable chamber size). In general, it is difficult to generate reliable, digitally modelled string attacks (transients) were one to try and digitally emulate the full guitar sound from samples of a 'plain vanilla' string lacking acoustic personality. In our framework, the mid-range and high frequency transient behaviours are preserved so the transients' sound signatures are kept as natural as possible.

Each wood resonator has a different acoustic behaviour. The sensor locations and DSP algorithm were defined according to the simulated and measured behaviour of a reference resonator (resonator no. 1, see Figure 9); all other resonators used these properties.

Several researchers have suggested the use of FEM (Finite Element Methods) for musical instrument design and analysis (Inta, 2007). The resonator's shape was designed in an iterative process using FEM (*Comsol Multiphysics* software), physical acoustics tests, and mechanical adjustments (see Figures 3 and 4). The goal was to find the bridge location, boundary conditions, and smallest surface area that can support vibrations that are as close as possible to the lower eigenmode of the acoustic guitar (around 100 Hz). The design process proceeded in several iterations, started with four rigid points on the boundaries, and converged on a pseudo optimal shape, with just three simple supportive points.

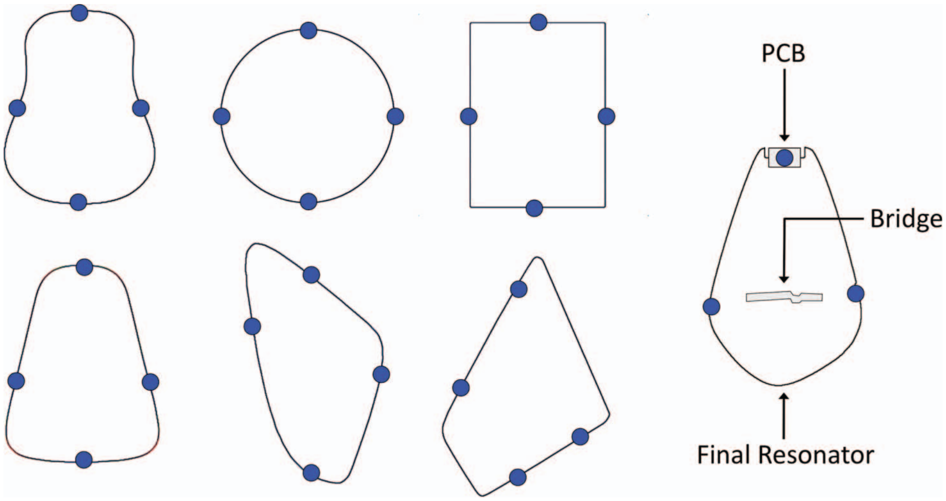

Fig. 3. In order to find the lowest eigenmodes for a given surface area, different shapes were simulated (here we present just seven of them). The shapes were modified slightly between simulations to search for a pseudo-optimal one. As part of the iterative process, we also looked for good support locations (shaded dots). We stopped this process after 20 shape simulations, selecting the shape at lower right with its three support points. From this, we define the location of the resonator PCB to be on the top support point. The bridge location was similarly defined next (see text).

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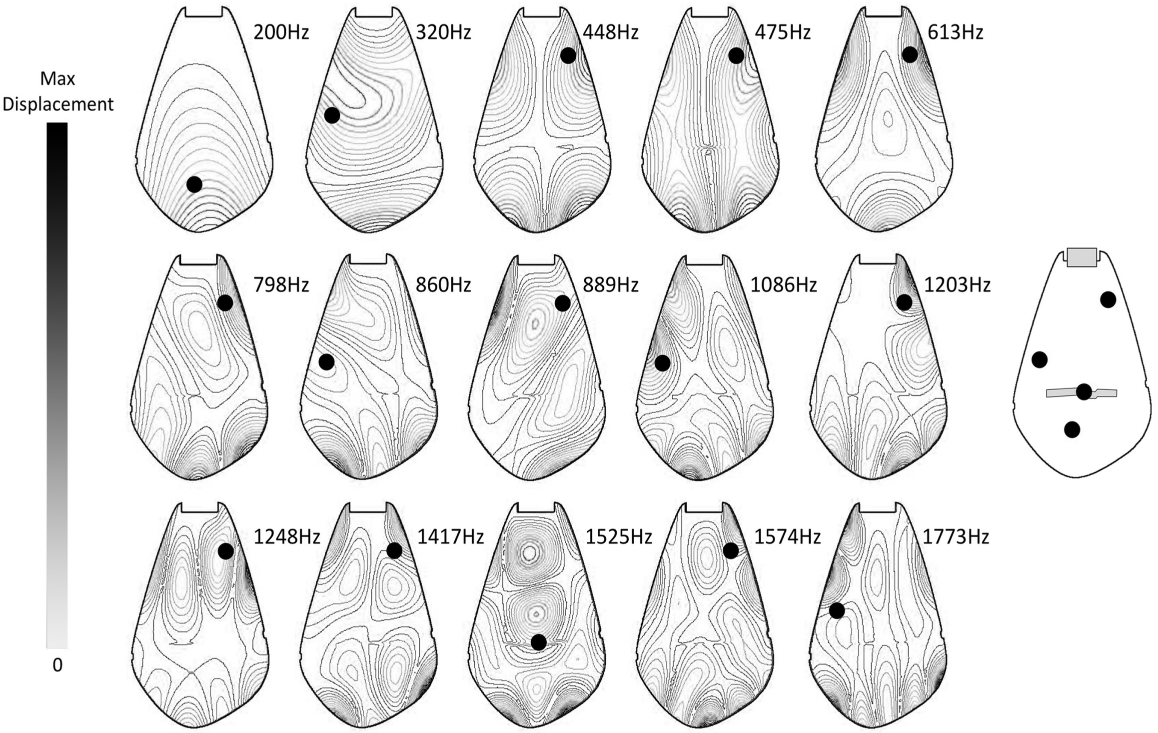

Fig. 4. FEM simulation of eigenmodes for the final resonator shape. This visual data was used to define the four sensor locations (at right). For each eigenmode, we detect the best sensing location (regarding maximal surface bending); then we cluster the eigenmodes into four groups according to a specific sensor location (shown on each eigenmode as a black dot).

