Chameleon Guitar

A Physical Heart in a Digital Instrument

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Submitted to the Program in Media Arts and Sciences, School of Architecture
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Master of Science in Media Arts and Sciences at the
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Abstract

Today's tools and instruments, whether musical or graphical, fall into two very distinct classes, each with its own benefits and drawbacks. Traditional physical instruments offer a richness and uniqueness of qualities that result from the unique properties of the physical materials used to make them. The hand-crafted qualities are also very important for these tools. In contrast, electronic and computer-based instruments lack this richness and uniqueness; they produce very predictable and generic results, but offer the advantage of flexibility, as they can be many instruments in one. I propose a new approach to designing and building instruments which attempts to combine the best of both, and I call this approach "hybrid instruments", since the resulting instruments exist simultaneously in both the physical and digital environments. The approach is characterized by a sampling of the instrument's physical matter and its properties and is complemented by a physically simulated, virtual shape or other digital signal manipulations. This thesis describes the key concepts of the approach and presents an actual example of such a hybrid instrument: the *Chameleon Guitar*. The guitar project contains several aspects: separation of the guitar interface from its acoustic content; division of the acoustic content into a physical part and a digital processing part; and maximization of the user's freedom in each of the domains. I provide a historical and technical overview; discuss related works, motivation and concepts, and present the design of the Chameleon Guitar. In addition the project evaluation by musicians and instrument-makers is described, together with future work and conclusions. I hope to demonstrate that this approach to building digital instruments maintains some of the rich qualities and variation found in real instruments (the result of natural materials combined with craft) with the flexibility and open-endedness of virtual instruments.

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Ken Parker
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Founder of Parker Guitars

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Table of Contents

1. Introduction

In this thesis a new approach to designing instruments is presented, combining the digital and the physical environments. This perspective is illustrated in the domain of musical instruments, specifically that of *guitar*s. The approach is rooted in three different fields: the human computer interaction (HCI) field, the musical instruments field and the field of industrial design. While the main goal of the project is to merge traditional[1] values and digital abilities, it seems that this connection naturally relies on the modern abilities to design and build objects, as well as on modern approaches for interaction with digital technologies.

In musical instrument-making, the importance of merging traditional designs and methods, with the ability to adopt new technologies has always been a major theme. Some musical instruments, such as the guitar, are a combination of several important properties. The guitar has a complicated interface giving a high degree of control, it has a history starting in the Stone Age, and it has a contemporary influence of our culture, including modern music and computer gaming. All of these make the guitar excellent platform for implementing the project's goal.

While most of this thesis focuses on the *Chameleon Guitar* itself (and all relevant supportive topics), it is important to discuss the broader context of this project. Object design is traditionally limited by physical world constraints, while the virtual environment is free from most of these limitations. Modeling the physical properties of an object in the computer (with CAD-CAM tools, for instance), in order to simulate its behavior under varying conditions (using digital tools such as Finite Element simulators), has been developed into an established research field. Parallel to this, development of computer graphics had led to an improved correlation between visual feedback and virtual environments. The field of object design can benefit from these advantages. A user can define a virtual shape and enjoy the simulated results, without actually having to build the object.

However, the virtual environment has the disadvantage of lacking a unique and authentic interface. Users appreciate craftsmanship qualities, uniqueness of materials, and physical details that may change over time. Though some of these can be simulated, the resulting computer model will be a product of property generalizations. After a unique object has been virtually modeled, it is not unique anymore, because it can be easily copied and manipulated.

Physical objects are commonly used in HCI research as tangible interfaces for manipulating digital data [1]. The amount of unique authentic information that can be embedded in physical objects is

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[1] In the thesis, "traditional" means the way a user envisions the tool, encompassing functional, aesthetical, and historical properties.

enormous, but we rarely use this complexity for tools. In most cases, the physical object helps us to control rich digital information, but what about the richness of the object itself? We can use the computer to monitor this information and to make it useful.

Musical instruments provide a good platform for testing different object design perspectives. 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 a significant role in defining the instrument's unique sound. It is difficult to find two acoustic instruments that sound the same, which leads to a deep connection between the player and its instrument. At the same time, digital technologies are playing a bigger part in creating and processing sounds, due to the flexibilities they provide for sound control.

The *acoustic guitar* owes its sound to its wooden chamber. The timbre and volume of the guitar depends on the shape of the chamber and the structure of the 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 behavior and its color over time or in different moisture conditions.

In this project I implemented a new guitar that combines physical acoustic properties with digital capabilities. The concept of the *Chameleon Guitar* is to separate the shape from the material and craft quality. A physical resonator, a replaceable piece of matter that gives the guitar a truly acoustic behavior, is situated under the guitar bridge. An array of sensors captures the acoustic behavior of the resonator (the displacement of its surface), while a computer simulation transforms the signal to the relevant programmable (virtual) shape or any other digital sound effect.

Thesis Roadmap

This document is divided into seven Chapters. In the second Chapter, *Guitar Background and Motivation*, I will discuss the development of the acoustic and electric guitar, as well as the state of guitars today, starting with acoustic instruments and acoustic guitars, and continuing to electronic musical instruments and the electric guitar. Next in this Chapter I will discuss the main problems of the field and motivations for this research. In the third Chapter, *Design Explorations*, I will present several different concepts suggesting a solution to these problems; the Digital *Chameleon Guitar* was the selected concept for the main project. The fourth Chapter, *Technical and Acoustical Background*, discusses the technical details needed to understand the context of the work, starting with acoustic fundamentals, and continuing to electronic guitar technology. In the fifth Chapter, *Technologies and Implementation*, I will present all the technical issues regarding the design, construction, sound processing and implementation of the Chameleon Guitar. In the sixth Chapter, *Evaluation and Future Work*, the project evaluation by musicians and instrument-makers will be presented, together with future work. In the seventh Chapter, *Design*

Potential, I will present inspirations from non-musical fields, discuss design concepts and approaches, and suggest possible contributions to other fields, such as HCI and product design. In the last Chapter I will present the thesis conclusions.

Fig. 1 The Chameleon Guitar with three resonators

2. Guitar Background and Motivation

2.1. Overview

The following Chapter is meant to give relevant information needed to understand the musical and historical context of the work. Only music-related topics are covered in this Section; other perspectives will be discussed in Chapter 7.

Section 2.2 covers the history and development of acoustic musical instruments in general, while Section 2.3 presents the history of the acoustic guitar, up-to-date. Section 2.4 gives an overview of different electronic musical instruments, and Section 2.5 presents an electric guitar history, including up-to-date topics.

I present the guitar's current status in Section 2.6, with relevant challenges, and propose alternative directions for guitar developments. I address design opportunities (in the fabrication stage as well as in sound processing) that arise by combining acoustic properties with digital technologies, and I explain why such a connection is important to the future of the guitar.

2.2. Acoustic Musical Instruments

A musical instrument is “any device for producing musical sound” (Britannica Online Encyclopedia [2]); the major classifications are percussion, stringed, keyboard and wind.

Fig. 2 Hunting bow and turtle's shell. From [3]

Evidence of musical instruments has existed since the beginning of human culture; archaeologists have found pipes and whistles dated earlier then 10,000 B.C. and clay drums and trumpets prior to 5,000 B.C. According to Franz Jahnel, in his *Manual of Guitar Technology* [3], many researchers believe that the string instrument originated with the hunting bow (Fig. 2), but they are not certain about its ancestry. It seems that an instrument similar to the modern *krar* (Fig. 3) existed around 4,000 B.C. in Western Asia.

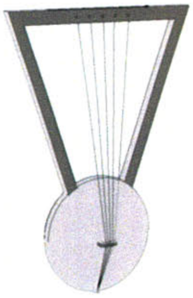

Fig. 3 The krar

Historically, the development of musical instruments depended on several elements, such as available materials, craftsmanship and technological skills, mythic and symbolic cultural vision, and patterns of trade and migration. Several factors affect the music produced by instruments; the most significant ones are materials, size and shape. A wooden stringed instrument sounds different than a metal stringed instrument, even if the two are otherwise identical. Note that the timbre of a wind instrument is more affected by the volume and shape of the air tube than by its materials.

The crucial elements of acoustic instruments are the vibrating parts (strings, membrane, air pipes, etc.) and volume-increasing parts (pots, gourds, wood chambers), which change the acoustic behavior depending on Helmholz resonance[2]. Thus, the complexity of the music depends both on technology and on human imagination and creativity.

Fig. 4 Nicolò Amati's violin,1669 [6]

The first step in the instrument-building process is selecting and preparing the materials. Wood used for wind or stringed instruments needs to be seasoned. For example, Kinkade explains the process of preparing the wood for acoustic guitar in [4]. Metals, which are widely used for strings, bells, trumpets and more, need to be manufactured and cast. Secondly, construction of all instruments is a required skill with great craftsmanship. The history of musical instrument-making includes multiple influences of cultures, musical style and workmanship. These qualities were developed through long practice, using a process of trial and error, constantly influenced by the discovery of new playing tones and techniques [5]. Instrument-makers have both preserved traditional approaches and have adopted new construction techniques.

The craftsmanship developed around instrument-making also required skills that were not directly related to acoustic values of instruments. Being acoustic determinants, musical instruments have been profoundly influenced by cultural and aesthetic factors, such as form and decoration. These influences give the instrument more value as time passes [7]. In the movie *The Red Violin* [8], the story focuses on the historical path of a 17th century violin, influenced by acoustic, aesthetic and mythic values.

Fig. 5 Guitar mass production line, Gibson's factory [9]

In many cases, modernity has simplified or even improved instrument-making. Since the Industrial Revolution, new methods have changed the manufacturing of instruments and new materials, such as plastic, replacing traditional ones. Yet, despite industrialization, producing a high quality instrument still requires great human craftsmanship; a violin glued together from mass produced parts cannot equal (acoustically nor aesthetically) one that has been constructed by an individual craftsman who is not satisfied with the work until everything is working together perfectly.

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[2] For more information on Helmholtz resonance see Chapter 4.

Fig. 6 The viol, from [10]

Historical Overview of Acoustic Instruments

Stringed instruments are significant in European musical history. Many varieties of plucked instruments were made and used in Europe during the Middle Ages and the Renaissance. Bowed instruments have influenced the musical identity of the region, and they have also played an important role in Asia and in North Africa. Many variations of bowed instruments existed in Europe, and by the 16th century they had been reduced to two main categories: the *viol* and the *violin*. Unlike the violin, the viol (Fig. 6) has a flat back, more strings than the violin (six or seven compared to four), and frets (the violin does not have any). The violin family, which was adopted by the symphony orchestras, was developed according to three main sizes: the violin is the smallest; the viola is the tenor, while the violoncello is the bass of the family.

Keyboard instruments developed only in Europe, for reasons that are not clear. The keyboard has been used successfully to control different resonators: bells, struck and plucked stringed instruments (the *piano*), and wind. The *organ* was very popular from the early Middle Ages through the 17th century, until the early 18th century, when the Italian maker Bartolomeo Cristofori constructed the first piano.