The number of sensors and their locations were defined next. FEM simulation was used to analyse the first 15 eigenmodes for a 2.5 mm Sitka spruce plate with boundary and support as described above. The eigenmodes were plotted and analysed graphically. Piezoelectric contact sensors are good for sensing surface vibration; however, they are much more sensitive to surface bending (derivative of the displacement) than orthogonal motion. The gradient maps of each eigenmode were analysed and clustered in four groups, according to their spatial patterns. The five lower eigenmodes were given priority in defining the sensor locations, in order to guarantee better coverage at low frequencies—locations were picked that had the highest bending displacement. Our goal was to minimize the number of sensors to be used: as such, we tried to define how few sensors were needed to capture the highest signal-to-noise ratio (SNR) from all 15 eigenmodes. At the end of this process, four sensors locations were chosen.

5.3 Design of the guitar body

The resonators define constraints on the body design. The guitar's body should be able to embed the resonator inside it, yet still be strong and ergonomic. Several elements are important for guitar ergonomics: weight, stability, body size, thickness and string tension. The strings' sustain, which needs to be as high as possible, depends on their tension. Most of the references for this section are based on interviews with instrument-makers (M. Coppiardi, 2008, videos, personal and e-mail interviews; K. Parker, 5 February 2009, public talk in the MFA, personal and e-mail interview) and useful references for acoustic and electric guitar-making (Hiscock, 1986; Kinkead, 2004).

The Chameleon Guitar defines a new guitar family and could be implemented using any guitar as its interface: e.g. classical guitar with nylon strings, acoustic guitar with steel strings, electric guitar with nickel strings, and others. This project is focused on evolving the guitar to a new stage; therefore we decided to base its interface on the most popular guitar type, the electric guitar.

An electric guitar has better sustain than acoustic guitars; the solid-body minimizes the strings' energy loss at the bridge. *The Chameleon Guitar*, however, does not have a solid body. Therefore, a long neck scale was chosen in order to maximize the strings' static tension for a given note, thus maximizing the guitar's sustain. On the other hand, a long neck scale with high tension can cause problems, such as a resistance to bending. Making the non-vibrating parts of the strings longer can minimize those problems. These factors influenced the design of the neck's head and the tailpiece location. A single-cut body was selected, due to the resonator's shape constraints on the body.

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Several 2D and 3D sketches were made in an iterative design process, before defining the final shape (see Figures 5 and 6). A 3D model of the guitar was then built in *Rhino3D*. Design efforts were made to make the aesthetic look of *The Chameleon Guitar* compatible with that of the current popular electric guitar family without making it too similar to existing models, while, at the same time, encouraging viewers to focus on the resonator. A turquoise colour was chosen to contrast with the warm resonator colors, which were expected to be brown wood tones.

After designing the guitar outline, more detailed designs were needed: designs for the mechanism to easily replace a resonator, selecting tuner types (*Steinberger Gearless Tuners*), the tailpiece (*Gotoh 510* Tailpiece) and materials for the guitar. The mechanism for the resonator replacement, called the *resonator tray*, was designed in *Rhino3D*. A key driver in its design was to allow a user to swap resonators in less than ten seconds. Aluminium and delrin have low friction coefficients, which make them good candidates for sliding elements.

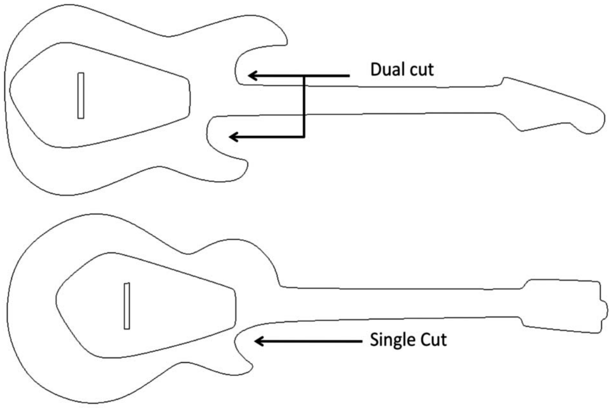

Fig. 5. Dual and single cuts in the body of electric guitars.

The tray itself was designed from aluminium, while the rails and the lockers were made from delrin.

The last design stage was to choose the woods for the guitar parts. Mahogany, which is better than maple for vibrating at low frequencies (mahogany and maple are the most popular woods for electric guitar necks), was chosen for the neck. Poplar was chosen for the main body frame: it is light, easy to work with and shares acoustic properties with mahogany. A carbon fibre structure is located inside the poplar body frame to add stiffness.

5.4 Electronics

The signal starts its path with the piezoelectric sensors, amplified in the *resonator PCB* analog circuit and digitally processed in the *SP unit*. The sensors are standard ceramic piezoelectric discs (common for musical uses) with a resonant peak at 7000 Hz (±600 Hz), 9.9 mm diameter and 0.12 mm thickness. A small disc size was preferred, in order to minimize the affected resonator surface. Voltage fluctuations (the sensed signal) develop on the sensors when a pressure field is applied, and are transmitted to the *resonator PCB* with thin coaxial wires. The ceramic discs were hard-fixed to the resonators with standard adhesive (more detail below).

The *resonator PCB* circuit was designed for five channels. Here, we only used four of them and left an extra channel for more design flexibility. In order to change the piezoelectric voltage signals from high to low impedance, they need to be buffered with a non-inverting op-amp. The piezoelectric sensors have a series electric capacitance that can implement a high-pass filter with a load resistor. The lowest standard note of the guitar is the E note (80 Hz). The sensor capacitance, 10 nF, as calculated from piezoelectric equation (Fraden, 2003) gives a filter cutoff (f3 db) of 32 Hz when the shunt resistor value is 0.5 MΩ.