Modern wind instruments have been developed in Europe since the 17th century on. *Trumpets* and *horns* were already used in Europe and Asia for military proposes and rituals. The *clarinet* emerged at the end of the 17th century and, like the *oboe*, developed into a family of instruments. The *saxophone* was invented in the 19th century in Belgium. Unlike other wind instruments, the saxophone never became a natural member of symphony orchestras, but rather then has been used by art-music composers, largely as a solo instrument.

Percussion instruments have mostly been refined in Africa, Asia and Native America.

Thus, although there have been numerous instruments developed over the years, very few have been widely adopted. The reason one instrument becomes more popular than another is not always clear, it is a complicated socio-cultural question. This question depends on many factors such as which composers or players utilize the instrument, its price, its interface complexity, its learning curve and its appearance. Bart Hopkin presents an alternative classification of instruments, proposing an interesting perspective on other acoustic possibilities for sound creation [11, 12]. His work includes the *Membrane Reed* (a membrane that is literally pulled to be a pipe, see Fig. 7), the *Musical Siren* and the *Branching Corrugahorn* (multiple tubes, with discreet notes). Hopkin merges traditional acoustic principles, experimental combinations of alternative interfaces, materials and sound production elements, through which he creates a collection of instruments that sound and look different than most popular ones, presenting alternative development branches of musical instruments.

Fig. 7 Branching corrugahorn (left) and membrane reed, from [11, 13]

2.3. The Acoustic Guitar

Acoustic guitars, unlike violins, do not share a well-defined standard. Plucked string instruments evolved and changed since the first days of the krar, and guitar continues to evolve these days. Jahnel describes string instruments' rich, historical development in Asia, Europe and Africa, beginning more than 5,000 years ago [3].

After the first days of instruments that used gourds and animal's shells, such as hunting bows, *lyres* and *kitharas*, the ancestor of the *lute* appeared in the Orient. The oldest evidence for long neck lutes was found in a figure on an ancient Hebrew clay tablet from 2,400 B.C. This is the first string instrument with a neck. It is believed that these instruments were mainly used to accompany singers or wind instruments. The *Mesopotamian lutes* had a single or double-string, with no pegs and a flat body; the body was apparently carved out of one piece of wood, while the string is believed to be made from animals' guts. After that, more evidence for long neck lutes and similar instruments were found in Egypt, Mesopotamia, India, Turkey and China, in a variety of sizes and materials (bone, wood, etc.), some of them even decorated. The top part of the body could have been a plate of wood or a membrane (animal skin).

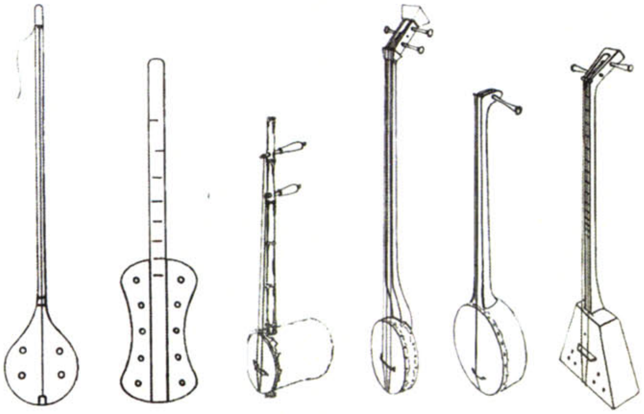

Fig. 8 Long neck ancient lutes, from [3]

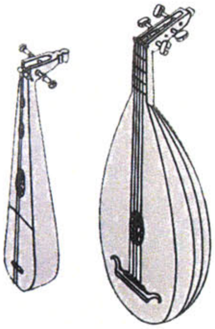

Fig. 9 Al' ud (right) and *rebeb*, from [3]

The *mizhar* and *barbat* had a shorter neck that merged with the body; the *rebeb* (Fig. 9) was the ancestor of the Arabic *al' ud* (600-900 A.D.) and the violin. Arabs were the first to bring the rebeb and the al' ud into Africa in 642, and from there to Spain in 711, where the al' ud got the name *lute*. A variety of lute versions were developed in Europe in the Middle Ages. The classical lute had arrived from Spain into central and Western Europe, while East Europe adopted similar instruments from the Near East. In the 16th, 17th and 18th centuries the number of lutes increased while it began to be a popular instrument in all of Europe. Lutes varied in the number of strings, tuning system, neck length, body size, having or not having frets on the neck, its decoration and more. They were particularly used in France but started to lose their popularity by the end of the 17th century. In Italy, Germany and the Netherland, lute playing continued until the end of the 18th century.

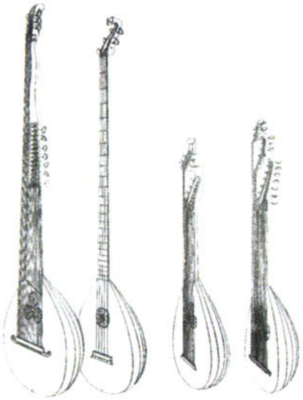

Fig. 10 European lutes, from [3]

The *classical guitar* evolved in Spain in the 13th century from *guitarra latina*, a type of lute. Like the lute, the guitar was built in many different forms and sizes in various countries, using different tuning styles. Darcy Kuronen, in his book *Dangerous Curves; The Art of The Guitar* [14], presents important guitar models since Belchior Dias' guitar, which is considered one of the earliest models known to have survived (Fig. 11). This Portuguese guitar from about 1590 has ten strings, a flat top and back, and is much smaller then the modern guitar. While its back is made from rosewood, the neck and top have been replaced over the centuries.

The guitar gained more popularity in Spain, Portugal and their colonies in the 17th century, while starting to appear more and more in Italy, Germany, England and Eastern Europe. It usually had ten strings. Like other musical instrument-makers of the period, the luthiers (guitar- and lute-makers) decorated their instruments with ivory, bones and exotics woods[3].

Fig. 11 Dias' guitar, 1590, from [15]

At the end of the 18th century, contributing to the development of the modern classical instrument, the guitar underwent several changes, the most visible being the six string standard. The fingerboard lengthened and the frets were changed from gut to metal or ivory; wood tuning pegs were replaced by metal worm gear tuning machines. One of the most important changes that took place inside the guitar is the development of improved ways to brace the thin top plate from soft wood (see Section 4.3). The size and shape of the guitar were also gradually changed: the body became wider and larger.

Classical and *flamenco guitars* that we know today are mainly the result of developments made by Spanish guitar-makers from the mid 19th century until the beginning of the 20th century. Antonio de

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[3] Those lutes and early guitars that survived till today do not have the same market value as other instruments (like the violin) from the same or similar makers [16]. Unlike the violin, which is still a popular instrument today, the early guitar is very different from the modern one, which makes it un-useful tool for most players.

Torres, who is considered the father of the modern classical guitar, was responsible for transforming this instrument into larger bodied classical guitars of today (see Fig. 12).

Steel string *acoustic guitars* (unlike the classical gut and later nylon string guitars) appeared in North America at the beginning of the 20th century. Several companies, such as C. F. Martin and Gibson manufactured guitars designed especially for steel strings, divided into two groups: *flat-top* and *arch-top*. Martin's Dreadnought models, and later Gibson's Jambo and Super Jambo, influenced the development of the flat-top since the first half of the century. Maccaferri's arch-top guitar was used by Django Reinhardt (1910-1953) but didn't become very popular. The Gibson's L-5 model (1924), on the other hand, became the basis for all successful arch-top guitars.

Fig. 12 Torres' guitar from 1882, from [15]

Fig. 13 Martin Dreadnought 28 and Gibson Super Jambo, from [17-18]

.

Fig. 14 Gibson L-5 arch-top guitar, from [19]

Design Alternatives

Fig. 15 W.J. Dyer's Harp guitar, from [20]

The history of the guitar is rich in design branches, with some existing for many years but never getting the chance to dominate, and designs that are high-end, experts' instruments that the average user cannot afford. Design alternatives are highly important to the evolutionary process: as cultural mutants that may influence the field in the future; as instruments that inspire makers and musicians; or as examples of what can and what cannot work.

The multiple necks and harp guitars that evolved from lutes with a similar concept hundreds of years ago are examples of such an alternative design branch. Those guitars vary in shape, size and number of strings, and although they are rarely seen in leading musician performances, they are still being made today for interest groups and collectors. Occasionally those instruments are more a demonstration of craftsmanship abilities than a practical, mainstream musical instrument.

Fig. 16 Pat Metheny's 42-string *Pikasso* guitar, from [21]

Fig. 17 Fender FR48 steel resonator guitar, from [22]

The *Hawaiian guitar* is an acoustic guitar that was developed in the first half of the 20th century for use in the very popular Hawaiian musical style (played by sitting with the guitar lying on the knees[4]). Related to the Hawaiian guitar, resonator guitars were developed in the 1920s and contain metal resonator cones that go into the body in order to increase volume.

Robert Shaw claims in his book *Hand Made Hand Played* [23] that today is the "golden age" of guitar-making, and that never in the history of guitar-making have so many new designs and models been built. Some of these instruments have defined new standards

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[4] Lap steel guitar is a general name for guitar designed to be played in that style.

for acoustic guitar-making, and inspired other makers to improve their skills.

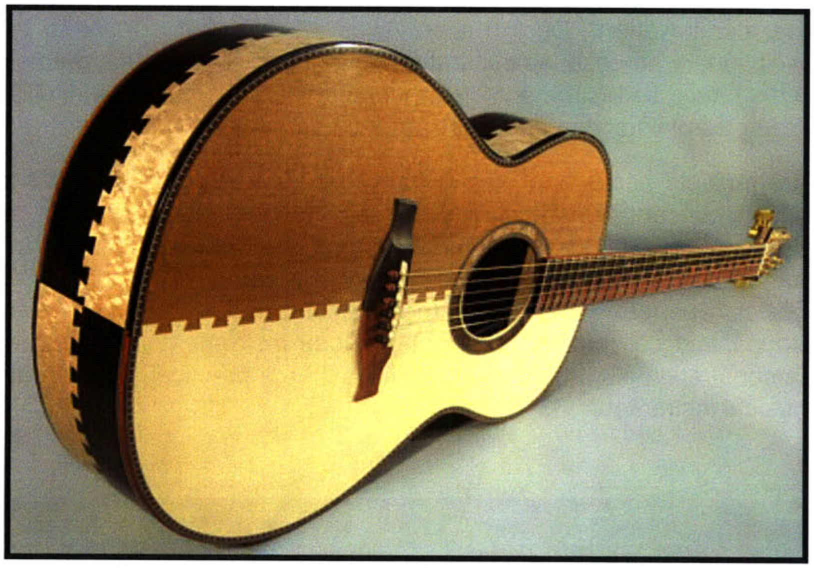

Fig. 18 Dovetail Madness guitar by Howard Klepper, from [24]

Fig. 19 L-45.7 guitar by Steve Klein, from [25]

While several makers and factories focus on high complexity decoration of existing models or imitation of old models, others are more interested in re-designing the functional structure of the guitar. For example, Steve Klein, in his L-45.7, presents an unusual body shape (Fig. 19) made by traditional materials and carbon fiber parts [25]. Howard Klepper in his Dovetail Madness guitar (Fig. 18) mixes wood types in an unconventional way, joining two types of wood into all elements of the guitar. The soundboard, for example, is made from spruce and cedar, glued and connected together in the middle [24].

Ken Parker in his new arch-top design [26-27] uses new materials for acoustic guitar-making: from exotic woods (pernambuco wood for the fret board) and unusual uses of common woods (poplar body for the sides and body's beck), high level metal craftsmanship (Mokume[5] tailpiece) or carbon fiber elements. Parker's design itself is innovative: the location of the sound hole, together with a special carbon fiber connection to the neck, frees part of the soundboard boundary and minimizes the amount of soundboard surface loss (see Fig. 20).

Blackbird Guitars created the Blackbird Rider Acoustic [28], a commercial guitar digitally designed and made from composite materials. This kind of new material enables a significant decrease of the chamber's size while preserving the instrument's loudness.

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[5] Mokume is a traditional Japanese craftsmanship method to create mixed-metal laminate with graphic patterns.

Fig. 20 Grace arch-top guitar by Ken Parker, from [26]

Fig. 21

Elisha Gray's musical telegraph, 1876, from [30]

2.4. Electronic Musical Instruments

The electronic musical instrument is mainly a product of the last century. However, the first true electronic instrument is Elisha Gray's *musical telegraph* from 1876: an array of tuned electronic buzzers, activated by switches on a musical keyboard. Joe Paradiso, in his article *Electronic Music Interfaces* [29], describes the classification and development in the field since that date.

The classification of electronic musical instruments is similar to that of acoustic ones (keyboard, stringed, wind and percussion) but also includes other groups, such as gestural instruments or wearable instruments. Some of these instruments were designed to imitate the behavior of their acoustic equivalent; others are more innovative and create new sounds and musical experiences. Side by side with the development of electronic technology, and later computers, the electronic musical instrument changed the way instruments produce sound, and how they can be controlled and played.

Fig. 22 V-150K Concert Select Silent Practice™ Plus Violin, from [31]

The electronic keyboard, began with Elisha Gray (Fig. 21), evolved in many directions: from the *electric piano*, which was designed to simulate the timbre of the acoustic piano; the *electric organ* and the *synthesizer* (analog or digital). Later MIDI[6] helped to connect synthesizers with other instruments or computers. *Electric drums* usually use acoustic pickups attached to the surface, and then process the signal electronically. Electric string instruments use magnetic pickups to sense steel string vibrations or piezoelectric sensors to sense[7] vibrations of a membrane, a plate or a bridge (as in Yamaha's V-150K *electric violin*, Fig. 22). The *Hyperinstrument* group in the MIT Media Lab created the *Hyperviolin*, an example of an expressive digital instrument, manipulating the acoustic timbre of the instrument with digital tools [32].

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[6] Musical Instrument Digital Interface, an industrial standard protocol for communication and control.

[7] More on sensors and DSP in Chapter 4.

In addition, unlike the traditional musical interface of those instruments, other innovative electronic instruments appeared. From the *Theremin* to the *DanceSpace* by Flavia Sparacino (here the whole body acts as a musical instrument), electronic sensing and control technology opened a door for new gestural interfaces. The development of these technologies, together with the new signal processing abilities developed in the second half of the 20th century, enabled the use of almost any object as a musical instrument, with enormous control abilities. For example, Raffle, Merrill and Aimi in *The Sound of Touch* created an interface to capture and manipulate the sound of any material scratched by a metal wand [33].

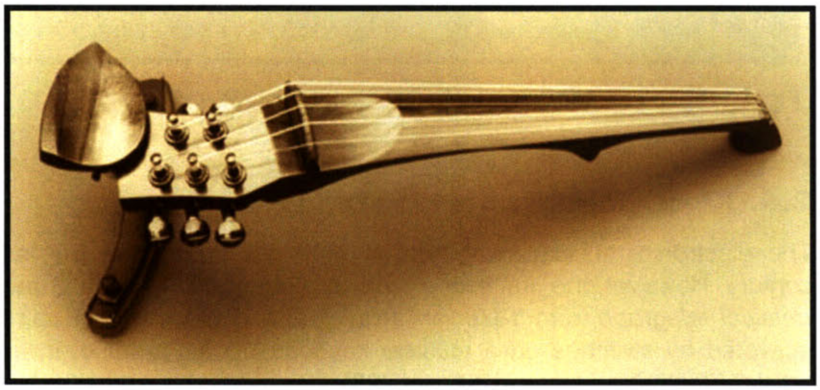

Fig. 23 The Media lab's Hyperviolin, from [32]

The development of electronic musical instruments occurred rapidly, and today digital controller and DSP processors are a bigger part of the musical instrument. Electronic instruments do not even approach the longevity of acoustic instruments, and digital instruments are in their infancy of development.

The challenges in this field are enormous: computers are able to create highly complex timbres or simulate physical models of an acoustic event [34]; Interfaces and control systems are developing quickly, adopting methods from relevant HCI experiences. The main problem is mapping: how to use the rich audio possibilities with the digital interface, and how to map a human gesture to sound, and control a signal. These problems, which were solved implicitly with acoustic instruments, will continue to pose challenge in the near future.

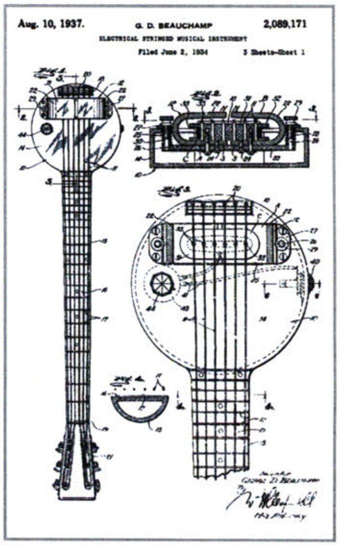

Fig. 24 George Beauchamp's Frying Pan's patent 1934, from [35]

2.5. The Electric Guitar

The Arabic al ud' is the ancestor of the European lute, from which the modern guitar evolve from. Beginning its development in Europe, the guitar owes its last development to American innovators.

After European instrument-makers immigrated to North America and brought guitar craftsmanship with them, the steel string acoustic guitar was developed, later evolving into the modern electric guitar; this process occurred almost entirely during the 20th century. The

Fig. 25 Gibson ES-150, from [39]

Frying Pan (Fig. 24) is the first *electric guitar* ever made [14]. George Beauchamp designed this guitar in 1931 and the Rickenbacker Electro factory manufactured it for seven years. It was a lap steel (see footnote on page 21) aluminum-bodied guitar with one magnetic pickup, designed to be played as a melodic instrument in the Hawaiian musical style.

Because the acoustic guitar wasn't loud enough, there was a problem using it as a melodic instrument for the popular jazz music of the period. In 1937, Gibson created the ES-150, an arch-top guitar with one magnetic pickup, based on Gibson's L-5 arch-top model (see Fig. 14 and Fig. 25). Charlie Christian, an important jazz player at the time, used the ES-150. The main problem with the amplified acoustic guitar is feedback, when sound waves arriving from the speakers feed the guitar soundboard with vibration, and the system oscillates. Lester (Les) Paul, one of the leading jazz players of that time, was the first to conclude that, if the guitar has a pickup, it does not need the soundboard to vibrate [36-38]. Thus he created the Log in 1939, the first guitar with a solid wood block behind the pickup (Fig. 26). This guitar, based on the Epiphone model (now belonging to Gibson) served Les Paul in concerts. He demoed the guitar to Gibson, who decided at the time not to adopt the invention.

Fig. 26 The original Log by Les Paul, from [40]

Fig. 27 From left: Fender Telecaster, Fender Stratocaster, and Gibson Les Paul, from [17,41].

Fig. 28 Merle Travis guitar by Paul Bigsby, from [42]

In the late Forties, the engineer and inventor Paul Bigsby produced one of the first solid-body guitars (Fig. 28), made for the country guitarist Merle Travis [42]. It was probably Bigsby's guitar that influenced Leo Fender, who manufactured the first ever, mass produced, solid-body electric guitar in 1951: the Broadcaster (later named the Telecaster, see Fig. 27). The Broadcaster was designed for easy fabrication (in order to lower its price) while creating a new design style. Gibson decided not to wait any longer, and produced the first signature model, the Gibson Les Paul, in 1952. Unlike the

Broadcaster, the Les Paul was an expensive model, made from mahogany and maple woods with an arched body, fitting the traditional quality of Gibson's brand. It was the first mass produced guitar to use humbuckers pickups[8]. In 1953, Fender produced the Stratocaster: a 3 pickup ash wood guitar with a tremolo bridge. Since then, the Stratocaster has become the bestselling guitar of all time [36], and together with the Telecaster and the Les Paul has become the most influential icons of the field.

Fig. 29 Gibson Flying V, from [17]

The use of electric amplification reduced the need for a big band, and made it easier to perform in smaller spaces [43]. Instead of a large orchestra, a small band with four or five musicians became popular. When electric tube amplifiers were fed with high voltage, they introduced a non-linear clipping effect to the sound, in other words, distortion. Musicians became used to this new sound, and rock & roll was born.

Fig. 30 Gibson Explorer. from [17]

Fender electric guitars were more commercially successful than that of Gibson. Due to its price, the Les Paul was not as popular as the Telecaster or Stratocaster. In 1960, Gibson stopped producing the Les Paul for several years. Two other Gibson projects, the Explorer and the Flying V from the late Fifties, were cheaper, adapting modern design styles (like Fender), to shapes that recalled one of car design styles of that period. However, these models completely failed in the market, probably because the designs were too innovative. At the beginning of the Sixties, Gibson introduced the SG model, which represented a design compromise that had more success.

In the late Sixties, when the blues' distorted sound began to be very popular (due to players such as Freddie King, Eric Clapton and Jimmy Page), the popularity of the Les Paul started to increase, and Gibson decided to resume manufacturing it. Today, an original Les Paul from the Fifties can be a very high-priced, collector's item, more expensive than any other guitar. A similar story happened with the Flying V and the Explorer, which achieved popularity mainly after famous blues player Albert King, and later Jimi Hendrix, used the Flying V, which went into production again.

Fig. 31 Gibson SG '61 Reissue, from [17]

Fender and Gibson are still the biggest guitar companies, and their old famous models continue to be popular to this day. Although over the years many new models were produced (such as the Fender

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[8] Two single magnetic pickups joined together, in opposite polarization. More information on signals and pickups in Chapter 4.