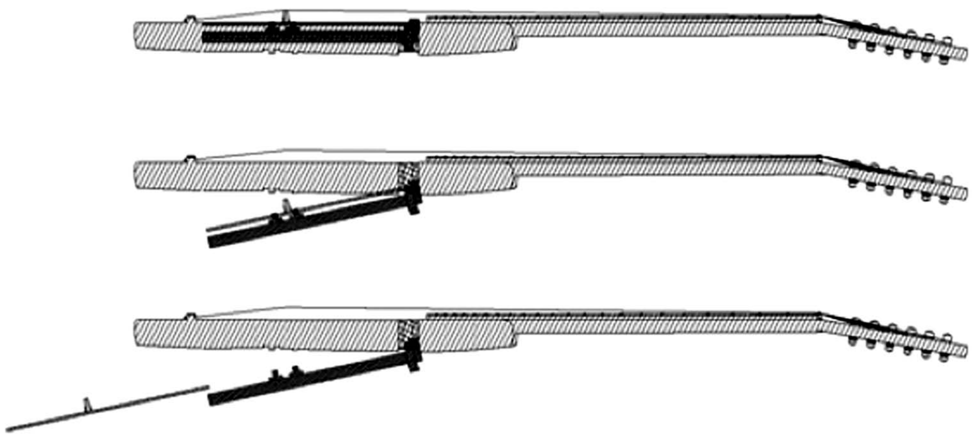

Fig. 6. The resonator tray operation.

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This guarantees that the guitar's relevant spectrum will not be suppressed. The first-order transform function of the filter is less relevant here, and will be taken into consideration in the DSP algorithm. The signals are biased to 2.5 V, and the PCB outputs are all line level signals. The PCB is powered from the *SP unit* with a LED power indicator, and grounded by the *resonator tray*, so that all the aluminum parts are grounded. A special socket connector is built into the *resonator tray*; the *resonator PCB* slides into it when a resonator is inserted into the guitar. In principle, each resonator can host a different set of electronics if desired, and it is trivial for each resonator to be uniquely identified via an ID on its PCB, allowing for a different suite of downstream signal processing options and effects to be enabled.

The *SP unit* that was chosen is the *Freescale's Symphony*$^{\text{TM}}$ *SoundBite Development Kit*, hosting a *Freescale Symphony*$^{\text{TM}}$ *DSP56371* (192 MHz, 24 bit fixed point processor—see Figure 7). The unit has eight audio line level inputs and outputs. The unit's sampling rate is 48 kHz, with 16 bit quantization levels. The analog-to-digital sampler includes an anti-aliasing filter.

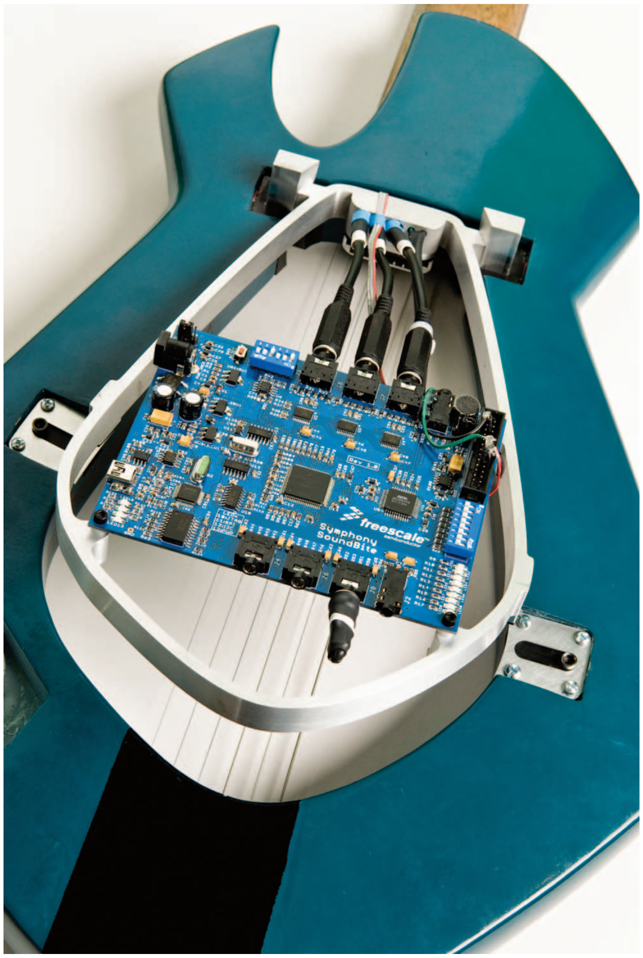

Fig. 7. *The Chameleon Guitar*'s backside showing the resonator tray and the SP unit.

Four line level inputs are transferred from the *resonator tray* connector to the inputs of the *SP unit* by coaxial wires. After digital processing, the output signal is transferred from a line level to an instrument level (in other words, a low impedance signal changed to a high impedance one compatible with standard guitar amplifiers) and then to the guitar output jack. The *SP unit* can also produce multichannel audio outputs.

5.5 Fabrication

The fabrication of *The Chameleon Guitar* body was done in two stages. Digital fabrication, based on computer modelling of the guitar, and hand-made modification (sanding, gluing, adjustment and varnishing). The guitar's neck and body frame were milled separately using a milling machine. The carbon fibre structure was glued inside the body with epoxy. The fretboard was made by hand; adjusting its dimensions, then inserting, trimming and sanding the fret wires. Then the neck was adjusted and glued to the body with epoxy. The guitar was sanded, varnished and polished, then the tailpiece, output jack, and tuners were assembled. The *resonator tray*, which was made in a milling process, was the last element to be assembled.