Fig. 32 Fender Jazzmaster, from [41]

Jazzmaster, Fig. 32), none of them gained the same popularity as these models from the first ten years of the development of the electric guitar. Several others guitar, from manufacturers such as Rickenbacker, Gretsch or Danellectro, gained some popularity. Since the Sixties, a lot of guitar models were designed that differed from each other in pickup configuration, neck scales, body materials, size and design.

In the late Sixties, Jimi Hendrix, who was a leading figure in rock, changed the image of the guitar forever. Hendrix was a gifted left hand player, who played a Fender Stratocaster and later a Gibson Flying V, with a unique heavy blues style. He was famous for his performance style, and although he wasn't the first player to use heavy distortion or to break his guitar on stage (The Who had done it before), he was the first to focus the show on the guitar. The guitar ceased to be just another part of the band; it started to become the main, leading instrument in the rock performance.

Fig. 33 Gretsch Brian Setzer Nashville, from [44]

The electric guitar developed to be part of a complex system, where the timbre and behavior of the instrument depends on a variety of external factors: distance from the speakers, room acoustics and body position, as well as execution factures, such as the way the strings are plucked or muted. Its high degree of freedom made the electric guitar a highly expressive instrument - and it influenced the guitar performance from then on. Since the days of the late Sixties, the term "Guitar Hero" is given to a talented leading guitar player. The Seventies were the years rock bands or individual stars built their fame around a unique sound or playing style. Guitar players like David Gilmour from Pink Floyd, Brian May from Queen, Jimmy Page from Led Zeppelin and Jeff Beck shaped the sound of the guitar as well as the image of the player and the performance.

Fig. 34 David Gilmour in a guitar solo, during concert in Munich, Germany, 2006, from [45]

Fig. 35 Rickenbacker 620 models, from [46]

Fig. 36 Eddie Van Halen in concert, from [47]

Fig. 37 Ibanez JEM7V Steve Vai, from [48]

The next stage in the development of the electronic technologies and the guitar resulted in an array of analog controllers and pedals that modified the guitar output signal [29]: from various types of signal clipping methods, to a Wah-Wah pedal, fuzz boxes, delays and reverb effects, octave dividers, and various others. An unusual effect was the Bag, by Kustom: an array of vocoders that injected the guitar signal directly into the player's mouth through a small speaker tube and then picked it up with a microphone.

When the lead guitar of the heavy metal music appeared in the Seventies, a new guitar was needed, one that would be built for that style (enabling fast playing, stable tuning and a light body). Companies such as Kramer, Jackson and Ibanez specialize in heavy metal guitars, while Japanese Ibanez became the biggest non-American guitar company. Ibanez introduced signature models for leading heavy metal players like Steve Vai (Fig. 37) and Joe Satriani (Fig. 38), using a very thin neck and Floyd Rose bridge locking system that allows extreme tremolo activities with heavy banding.

Leo Steinberger developed new guitars based on new materials (plastics and fibers) and new mechanical elements. His new designs gained some popularity at the beginning of the Eighties but fell out of favor quickly. Eventually Gibson bought Steinberger's company. Ken Parker had a similar experience with the Fly: a uniquely shaped guitar with good acoustic behavior for an electric guitar first introduced in the mid Nineties (see Fig. 39). The Fly is built from spruce wood and carbon fiber, has new pickups and a very light agronomic body. Although it became very famous, the Fly was not a big success in the market.

Fig. 38 Ibanez JSBDG Joe Satriani, from [48]

Fig. 39 Parker Fly, from [49]

The Electric Guitar and The Amplifier

Amplifiers and speakers played a very important part in electric guitar development since its first days. Dave Hunter, in his book *The Guitar Amp Handbook*, presents important models of tube amplifiers [50], such as Fender's 'TV-front' Deluxe from 1951 that contained a built in speaker, Vox's AC15 from 1962 or Marshall's JMP50 (amplifier only) from 1971. Each amplifier had a unique sound signature. It is common to think of the amplifier and the speakers as part of the electric guitar instrument: the sound depends on the player's techniques, the guitar, the signal path (pedals and effects), the amplifier and the room acoustics.

Fig. 40 Fender Deluxe 1951, from [51]

Fig. 41 Marshall JMP50 1974, from [52]

Although solid-state amplifiers (based on power transistors instead of tubes) are cheaper and more stable, and today contains embedded sound processing tools, tube technologies are still popular in audio amplifiers. The audiophonic quality of the tube amplifiers, together with the sound signature of the famous "guitar heroes" from the Sixties and Seventies (and also aesthetic value of the tubes), help keep them popular. Today, new tube amplifier models are still being designed, like Soldano's Decatone from 2000 or Mojave's Coyote from 2004. The modern tube amplifiers use hybrid technologies (tubes and op-amps) and modern PCB layout techniques.

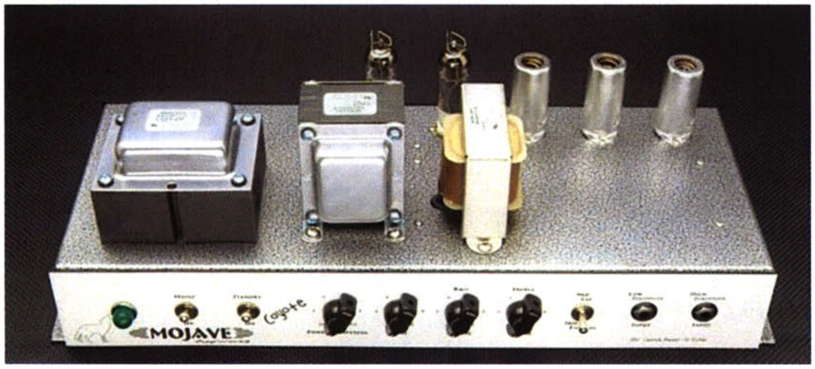

Fig. 42 Mojave Coyote tube amplifier, from [53]

The Guitar and Digital Technology

Since the first days of the synthesizer, a lot of effort was made to embed synthesizer abilities into the guitar. Starting with envelope followers (using filter banks) and continuing to pitch extractions (that then can drive an entirely synthesized sound source)[9], musicians and engineers tried to merge the most popular instrument with higher technologies.

Fig. 43 SynthAxe. from [54]

Detecting pitch and envelope and then applying a synthetic timbre is one way to achieve sound flexibility while preserving expressivity. In this way, full control of the timbre is achieved, using methods taken from the synthesizer's field; but the sensitivity of the instrument is not damaged. More sophisticated methods, based on articulation detection, can be used to expressively control the timbre. High-level signal processing abilities (and sometimes artificial intelligence tools) are needed to achieve such control. The most complicated part of the process is to model the transient[10] (in low latency) without damaging its unique sound signature.

When digital technologies first met the guitar in the Seventies, an easier approach was chosen. The first guitar synthesizers were mainly monophonic, analog devices that were unreliable and complicated to use; they sometimes didn't even include strings. The only similarity to the guitar was the way it was held, but those instruments lacked expressivity.

Fig. 44 Ztar Z7-S MIDI, from [55]

In the mid Eighties, the guitar controller began evolving significantly away from its familiar form, with many devices developed that weren't real guitars; they were expressive control over MIDI synthesizers. The SynthAxe (Fig. 43), invented by Bill Aitken, supported two sets of strings; one set, short length strings across the guitar's body, was used to detect picking, and another set was running down the fret board for, was used to determine pitch.

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[9] More information on signal envelope and filter banks in Chapter 4.

[10] The transient is very important part of the signal. See Chapter 4 for more information about it.

Zeta Music also made an interesting hybrid guitar: a guitar with a multimodal MIDI interface, which 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).

Fig. 45 Gibson Les Paul Robot, from [17]

Fig. 46 Line 6 Variax, from [56]

In recent years, as signal processing capabilities have improved, there has been a shift away from the dedicated MIDI guitar controllers, described above, back toward existing, standard electric guitar interfaces that identify the playing features by running real-time DSP algorithms. The Line 6 Variax guitar (Fig. 46) gives a variety of preset sounds, from classic acoustic and electric tones to sitar and banjo [56]. It allows the player to plug into a computer and customize a chosen tone, while the hexphonic piezoelectric pickup, located on the bridge, transfers the signal to a DSP unit located on the guitar [56]. Expressive playing and sound flexibility are enhanced with the digital guitar. Another example is Fender's VG Stratocaster [41], a hybrid electric and digital guitar. The Gibson Robot Guitar series uses a DSP unit on the guitar to control the automatic string tuning mechanism [17].

Design Alternatives

Earlier I discussed the design alternatives of the acoustic guitar. The electric guitar does not have the same acoustic constraints; it just needs a solid-body behind the bridge and pickups. This makes it easier to modify the guitar's shape, from the Gibson Flying V to the Ibanez Iceman, or to add more than one neck. Numerous graphic elements and finishing styles have been applied to the electric guitar to achieve a unique expression or help in style branding (Steve Vai's guitar is one good example for that, see Fig. 47). Most electric guitars have two or three pickups and three or five controls (pots and switches). However, different manufacturers tried alternative combinations of multiple pickups and controllers, such as the First Act's Cheap Trick guitar [58], custom made for Rick Nielsen (Fig. 48).

Fig. 47 Ibanez Jem 77GMC, from [57]

Boutique guitars hand-made or costume-made, serve the player's need for individual sound and visual expression. Brian May's guitar, made by him when he was a teenager, is a famous example. May, the guitar player of Queen never replaced his guitar, which is still in use today. Manne Guitars is an Italian guitar boutique [59], producing guitars from alternative wood sources, such as an old whiskey barrels (Fig. 49). RedEye RPM [60] is a rapid prototyping company that 3D prints solid bodies for guitars, using a digital manufacturing technology.

Fig. 48 First Act's Cheap Trick guitar, custom made for Rick Nielsen, from [58]

Ulrich Teuffel is a German designer who produces unique guitars [61]. His Birdfish model (Fig. 50) is an electric guitar that allows the player to replace wooden supports. 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. Walter McGrew patented a guitar [62] with a replaceable resonator, located in a solid structure with one magnetic sensor. This resonator includes a bridge (similar to the arch-top acoustic guitar's bridge) so the string vibration energy is transferred directly to the resonator.

Fig. 49 A Manne guitar produced from an old whiskey barrel, from [59]

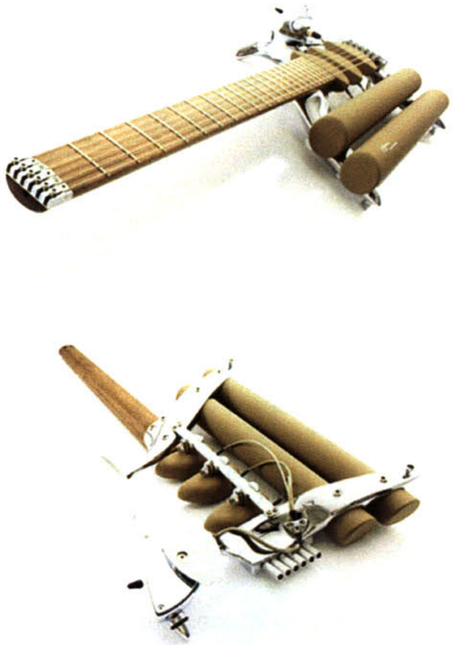

Fig. 50 Teuffel's Birdfish guitar, from [61]

2.6. The State of Guitar Development

The evolution of musical instruments, as presented in this Chapter, always depends on cultural contexts, craftsmanship skills, technical abilities and musicians. Why one instrument succeeds while the other does not, is a complicated question that requires deep social research. One thing is clear, though: when a certain musical style becomes popular, the instrument that is making this music becomes popular as well. In music history we see a close coupling between musical style, culture and instruments. On the other hand, when such a connection is too successful, it is difficult to modify or change the instrument [5, 63].

Fig. 51 Antonio Stradivari, by Edgar Bundy, 1893: a romanticized image of a craftsman-hero, from [64]

Fig. 52 Niccolò Paganini , by Jean Auguste Dominique Ingres, 1819, from [65]

Let's look at the violin, an instrument that has not changed in nearly 150 years. The violin was a very popular instrument in the Baroque and Classical musical periods (as an important member of the orchestras, and as an important solo instrument). Looking at its history, we find that the violin almost did not change since 16th century [7], when Andrea Amati designed the first modern violin. Antonio Stradivari (Fig. 51) was a student of Nicola Amati (Andrea's grandchild) and refined the violin shape to its contemporary standard in the beginning of 18th century. Niccolò Paganini (1782 – 1840) was an Italian virtuosi player who set new standards for playing techniques (Fig. 52). The violin shape remains unchanged. However, around 1870, the standard pitch raised to 440Hz and required a longer neck to be installed in all Baroque violins; also, the fingerboard was replaced with one made of ebony due to the greater resilience of the popular steel wound strings. From the mid 17th century to the mid 19th century violin standards (its craftsmanship and playing techniques) were created, reflecting cultural influences and technical abilities of the time. From this point on, very few changes were applied to the violin. Even today, the violin community is extremely conservative: referring to old icons in instrument-making style, a modern player would prefer to use a Stradivarius instrument rather than a newly made one. Modern designs and modern tools are not popular in violin-making since players request a violin as close as possible to the original instrument. In fact, back in the 17th to 19th centuries the "important" violin music was written for players and instruments. From that point of view, the classic violin is a "dead" instrument because the violin community does not inject any innovation into it at all and electric violins are in general rejected for classical use.

The development of the guitar in the 20th century depended on the evolution of our culture and technology, mainly in North America and Europe. Side by side with the developments in radio broadcasting and recording techniques, people began to relate more to players and performers than to composers of music, starting with the American jazz and blues players in the first half of the 20th century to the American and British rock stars of the second half of the 20th century. From the analog radio days to digital video, the media has played a major role in making a certain musician a cultural icon: performance style thus becomes a major part of the media "package" (Fig. 53-55). The political and cultural movements of the Sixties also helped shape the popular modern electronic music as an important phenomenon, extended it from its purely musical context [43, 63].

Fig. 53 Early records (1908) vs. Apple's iPod Touch II (2008), from [66]

Fig. 54 British rock band Queen doing a concert in Ukraine, 2008, from [67]

Fig. 55 Chuck Berry in concert in the 1950th ,from [68]

Today, after 50 years of pop music, we can analyze major developmental events. Guitars, both acoustic and electric, were the most popular instruments of the 20th century in the USA[11]. However, the main electric models are still the popular ones from the Fifties, and the main acoustic models are still the popular models from the

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[11] According to [69], the guitar and piano market sizes are equal and bigger then all other musical instruments (around 1 billion dollars each at 2004 in USA). However, the average guitar is much cheaper than the piano, and many more guitars are being sold.

days before the electric guitar [36]. The iconic "guitar heroes" are the popular players from the Sixties and the Seventies. By learning from the violin's history, we can assume that the evolution process may have stopped in the guitar field. New innovative models, from the first digital guitars of the Eighties or the highly expressive Parker Fly or Steinberger's models, have not earned significant market success, and even relatively successful guitar companies (like Ibanez) cannot compete with the iconic models from Fender and Gibson [36, 70].

This differs from what happened in consumer electronics, where for the most part reliable and cheaper Japanese products replaced the leading American ones. The guitar's image does not depend just on its technology; players are showing a complex relationship with their instrument by seeking uniqueness and individual expression and admiring conservative icons. Unlike other consumer electronic devices easily adopted by the younger generations, in the guitar field, the new generation still refers to older icons. The individuality of the beginner player may be expressed in different guitar colors or graphics, but not so much in adopting innovative technologies.

The computer graphic field (CGI) plays a major role in the consumer electronics population. Since the Eighties, the field of computer gaming and virtual environments has been introduced to us. As computer graphic abilities improved, computer games evolved, and today it is an important leading market. For instance, the *Guitar Hero* is an interface that allows users to take part in a virtual musical experience, without the need to know how to play (see Fig. 56-57). In the last few years, musical interfaces for computer games have been developed, and today their market size is even bigger than the size of musical instrument one [9]. Today, Guitar Hero is a cultural icon. Where the digital guitar failed, computer games succeeded as a digital interface for the guitar experience. Thus, Guitar Hero offers two major innovations: the ability to take part in a virtual musical experience and a new interface.

While physical interfaces for a musical experience are an interesting research direction, I focus on the virtual experience. Virtual representation of musical instruments allows the player to take part in an imaginary experience, which is otherwise inaccessible to him. Virtual abilities are important because of the freedom they add to the experience. Adding this quality to conservative guitars (acoustic or electric) may pave their way to the next technological revolution. By making the guitar (or parts of it) digital, we create an option that connect it to the virtual environment, which can be used to help teach people music, extend their interaction with other players and audiences (real or virtual), and to extend the guitar's acoustic potential.

Technically, today we have the technology to make this happen. The field of physical modeling of instruments continues to improve, and the field of DSP is constantly evolving. Using new abilities to model the acoustic behavior of instruments (or the environment) is a way to get rid of technical limitations in instrument-making. However, the development of a musical instrument must rely on historical and cultural contexts. The leading musical instruments and tools rely on a long history and cannot easily be replaced. The biggest disadvantage of the digital domain is its lack of authenticity. Digital representation is not unique or tangible.

Fig. 56 Guitar Hero: Computer game, from [71]

Fig. 57 Guitar Hero controller, from [72]

Wood is unique, and each wooden instrument has a unique sound signature. While acoustic and electric guitars are popular, digital technologies does not have a significant influence on the guitar field. Although it is difficult to change a popular musical instrument, a big innovation in an instrument can gain popularity when linked to a relevant cultural event [63]. By preserving some of the guitar's acoustic parts, and connecting them to digital technologies, we create a link between craftsmanship, sound authenticity and uniqueness, with high flexibility.

3. Design Exploration

3.1. Overview

This Chapter introduces a new concept in string instrument design: the *Chameleon Guitar*. This innovative design preserves the unique properties of the wood used to craft guitars, offering an instrument that musicians can use to create and modify the timbre of their guitars. Two previous projects exemplify this approach, which challenge the limitations placed on the use and fabrication of string instruments. Traditionally, acoustic guitars cannot be modified once they are made; it is not part of the player's experience to "play with" the structure of the instrument. Acoustic guitars are highly crafted and offer acoustic integrity, but they offer no flexibility for sound design control.

In Sections 3.2 and 3.3 I will present two pre-concept designs that are graphic works and have no physical instantiations: the *reAcoustic eGuitar*, an acoustic guitar printed using rapid prototyping technologies, taking advantages of digital modeling abilities, and the *Modified Krar*, merges the reAcoustic eGuitar concept with an ancient instrument. The *Chameleon Guitar*, its analog and digital versions, will be presented in Sections 3.4 and 3.5. These are an electric instruments (that were actually built) based on a physical resonator: a hybrid guitar, in which the sound is being created in an acoustic resonator and processed in a signal-processing unit.

All the concepts presented in this Chapter are based on a string instrument with replaceable acoustic parts. The reAcoustic eGuitar uses digital technology in the design of new guitar parts; the Chameleon Guitar uses analog and digital technologies for an innovative sound processing approach.

Technical Vision

This Chapter presents the implementation of the vision presented in Section 2.6; this vision can be implemented using cross-field technologies. The next Chapter, *Acoustical and Technical Background*, presents technical tools that are relevant for allowing such a connection. While deciding not to change the conventional musical interface (strings, neck and frets; a guitar that is played like a regular guitar), the instrument's timbre can be modified by changing digital and acoustic elements.

A linear sound source can be modeled as a poles-zeros system (see Section 4.4); part of this system can be implemented physically while part of it can be implemented digitally[12]. The physical part, which adds authentic properties to the model, can be used as a natural, stand-alone acoustic sound source or as a vibrating element for a

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[12] The acoustic guitar is not a linear system. However, for this thesis I will assume linearity. More information on that in Chapters 4 and 5.

single sensor or an array of sensors. The sensor array will detect the rich acoustic information in real-time, and then feed a signal-processing module. While the physical element has its poles-zeros behavior, the number of sensors used and their location changes the response of the captured information. The processing unit can be used to minimize the error between the acoustic sources and a required target and to modify the signals from the physical unit sensors.

Electronic tools, such as filter banks or parametric equalizers (see Section 4.4) can help to filter the required spectral behavior from the physical element. Using a programmable, digital unit to implement these tools, we can achieve high system flexibility and also implement other digital effects, taking advantages of the multiple acoustic inputs. This approach creates powerful and rich possibilities. In the next Sections, I will present various implementations based on the idea described here.

3.2. The reAcoustic eGuitar

The main benefit provided by the *reAcousic eGuitar* is allowing a musician to be involved in creating and modifying the acoustic guitar timbre and sharing this design with the guitar community in a way that is accessible for copying and modifying by others.

Gershenfeld [73] presents a future realm in which personal 3D printers become as common as color printers are today. This vision relies on the assumption that 3D digital modeling (like Rhino3D or Solidworks) will become an intuitive and easy to use. Rapid prototyping materials already have a broad range of qualities. Synthetic materials, such as carbon fiber, epoxy composites, and 3D printing technology are used today in acoustic and electric guitars (see Chapter 2). As in the case of the Blackbird Rider Acoustic, the new material enables a significant decrease of the chamber's size while preserving the instrument loudness. Ra Inta suggested using Finite Element Method (FEM) tools for designing guitars and modifying their braces [74].