5.6 Signal processing

5.6.1 General

The signal processing algorithms that we used in our work were developed and tested using *Matlab* and implemented on the above-mentioned *SP unit* in C code, using the *Freescale's Symphony*$^{\text{TM}}$ *Studio Development Tools* and based on *Freescale's Eight-channel-C-template* C code software (48 kHz 16 bit, one sampling cycle latency). The development tools included DSP memory and device mapping, as well as analog-to-digital convertor and digital-to-analog convertor drivers.

The main goal of the DSP algorithm that we designed is to implement a virtual chamber based on the physical resonator, i.e. to manipulate at least one resonator's signals (resonator no. 1) and re-construct them to minimize the difference D between *The Chameleon Guitar*'s output impulse response[1] signal (captured by a microphone, 20 cm in front of an *Acoustic AG15 15 W 1 × 8 Guitar Combo Amplifier*) and the reference guitar impulse response (see Section 5.1):

$$D = s_r - \sum_{j=1}^{4} \sum_{j=0}^{N} c_{ij}(s_i \cdot h_j).$$

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[1] Impulse response here is as described in Section 5.1.

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This is an equalization problem, finding the correct frequencies and amplitudes of band pass filters. The reference guitar's signal is s_r, each sensor's signal is s_i (i is signal's index, from 1 to 4), the band coefficient per signal channel is c_{ij}, and the infinite impulse response (IIR) filters are represented by h_j. The minimization of D was achieved here through an experimental, brute-force iterative process as described below. The D value can be minimized by a proper filter bank design (h_j values) and the choice of correct coefficients (c_{ij}). First, each of the raw sensor signals (after sampling) is processed through a filter bank with its bands tuned according to the reference guitar's formants: for each band, the filter cut-offs were tuned (by eye, based on a *Matlab* graph) to fit the reference acoustic guitar formants, and c_{ij} was tuned to fit the formant amplitude. For the minimization of D, for each band just the ideal s_i was chosen—the best c_{ij} candidates were selected, and for the rest were tuned to zero. The amplitude and decay rates of each band were scaled in order to best achieve the required reference level. However, when more than one sensor signal (s_i) produced a good candidate for a specific band, the one with the higher SNR was chosen. After tuning the signal-processing algorithm to minimize D, adjusting it to a sound like a smaller or bigger guitar chamber was relatively easy.

As the acoustic waves in the guitar approach its resonance modes, the decay rates at the corresponding frequencies are slower. An IIR filter can imitate such a behaviour coherently; the distance of the filter's poles from its region of convergence (ROC) tunes the resonance behaviour of the IIR. The IIR can add a slower decay rate to the transferred band, i.e. by tuning the filter bank's IIR coefficients, we can fit artificial reverberation to selected bands. Our filter bank was implemented by a *Second Order Section Direct Form II* filter (see Figure 8). The filter bank implementation is simple, and is based on summing all of the bands in the time domain (while ignoring phases).

The impulse response of resonator no. 1 was used for tuning the filter banks. The IIR coefficients were optimized in *Matlab*'s *FDAtool* using a brute-force manual process. This *Matlab* system required 14 bands and mainly processed resonance modes below 1 kHz. It was implemented on the guitar with fewer bands (starting at seven and leading down to four). In practice, the resonators projected an acoustic sound that could not be ignored, which was mixed with the processed sound. Morphing between the guitar's acoustic sound (attenuating directly from the resonator) and the *SP unit* output (after amplification) tends to give interesting overall results: the sound in the recording studio has a stereo quality, depending on the positioning of the guitar and the amplifier in the room. Overall, we can say that the guitar digital processing contributes mainly to the lower modes, and the sound reflected directly from the resonator contributes more to the middle and high frequency range (see Figure 9).

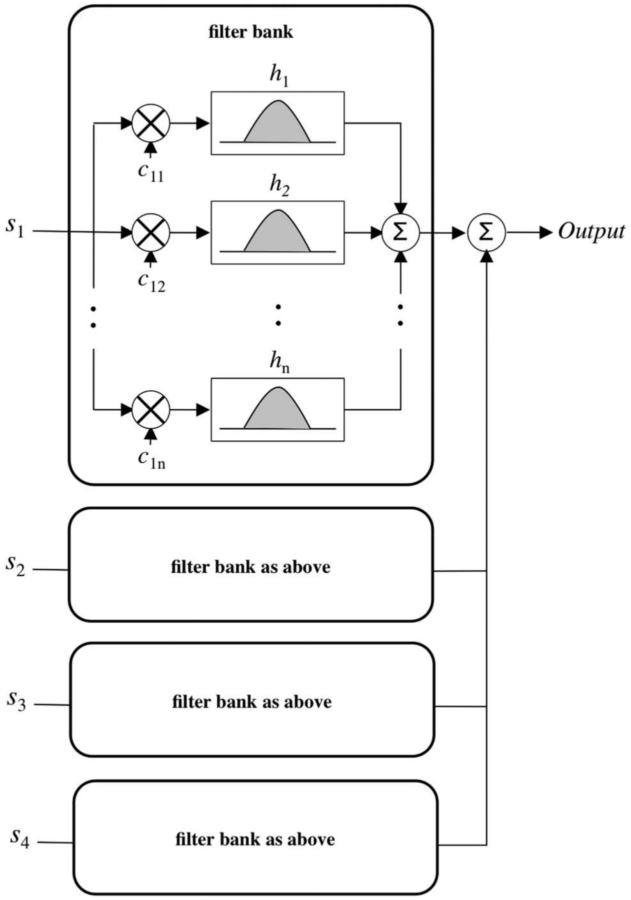

Fig. 8. The digital signal processing chain.

5.6.2 Alternative algorithms

The algorithm described above is a suggested implementation of a virtual chamber. However, the use of a DSP unit enables implementation of a variety of sound processing techniques and synthesized algorithms. Lazzarini, Timoney, and Lysaght (2008), for example, describe adaptive frequency modulation synthesis based on an acoustic oscillator instead of an electrical oscillator. Smith (2010) in *Physical Audio Signal Processing* describes many different sound effects that can be implemented digitally, such as virtual distortion.