Designing sounds digitally, using 3D modeling tools, allows the player to share the experience of the guitar-maker. Combining 3D modeling with simulation tools like FEM, we can simulate the physical behavior with a computer model. This approach might lead to a change in the relationship between players and their instruments. Players can take part in designing their own acoustic sounds, by modifying the physical structure of their instruments, revealing the characteristics of new materials.

The reAcoustic eGuitar invites players to become creators of their acoustic instruments and sounds, with endless possibilities for re-shaping both. Players may customize their own sounds by assembling different small chambers instead of using a single large one. Each string has its own bridge; each bridge is connected to a different chamber[13], so that changing the chamber size, material or shape changes the guitar's sound.

Fig. 58 The reAcoustic eGuitar

In the reAcoustic eGuitar vision, digital technology is used to design the acoustic guitar structure. It presents a novel sound design experience between users, their objects and the digital environment. Re-designing the guitar according to the characteristics of rapid prototyping materials could lead to timbre innovations. Open source and shared file environments could create a reality in which a player downloads or designs his own sound cells and plugs them into his instrument (see Fig. 59).

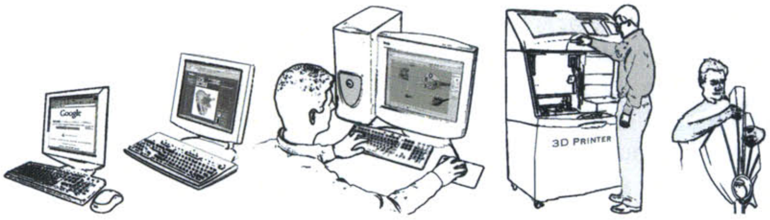

Fig. 59 Downloading, modifying, printing and assembling guitar parts

By creating digital timbre using a computer, getting a physical model of a shape that implements that timbre and then printing it, the reAcoustic eGuitar offers a new experience for the guitar player and designer. Although the reAcoustic eGuitar presents many new possibilities, there are some disadvantages to the reAcoustic eGuitar concept. The fabrication process is expensive and wasteful; further, it does not preserve the tone uniqueness as wood does.

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[13] For more information on guitar parts and their functionality see Chapter 4.

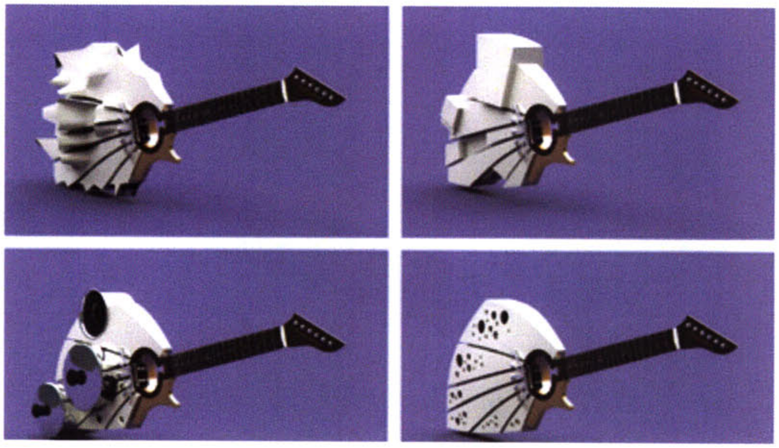

Fig. 60 The reAcoustic eGuitar: four variations

3.3. The Modified Krar

The *Modified Krar* attempts to combine the previous concept with a traditional instrument, without damaging its interface. The krar is one of the ancestors of modern string instruments. It is still a popular instrument in East Africa, used for native music, but it can be modified to serve western musical developments [75].

The Modified Krar is a concept design, embedding elements that were presented earlier in this Chapter. One of the challenges of the *krar* today is to fulfill the needs of young musicians to combine their local traditional music with modern music, in search of new timbres and multi note scales.

The Modified Krar project was developed by my undergraduate researcher, Melodie Kao, in collaboration with Mulato Astatke. It is a krar with a sliding structure that allows the player to change resonators. The resonator can be a plate, a membrane or a chamber, made from any material. The resonators will have several sensors and an analog signal-processing unit, to filter and construct the signals to one output.

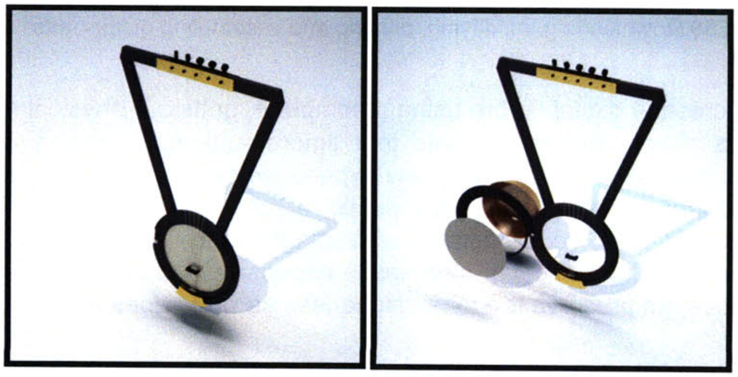

Fig. 61 The Modified Krar, by Melodie Kao

3.4. The Analog Chameleon Guitar


Fig. 62 The Analog Chameleon Guitar, resonator tray open

The former project led to a hybrid vision for guitars: a physical resonator in a simulated guitar. The motivation of the *Chameleon Guitar* project is to make the reAcoustic eGuitar concept doable while preserving the sound uniqueness provided by traditional methods of craftsmanship. In this concept, a musician can still be involved in creating and modifying acoustic guitar timbre, as well as sharing designs with the guitar community.

Fig. 63 Chameleon Guitar, analog version

This is a concept that combines the values of a synthesized guitar (like Line 6 Variax, Section 2.5) with the uniqueness of a wooden acoustic guitar's tone. By doing so, we can achieve expressive playability in a unique tool that also enables the player to design the required sound with a signal-processing unit.

The Chameleon Guitar focuses on the influences of the chamber on the sound of the acoustic guitar. The chamber's main parameters are the shape and material[14]; the chamber's structure and shape can be simulated in the signal-processing unit and used as a chamber-like effect. The material itself will not be synthesized or modulated. In this way we will get a hybrid chamber: part of it is physical (the guitar's resonator) and part of it is virtual (see Fig. 65).

In Section 2.5 I discussed the Birdfish guitar and the Walter McGrew guitar patent, which allows replacing resonators in an electric guitar with magnetic sensors. Similarly, in the Chameleon Guitar a replaceable slice of material can easily be inserted.

In the Chameleon Guitar the resonator is a small soundboard with an arch-top guitar bridge solution. The strings are tied to a tailpiece (see Fig. 63). The resonator can be swapped by opening an aluminum tray in the back of the guitar (Fig. 62). The resonators have four or five piezoelectric sensors located in different places on the resonators, to capture different vibration modes. The analog signal-processing unit is located in the back of the guitar; it merges the signals into one[15] and acoustically compensates the output to imitate

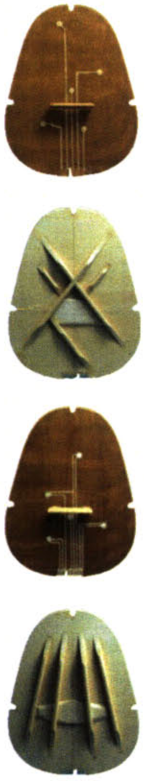
Fig. 64 Analog version's two resonators: front and back, 'x' bracing style and 'fan' bracing style

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[14] See Chapter 4 for more technical information on acoustics.

[15] This idea relies on the assumption that the relevant wavelengths are big enough so phase cancelation can be ignored. See Chapters 4 and 5.

the sound of a full acoustic guitar of an average size[16], using analog filters. Several resonators were checked and proved to sound differently. That is to say, a change in resonator structure (Fig. 64) leads to a change in output timbre[17].

3.5. The Digital Chameleon Guitar

The analog version of the Chameleon Guitar was used as a proof of concept for the digital one. While the analog version did not incorporate detailed design or ergonomic preference, the digital version, which is the main focus of this thesis, was designed and built to be used by guitar players and to present a new ergonomic and aesthetic solution.

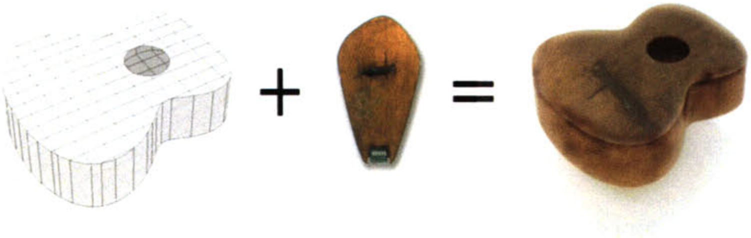

Fig. 65 The Chameleon Guitar concept: virtual shape with a physical resonator

Fig. 66 The Chameleon Guitar, the digital version

As with the analog version, the digital Chameleon Guitar presents a three-element instrument: the body, the resonator and the digital signal-processing (DSP) unit. The body is the platform that holds the two other elements; it is the guitar's interface. Underneath the guitar interface, there are two controllable parts: the programmable DSP and the replaceable resonator.

By combining the digital with the physical, I believe we can merge both worlds' 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 flexibility; the digital part can be controlled, thus extending the acoustic experience to the virtual domain. In Chapter 5, I will present the Chameleon Guitar and its resonators in more detail.

Fig. 67 Digital version's resonator, back side, with 4 piezoelectric sensors

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[16] The analog version was built and tested but without giving the user the option to apply different guitar sizes. It leads to an improved design for the digital version.

[17] Audio samples can be found in www.thechameleonguitar.com, also listed in the Appendix.

4. Acoustic and Technical Background

4.1. Overview

The following Chapter is meant to give relevant information needed to understand the technical aspects of the work. Section 4.2 presents a technical acoustic background; only topics that are relevant to this research are covered. In order to fully appreciate the technology developed here, an understanding of these topics is needed. Section 4.3 presents the acoustic guitar technology. In Section 4.4 a background of electric signals, sensing and sound processing is given. Similar to Section 4.2, this Section is important for the reader interested in a technical understanding of the project. Section 4.5 presents the electric guitar technology.

4.2. Acoustics Fundamentals

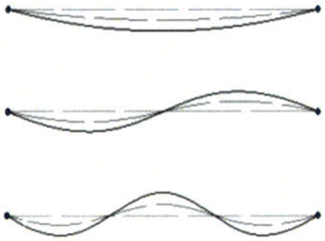

Fig. 68 Harmonic String (three modes of vibrations)

Prior to discussing how acoustic instruments work, we need to start with fundamental vibration mechanisms. For further reading, Rossing and Fletcher [76] give a good general overview, Lamb [77] or Cremer, Heckl and Unger [78] are much more technical. I will start with an acoustic explanation of a harmonic string, a string tight between two fixed boundaries[18]. By assuming small string diameter and homogeneous material with zero stiffness, the one dimension wave equation describes the string's vibrations,

$$\frac{\partial^2 y(x,t)}{\partial x^2} + \frac{1}{c^2}\frac{\partial^2 y(x,t)}{\partial t^2} = 0 \quad , \qquad \textbf{Eq. 4.1}$$

while y is the string's displacement, x is the position and t is time. To calculate the speed of sound c we can use this equation:

$$c = \lambda f = \frac{T}{\rho},$$

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[18] Some of the references mentioned prefer to start from basic oscillators (mass and a spring, for example).

where f is vibration's frequency, λ is wavelength, T is string's tension and ρ is mass density per unit area. The string's wave equation (steady state with fixed boundary conditions) can be solved using a separation of variables $y(x,t)=Y(x)T(t)$:

$$\begin{aligned} Y(x) &= A\sin(k_n x) + B\cos(k_n x) \\ T(t) &= C\sin(k_n ct) + D\cos(k_n ct) \end{aligned} \quad \textbf{Eq. 4.2}$$

Fig. 69 String's third vibration mode: two nodes (blue dots)

A, B, C, D are coefficients, depend on the initial and boundary conditions and k_n is the wave number. The discrete set of k_n corresponds to the discrete set of Y_n (position) or T_n (time) which are the modes of vibration (see Fig. 68). The nodes are the places where the vibration energy of a specific mode is zero (see Fig. 69). The general form of the string's wave equation is the homogeneous second order linear ordinary differential equation:

$$m\ddot{\zeta} + R\dot{\zeta} + Kx = 0 \quad \textbf{Eq. 4.3}$$

The mass of the vibrating element is m, R is the damping coefficient and $K=2\pi f/c$ is constant. A forced vibration (like when plucking a string) can be represented by the inhomogeneous form,

$$m\ddot{\zeta} + R\dot{\zeta} + Kx = f(t) \quad \textbf{Eq. 4.4}$$

of Eq. 4.3, where the damping coefficient R controls the decay rate. When $R=0$ we have standing waves, harmonic vibrations in the string with no decay. When y is a function of position x and time t, the solution for the differential equation will be a complex exponent. If $R\neq 0$ we introduce damping to the equation, and the solution will be a complex exponent multiplied by a decaying exponent (the decay rate depends on the frequency f). An inner damping can be caused by air friction or energy losses in the supports.

In an ideal string, inner damping is not expected. While a membrane is a two-dimensional version of a string, bars and plates are different

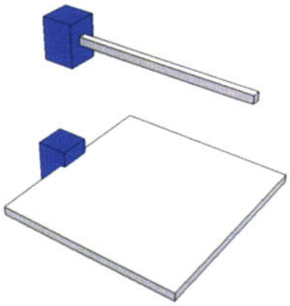

Fig. 70 Bar (Top) and plate (bottom) with one rigid clip

cases (see Fig. 70); here we are introduced to material stiffness. In strings and membranes, we only met transverse waves. In bars and plates we meet longitudinal waves as well. The longitudinal waves do not contribute to the projected sound, but they are important to the way the vibrating energy propagates in the material (see Fig. 72). While bars are one-dimensional (like strings), plates are two dimensional (like membranes).

There are three main options for boundary conditions in a bar (see Fig. 71): fixed (rigid), simply-supported and free (see Fig. 69). These are the mathematical equivalents to those definitions:

1) Fixed boundary: $y_0 \neq 0$; $\partial y_0/\partial t \neq 0$

2) Simply-Supported boundary: $y_0 = 0$; $\partial y_0/\partial t \neq 0$

3) Free boundary: $y_0 = 0$; $\partial y_0/\partial t = 0$

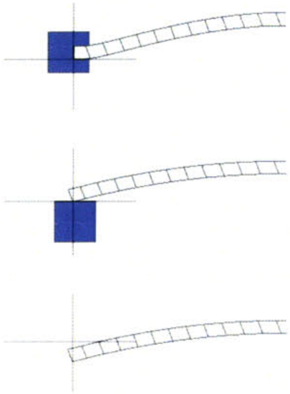

Fig. 71 Top to bottom: fixed, simply-supportive and free boundaries

While free boundaries allow representation of bigger wave lengths (i.e., a lower frequency for the first mode of vibration), fixed boundaries push the low vibration modes towards higher frequencies. The simply-supportive case is somewhere in between.

Leissa [79] gives a detailed analysis of the vibration of plates, with different shapes, materials properties, coordination systems and boundary conditions. The differential equation to represent transverse vibration in a plate is:

$$(\nabla^4 - k^4)y = 0$$
$$k^4 = \frac{\rho(2\pi f)^2}{D} \,, \qquad \textbf{Eq. 4.5}$$

Where $\nabla^4 = \nabla^2\nabla^2$ (∇^2 is Laplacian operator), and D is the flexural rigidity:

$$D = \frac{Eh^3}{12(1-\nu^2)} .$$

E is Young's modulus (measure of the stiffness); h is plate thickness and ν is the Poisson ratio (ratio of the contraction or transverse strain). In polar coordinates, the Laplacian operator is:

$$\nabla^2 = \frac{\partial^2}{\partial r^2} + \frac{\partial}{r\partial r} + \frac{\partial^2}{r^2\partial\theta^2} .$$

The solution for Eq. 4.5 recalls the solution for a string:

$$y(r,\theta) = \sum_{n=0}^{\infty}[A_n J_n(kr) + B_n Y_n(kr) + C_n I_n(kr) + D_n K_n(kr)]\cos(n\theta) +$$
$$\sum_{n=0}^{\infty}[A_n^* J_n(kr) + B_n^* Y_n(kr) + C_n^* I_n(kr) + D_n^* K_n(kr)]\sin(n\theta)\,, \quad \textbf{Eq. 4.6}$$

where J_n, Y_n, I_n and K_n are modified Bessel functions from the first and second kind (respectively), and A_n, B_n, C_n and D_n determine the mode shape and are solved by the boundary conditions. It is easy to see that the solution depends on the material's properties (stiffness, density and strain) and structure (boundary conditions and thickness). In reality, acoustic plates (like the guitar tops) are made from wood, which is an anisotropic material; its properties may not be the same in all the directions and different types of wave propagation may be developed on the plate (see Fig. 72. Just the transverse waves drive the acoustic airwaves).

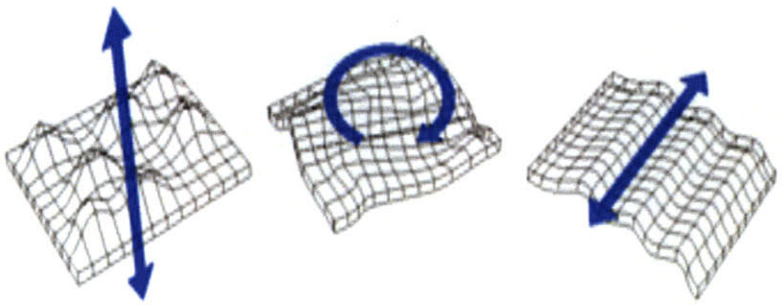

Fig. 72 Different waves in a plate: from transverse waves (left) to longitudinal waves (right)

The boundary conditions can be a combination of free, fixed and simply-supportive boundaries, while the shape and thickness can be anything feasible (see Fig. 73). This makes it very difficult, and some times even unpractical, to solve analytically the wave equation for a vibration of a real plate. Numerical solutions, like Finite Element Methods [80], offer a much more practical approach[19].

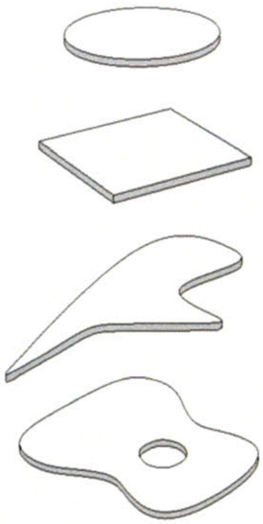

Fig. 73 Different plate shapes

Acoustical Propagation

Sound waves are created by fluctuations in sound pressure [81]. Any body that drives air can create those fluctuations. A string may be too thin to attenuate a sufficient amount of air when vibrating, but a membrane or a plate, which has a much bigger surface, can create significant sound. When the distance between a vibrating point

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[19] See section 5.2 and 5.3.

source and a target is much farther than the wavelength $r >> \lambda$ (far field), we assume that the acoustic waves progress in plane waves (see Fig. 74):

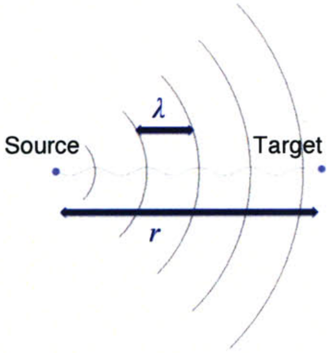

Fig. 74 Point source: wave length vs. target distance

$$p(r,t) = A_0 e^{j(kr-2\pi ft)} , \qquad \textbf{Eq. 4.7}$$

where A_0 is the amplitude and k is the wave constant. When the source is closer to the target then the length of the wave, the practical representation of the point source is:

$$p(r,t) = \frac{A_0}{R} e^{j(kr-2\pi ft)} , \qquad \textbf{Eq. 4.8}$$

However, when the source isn't a point source, a different analysis is needed. While the sound that attenuates from a point source is a monopole, the sound that attenuates from a string can be modeled as a dipole, and the sounds that attenuate from a plate can be modeled as a multi-pole.

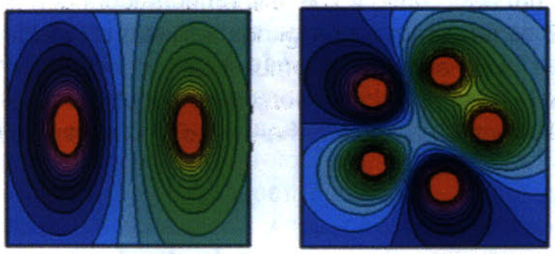

Fig. 75 Dipole field (left) and multi-pole field. Red dots are the sources, blue is positive propagation and green is negative, from [82]

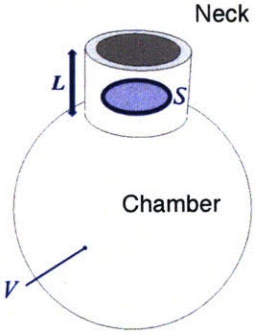

Fig. 76 Helmholtz resonator

In reality, most of the oscillators and vibrating sources does not standalone; most of the time they are a part of a bigger system. When a plate is connected to a chamber (like the guitar's sound box), we get coupled resonators: two systems with resonance modes that are connected to create a new system, with its own resonance behavior. If a soundboard is considered a plate, then the model of a chamber is similar to that of a spring with a mass. While the spring's constant k is related to the volume of the chamber, the mass is related to the air inside the resonator's neck (the hole). This is called the Helmholtz resonator [76, 77], and its first fundamental frequency is:

$$f_0 = \frac{c}{2\pi}\sqrt{\frac{S}{VL}}\ , \qquad \textbf{Eq. 4.9}$$

where S is the cross section of the hole, L (in guitar chamber it is the top plate thickness, see Fig. 82) and V is the volume of the chamber.