The Chameleon Guitar resonator has four authentic channels. All of them represent the same acoustic event, but each has a different timbre, as the pickup responsible is at a different location. Each of these signals is a different superposition of the resonator's eigenmodes (with phase difference that can be ignored for low frequencies). The distance between the signals can be represented as D_{nm}:

$$D_{nm} = \sum_{j=0}^{N} c_{nj}(s_n \cdot h_j) - \sum_{j=0}^{N} c_{mj}(s_m \cdot h_j).$$

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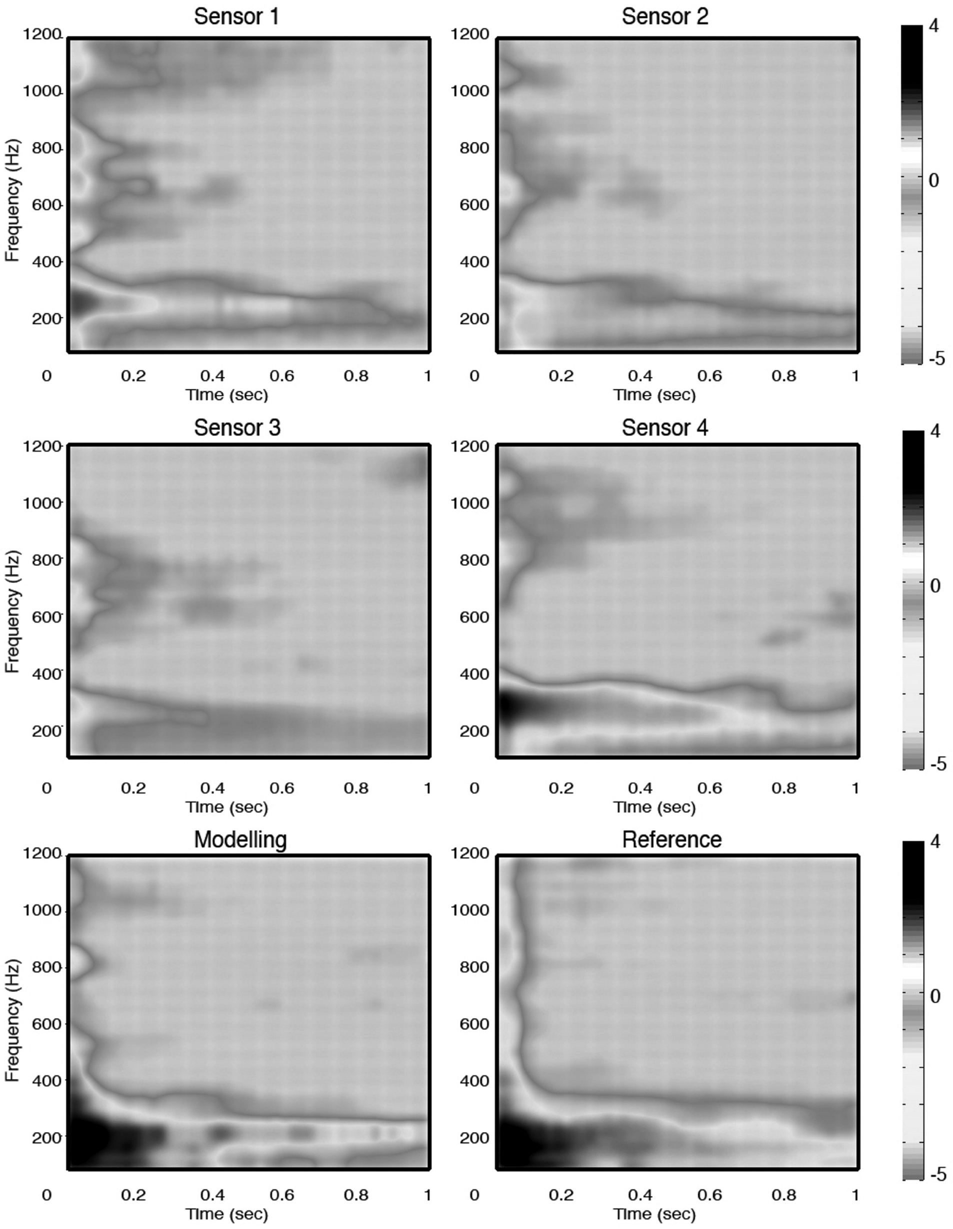

Fig. 9. Logarithmic, smoothed spectrograms of the impulse response for each sensor, showing also the final SP output as well as the reference. These plots (excepting that of the reference) are for the Sitka spruce resonator (see Figure 10, no. 1).

D_{nm} is highly dependent on the medium; it is a unique property of the resonator, which contains rich acoustic information that can be used to synthesize or control the sound; for example, using the output of one sensor to manipulate another sensor's signal.

A suggestion for such processing is described in this relation:

$$S = s_4 * \sin\left(b_1 * IIR(s_2, Hd_{14}) + b_2 * s_3\right) + b_3 * s_2.$$

This is a combination of phase modulation with a distortion effect, depending on the b_i coefficient values. The amplitude of s_4, which is low-frequency oriented, controls the clipping of the non-linear part of the formula (inside the sinusoid). At the same time, s_2, which is mid frequency oriented, provides a natural signal. In the case of a resonator that allows easy, non-coupled manipulation of s_4, such as in resonator 6, which is divided into two plates that are connected with a 4 × 6 × 50 mm wooden bar in the backside (see Figure 10, no. 6—the small plate, which is flexible, and easily manipulated contains s_4), an interesting overall effect is given. As mentioned earlier, the signal processing suite accompanying each resonator can easily be customized to the sonic palette that the resonator suggests.

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5.7 Resonators

The resonators' designs were a long process of trial and error. All resonators have four piezoelectric sensors located in the same place. The first four resonators are more conservative; all of them include wooden soundboards supported by braces and a glued bridge, varying only in their structure and materials (see Figure 10 for a detailed description). The last four resonators test different ideas—embedding springs, an acrylonitrile butadiene styrene (ABS) plastic chamber, screws or complex boundaries and connections. Different players have tested all of these resonators.

3D models of the soundboard and the bridge were built in *Rhino 3D*. Wooden blocks were prepared, sometimes by gluing two pieces to make a joint block, where the wood-cuts and grain direction were selected in a traditional way. Then, the resonator's shape was milled using *Shopbot CNC* machine and cut with a Universal Laser Cut machine. The bridges were made in a similar way, and glued with epoxy to the resonators after location adjustment.

All the resonators were hand-finished, first sanded or trimmed with a scraper,[2] then varnished using different techniques for protection and aesthetics. The *resonator PCBs* were glued to the resonator with *epoxy*. The sensors were glued with special *ethyl cyanoacrylate adhesive*, and were protected with a thin balsa ring. Coaxial wires connected the sensors with the *resonator PCB*, sometimes guided by small plastic elements. All the resonators have plastic or wood bindings at their edges to protect them from damage.

Fig. 10. Top: a group of eight resonators. The first four are more traditional, made from wood only. The last five are more experimental, including loose screws, springs, free plates or plastic chamber with rice or water. Resonator no. 1 was used as the reference for algorithm development. Bottom: resonator backside (no. 4). This resonator is arched, with all the sensors on its back.

6. Evaluation

Fifteen guitar players took part in the evaluation of the project. The players varied in their usual playing time, from 0.1 to 17 h per week. The average weekly playing time was 4.3 h. The players were asked about their favourite music style and the type of guitars they normally use. For our study, each of the players used the guitar for an hour in an acoustic recording studio.

After introducing the guitar's concept and its technical aspects, the participants were asked to play the guitar and use all of its eight resonators, for about seven minutes per resonator. The participants tried three different digital processing options: big chamber digital processing, small chamber digital processing (Section 5.6.1) and a digital effect (Section 5.6.2). Each participant played in his or her preferred musical style. The participants were asked to replace at least one resonator by themselves and to examine the tangible qualities of the resonators (such as knocking and scratching the resonators' surface). The evaluation results are summarized here—more detail is presented in Zoran (2009).

6.1 Concept and contribution

The first question the participants were asked was if they would like to have *The Chameleon Guitar*. Answers were rated on a scale from one to seven (one represents 'no' and seven represents 'definitely'). The average response was 6.33, with standard deviation of 1.18, which is a very positive answer. Then the participants needed to select the most important properties of *The Chameleon Guitar*, the role that best fits the guitar, and the musical style that best fits the guitar.

The participants were asked about the contribution of *The Chameleon Guitar* to the guitar and the field of music in general. The dominant answers were the guitar's new acoustic sound possibilities and new expressive ways to play the guitar (together with new sound effects). Several players mentioned the new craft and hobby options: players would be able to reconsider form and materials, and could experiment with many different sounds by themselves. Few answers referred to the emotional connection and unique narratives linked to each of the

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[2] A sharp steel plate, used for trimming wood surfaces.

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resonators. Some said this could lead to new sound possibilities and to a new collecting culture (most serious players have several guitars, and develop a particular bond with each—here, a player would collect unique resonators, each representing different acoustic/sonic properties and aesthetic values). Going further, some participants predicted that new iconic original sounds could appear, associating the new sounds with resonators instead of with the guitar itself.

The participants were asked if it is easy to replace a resonator, on a scale from one to seven (one represents 'no' and seven represents 'definitely'). The average answer was 4.6, with a standard deviation of 1.4; this means it is not easy enough, although the replacement itself does not take more than 15 s. Some of them complained that the *SP unit* (the DSP on the back of the guitar) needs to be covered and protected from the player's body, an obvious modification were this instrument to be produced.

6.2 Digital abilities

The participants were asked if the digital abilities are interesting. While all of them answered positively, their explanations differed one from another. The ability to manipulate digital effects with a tangible acoustic interface, such as in resonator no. 6 (see the explanation in Section 5.6), seemed to be very compelling for the majority of players. Some of them wrote that this allows them to expand the playing experience. Several participants believed the expressive control of digital effects from the resonator can serve as an interesting alternative to guitar pedals.

For a few of the participants, the digital capabilities suggested a big potential to create new sounds. Some of them, however, indicated that this potential still needed to be developed further. One participant said the current algorithm could be implemented with analog processing, and that the degree of digital control was not developed enough. There are some disadvantages in using a computer for sound processing (e.g. there is a prejudice that computers are not aging nicely as wood, and the guitar community still rejects the integration of digital technology into the guitar body) and one participant was not sure about the argument of implementing the computer over an analog circuit.

6.3 Resonators

The participants were asked how many resonators they felt they might use (unlimited by our collection of eight resonator). The average answer was 4.2, with standard deviation of 2.6. Then they were asked to choose their preferred three resonators, and to explain their selections. More analysis of the reaction to conventional versus novel resonators is presented below.

6.4 Instrument-makers evaluation

Instrument-makers also qualitatively evaluated *The Chameleon Guitar*. The guitar was presented to individual guitar-makers and to violin-makers. The guitar-makers gave an inside perspective, while the violin-makers provided a comparatively unbiased point of view. The project was discussed freely, regarding its concept, technical issues, and optional contributions. The majority of instrument-makers said they would be willing to develop resonators if the market demanded it. Some suggested to keep on improving the sound quality, and to have at least one resonator that was acoustically optimized.

7. Discussion

The Chameleon Guitar was designed and built to implement a new concept of an acoustic-digital hybrid instrument, based on discussions with instrument-makers, experience from the preliminary prototype and the capabilities of digital simulation. While 15 players formally evaluated it, at least 15 more players tried it within a total period of ten weeks. During that time, two groups of resonators were made and 15 different resonators were tested, and the *resonator tray* was opened at least 300 times. The project was discussed with designers and engineers, demoed multiple times, and received significant press coverage.

The concept seemed to be compelling to the majority of participants. Players from different musical styles, as well as instrument-makers, understood the idea and its potential well. It seems that the new combination of digital and hybrid features interest the majority of those in the study, while allowing maximum flexibility in both domains.

The player participants responded very positively to the question 'would you like to have such a guitar', and were consistent on the uses and role they believe this guitar would be appropriate for. The players that liked the guitar less are generally players who are not used to this guitar interface (such as players who prefer nylon strings). It seemed that hollow body guitar and electric guitar players enjoyed *The Chameleon Guitar* more.

After analysing the survey forms, no correlation was found between the participant's favourite musical styles and the role they saw for *The Chameleon Guitar*. While the most important property of the guitar, according to the players, was its new sound potential together with the option to replace resonators, players tended to associate the guitar to rock, jazz, contemporary music and folk music styles, which are more experimental musical fields (unlike classical music or blues).

The participants referred to the new sonic possibilities as one of the most important contributions of *The*

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Chameleon Guitar, but did not correlate this property with the guitar itself. They correlated sound qualities with resonators. None of the answers to the questions about improving the guitar dealt with sound, and although all the players and instrument-makers believed its digital abilities were important, most felt that it contributed as a sound effect rather than a sound source.

In general, this means that the guitar's digital processing abilities do not yet have a significant identity. More work thus needs to be done to enlarge the digital capabilities. The question of how to control the software, by tangible interfaces on the resonators themselves or by electronic controllers on the guitar, still needs to be tackled. When considering the high degree of complexity that digital processing adds to the sound, we also need to discuss the off-line sound design interface: how an external computer interface takes part in simulating, modifying and controlling the preferred sound, and how the unique properties of each resonator can be leveraged and maximized with digital sound design.

All the subjects correlated sound qualities with the resonators and recognized that the resonators' replacement, together with the sound possibilities, are the most important properties of the guitar. However, when asking the players how many resonators they would like to have, the average answer was 4.2. A lot of guitar players own more than one guitar, and 4.2 does not seem to maximize the innovation potential. On the other hand, instrument-makers suggested experimenting with as many resonators as possible. When discussing this conflict with players, the most common answer was that they chose resonators from the collection that they had seen, and they believed that after trying more resonators for a longer period, they may want to have more. It was difficult for the average player to imagine a new type of resonator. However, instrument-makers could easily discuss new resonator designs.

By analysing the popularity of different resonators, we learned that the second group of resonators (no. 5 to no. 8, the more experimental resonators), were preferred. Here, the most popular resonators were no. 6 and no. 8, and the main argument for their popularity relies in their novelty, unexpected behaviour (although sometimes this behaviour was actually produced by the digital effects), higher expressivity, and experimental options. Loose elements and embedded chambers have a lot of potential—although experimental guitar artists have explored such ideas, they are still relatively unknown to the guitar-playing mainstream. *The Chameleon Guitar* provides a platform well suited to exploration of such concepts. It can be interesting, for example, to combine these with other mechanical elements (such as wheels or wires) and to redesign the use of the spring (resonator no. 7, see Figure 10).

The first group of resonators (no. 1 to no. 4, the conservative group) received less popularity from the players, although almost all participants chose at least one resonator from that group in his or her selection. Here, the main reasons for choosing a resonator were sound and aesthetic qualities, referring to acoustic guitar standards. However, the preferences varied for each participant, where the selection of good sound or 'the most beautiful' resonator depended on personal preference. Each one of the resonators got the title 'sounds best' or 'the most beautiful' from different players. For the instrument-makers, the conservative group was more interesting than the experimental one, perhaps because of their bias towards quality in standard guitar design. In general, sonic qualities, interface issues, narrative properties, and aesthetic qualities were related to the resonators, more than to the guitar.

The tuning of the guitar, which varied when resonators were replaced up to half-a-tone, can be stabilized by adding a fine-tuning mechanism to the resonator's bridge, allowing the user to set all the resonators to the exact location (and string action) under the strings' load. Another option is to use automated mechanical tuning, which automatically re-tunes the guitar after replacing a resonator.

Although a resonant chamber with acoustic pickups can aggravate feedback problems, in practice it was not a significant problem with *The Chameleon Guitar*. While feedback accrued when amplifying the resonators' raw signals directly, the low-pass nature of our digital processing prevented it from becoming a practical problem. In that context, the guitar was recorded and evaluated in a sound studio, and it still needs to be examined in concert conditions, which may introduce different challenges.

8. Conclusions and future work

The Chameleon Guitar is the product of a year and a half of development, inspired from both the digital and the physical musical instrument landscapes. This new approach to designing guitars was tested successfully, and proved itself over time. The guitar and its resonators functioned well, were evaluated by 15 players, and tried by many more. Several mechanical changes need to be made to the current guitar model, such as a new design for the *resonator tray* and new tuners. Other than that, the guitar is stable, ergonomic, and offers an open-ended selection of timbres.

The main goal of this work was to merge traditional values with digital capabilities. Based on our evaluation results, we can say that it was fairly successful. The main contribution of *The Chameleon Guitar* lies in its innovative solution to use replicable, acoustic resonators with electronic processing, while enjoying a higher degree of acoustic information captured from these resonators by several sensors (relative to the single surface sensor

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that is commonly in use in acoustic guitars). While any digital algorithm to create sound can be easily reproduced and copied, each wooden piece is unique and has a spatial-acoustic behaviour. Here, we combine this acoustic uniqueness with the digital environment, leveraging the unique acoustic signature of each resonator with a palette of appropriate digital sonic transformations. In addition to this success, the process of experimentation and risk taking in the design of resonators resulted in innovative expressive abilities. It seemed that the community of instrument-makers felt more attached to the traditional approach, while the guitar players were more excited by the experimental approach. We believe that both of these endeavours need to continue being developed together by introducing traditional values into experimental solutions. As a quality criterion, it is important to have at least one resonator that sounds like a good acoustic guitar. While the sound produced by several resonators (together with the digital processing) is already being recognized as an acoustic guitar sound (by all listeners), more work, acoustically and digitally, needs to be done in order to compete with the sound of high quality acoustic guitars. This goal may be achieved by improving the resonator design, sensor positioning, and digital processing algorithm.

The instrument's digital capabilities have a huge promise that interests users, especially because of their potential to enlarge and expand upon the resonator's unique physical properties. However, richer digital processing options still need to be investigated. A visual feedback and control scheme is also needed, dependent on the guitar and resonator design—each resonator lends itself to different expressive affordances.

More generally, this approach could be easily implemented in other string instruments, such as the violin family, and with a bit more effort could even be developed into a piano solution.

The external computer interface for modifying the digital content of the instrument is a different topic that requires more research. One can envision, for example, a simple high-level application programming interface (API), that would enable each resonator to bring up a particular set of options and adjustments on an attached PC, allowing the player to appropriately modify the guitar's sound based on meaningful parameters (as opposed to adjusting filter coefficients or directly writing code, although that's always an option for those so inclined). The potential is huge: in this system, we can connect a sound-making object to virtual environments in a very fluid fashion. This connection can demonstrate how physical objects can share in the same media revolution as digital objects, and opens up new possibilities for future forms of interactive entertainment. Such a connection can lead the way in combining craft, tradition, and acoustics with the digital environment, opening up a new future for hybrid design of objects.

References

Bevilacqua, F., Rasamimanana, N., Fléty, E., Lemouton, S., & Baschet, F. (2006). The augmented violin project: Research, composition and performance report. In *6th International Conference on New Interfaces for Musical Expression (NIME06)*, Paris, France, pp. 402–406.

Cadoz, C., Luciani, A., Florens, J.L., & Castagné, N. (2003). Artistic creation and computer interactive multisensory simulation force feedback gesture transducers. In *3rd International Conference on New Interfaces for Musical Expression (NIME03)*, Montreal, Canada, pp. 235–246.

Fender website. (2009). Retrieved 15 July 2009 from www.fender.com

Fletcher, N.H., & Rossing, T.D. (1990). *The Physics of Musical Instruments* (2nd ed.). Berlin: Springer.

Fraden, J. (2003). *Handbook of Modern Sensors: Physics, Designs, and Applications* (3rd ed.). Berlin: Springer.

Gibson website. (2009). Retrieved 15 July 2009 from www.gibson.com

Hiscock, M. (1986). *Make Your Own Electric Guitar*. Basingstoke: NBS Publications.

Howard, D.M., & Rimell, S. (2003, 6–9 August). Gesture-tactile controlled physical modeling music synthesis. In *Proceedings of the Stockholm Music Acoustics Conference, SMAC-03*, Stockholm, Sweden, Vol. 2, pp. 697–700.

Hughes, T. (2004). *Analog Man's Guide to Vintage Effects*. Branford, CT: For Musicians Only Publishing.

Inta, R. (2007). *The acoustics of the steel string guitar* (PhD thesis). University of New South Wales, Australia.

Jehan, T., Yound, D., Bell, J., & Lunn, C.V. (2005). *Hyperviolin*. Cambridge MA: MIT Media Lab.

Kinkead, J. (2004). *Build Your Own Acoustic Guitar*. Milwaukee, WI: Hal Leonard.

Lähdeoja, O. (2008). An approach to instrument augmentation guitar. In *8th International Conference on New Interfaces for Musical Expression (NIME08)*, Genova, Italy.

Lazzarini, V., Timoney, J., & Lysaght, T. (2008, 1–4 September). Asymmetric-spectra methods for adaptive FM synthesis. In *11th International Conference on Digital Audio Effects 2008. DAFx-08*, Espoo, Finland.

Line 6 website. (2009). Retrieved 15 July 2009 from www.line6.com

Machover, T. (1992). *Hyperinstruments: A Progress Report 1987–1991*. Cambridge MA: MIT Media Lab.

Merrill, D., & Raffle, H. (2007, 28 April–3 May). The sound of touch. In *CHI 2007*, San Jose, CA, USA.

Paradiso, J. (1997). Electronic music interfaces: New ways to play. *IEEE Spectrum Magazine*, *34*(12), 18–30. Retrieved 15 July 2009 from http://web.media.mit.edu/joep/SpectrumWeb/SpectrumX.html

Siminoff, R. (2007). *The Art of Tap Tuning*. Milwaukee, WI: Hal Leonard.

Smith, J.O., III. (2010, 21 December). *Physical Audio Signal Processing. Beta Version*. Stanford, CA: W3K Publishing.

Smyth, T., & Smith, J.O., III. (2002). Creating sustained tones with the cicada's rapid sequential buckling mechanism. In *2nd International Conference on New Interfaces for Musical Expression (NIME02)*, Dublin, Ireland.

SynthAxe website. (2009). Retrieved 13 August 2009 from http://www.hollis.co.uk/john/synthaxe.html

Teuffel website. (2009). Retrieved 15 July 2009 from www.teuffel.com

Thompson, A. (1997). *Stompbox—a History of Guitar Fuzzes, Flangers, Phasers, Echoes & Wahs*. San Francisco, CA: Miller Freeman Books.

Vanegas, R. (2007). The MIDI pick—trigger serial data, samples, and MIDI from a guitar pick. In *Conference on New Interfaces for Musical Expression (NIME07)*, New York, USA.

Zoran, A. (2009). *Chameleon Guitar – a physical heart in a digital instrument* (Master thesis). MIT Media Lab, USA.

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