Acoustic Waves and Musical Sound

In real life, the sound that we hear is a superposition of air vibrations in the human sensitivity range (20Hz – 20KHz). When plucking a string in x_0, we drive all the frequencies that correspond to non-zero modes of vibration in x_0. This is similar to solving the string's inhomogeneous wave equation. Assuming no energy is lost in the boundaries, all the vibration modes are harmonics of the fundamental frequency (depending on the actual length of the string L). The fundamental frequency is the pitch (the musical note) of the sound. The selection of x_0, influences which of the harmonics will be active. A vibrating plate L can vary in range, so there is more than one option for a fundamental frequency, and the spectral image is more complicated. However, the sound we hear is not exactly what was emitted from the source. This sound depends on the relative position of the source, the environment and us: distance, angle and sound reflection from the environmental objects affect the sound we hear. In a musical context, we call sound's identity a *timbre*, which relates to the spectral properties of the sound and its envelope in time (regardless of its pitch; see Fig. 77-78). To analyze both properties, it is common to use a spectrogram[20]. Timbre is being used to describe sound qualities, and relies on the properties of the oscillator and the properties of the propagation medium. When applying vibration in a certain frequency, we influence the musical note, by choosing how to apply the vibration (properties of the vibrating source, the attack and the environment) we influence the timbre. Two pieces of wood will always have a different timbre while vibrating at the same fundamental frequency, and the reason is that they will never share the same material properties (more on wood properties in [83]).

The moment that a vibrating element receives an external energy impulse is called an attack. With a string, for example, the moment of attack can be when the user plucks the string. The attack is the transient from one string behavior to another. The signal can then be divided into three parts (see Fig. 79); notice the third part is almost a standing wave (multiple a slow decaying function); this section is where we hear the pitch, which is easily recognized by the ear. In the transient itself, the signal becomes semi chaotic. At this singularity point, energy is contained at all frequencies. The decaying functions control which frequency decays faster consist of important

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[20] A three axes plot, can be visualized as an image or 3D surface. The x dimension is the spectrum; the y is time and z represent energy. See page 77 for an example.

psychoacoustic information. This period of the signal is very important to the timbre (more on psychoacoustics in [84]).

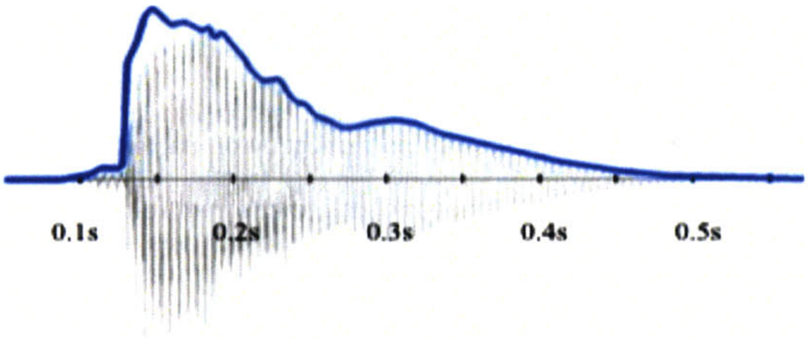

Fig. 77 Example of sound signal's characteristics: envelope (the blue line) above signal (gray line)

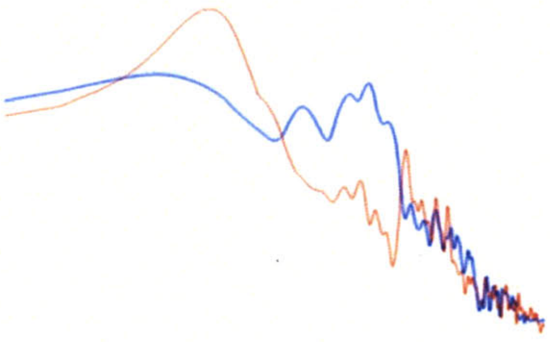

Fig. 78 Example of sound signal's characteristics: spectrums (same signal as in Fig. 77) of two logarithmic spectrums of 1000 samples. The blue line is from 0.15sec and the red line is from 0.35sec

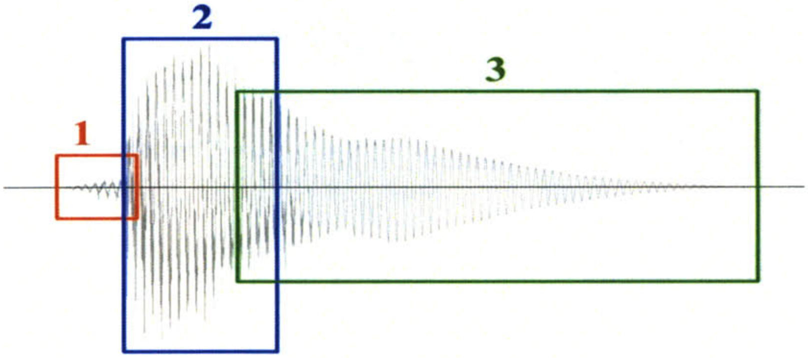

Fig. 79 Three sections of an attacked string (same signal as in Fig. 77): 1. The pick touches the string; 2. The transient contains energy at all frequencies. This energy decays quickly to the standing waves; 3. Almost a standing wave, decaying slowly

4.3. Acoustic Guitar Technology

Ra Intra in his thesis work explains and analyzes the physics of the acoustic guitar [74]. The main parts of the modern flat-top acoustic guitar are the neck and the body, which contains an air cavity (a chamber or sound box). 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 that is the top part of the neck. The neck itself is usually made of a harder (but flexible) wood, such as mahogany or maple that resists the string tension (which is around 74kg for metal strings in rest for standard tuning). The fret board is usually made from hard wood, like maple, ebony or rosewood, which holds the metal frets in place and does not erode easily. The guitar strings are tight between the bridge (from heavy wood, like rosewood or ebony, glued on the sound board), and the tuners on the headstock (from metal, wood or plastic). The string's actual vibration length L is the distance between the saddle and the nut (or a fret, when a finger is pushing the string to the fret board). When the strings vibrate (nylon or metal strings), they transfer vibrations, via the bridge, to the soundboard, which then starts to vibrate. The soundboard in turn drives the air, which is the sound we hear. Although all the guitar parts vibrate, and there isn't a real fixed part in the guitar, the sound 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 affecting the sound. The back and sides of the chamber are usually made from hard woods (rosewood, maple or mahogany), in order to prevent the energy from being damped there. Supportive bars (braces) made from spruce or maple, add more stiffness to the chamber's plates and influence its vibration modes.

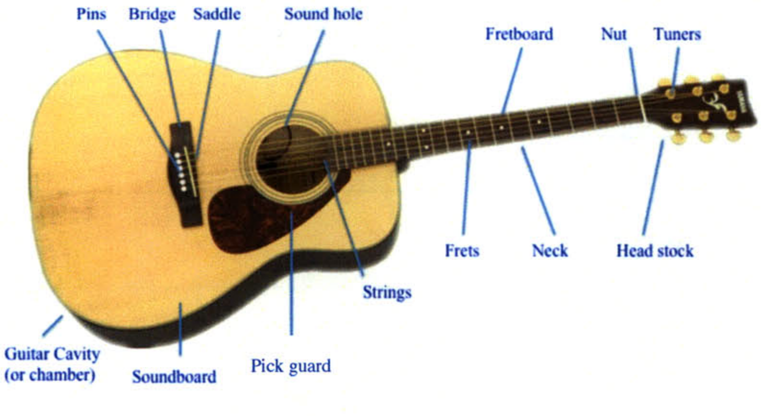

Fig. 80 Structure and parts flat-top acoustic guitar. Guitar image from [85]

In the arch-top guitar family, unlike the flat-top, the soundboard (top plate) is arched, usually carved from a bigger wooden block, similar to the violin. The strings are tight to the tailpiece, and instead of pulling it, they are pushing the bridge (located in the top arch of the curved soundboard) away.

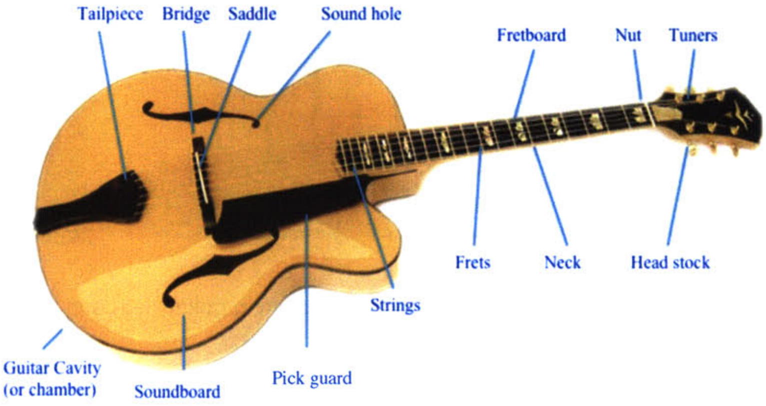

Fig. 81 Structure and parts of the arch-top acoustic guitar. Guitar image from [86]

While the actual length of the vibrating strings relates to pitch, the body's shape and structure relate to the guitar's timbre. When a string vibrates according to Eq. 4.4, it attenuates the bridge that is not a real fixed edge. The bridge then drives the soundboard. However, not all the harmonics are actually transferred to the soundboard; this depends on the vibration modes of the guitar's body, which is a coupled vibrating element constructed from the soundboard (similar to a plate behavior, Eq. 4.6) and the Helmholtz resonator (Eq. 4.9).

The string type is very important to the guitar's sound; nylon strings give a more "round" sound (energy concentrates around lower harmonics) than the "bright" sound of metal strings (energy more biased to higher harmonics). 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 and span a relatively large area (big soundboard), and a structural reinforcement is required. This is usually in the form of wooden braces. The bracing system, especially that of the soundboard, 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 vibration modes (frequencies and patterns; for more information refer to [74, 76]). The art of bracing the top plate of the guitar is highly important to the sound of the guitar, such that different guitar styles usually have different bracing design. Below you can see two bracing examples by Shel Sax (Fig. 83-84, [87]). The expertise of the guitar-maker depends on his ability to control the sound by delicate bracing craftsmanship [88].

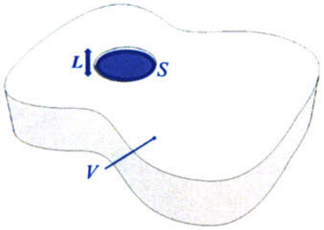

Fig. 82 Guitar chamber Helmholtz resonance properties

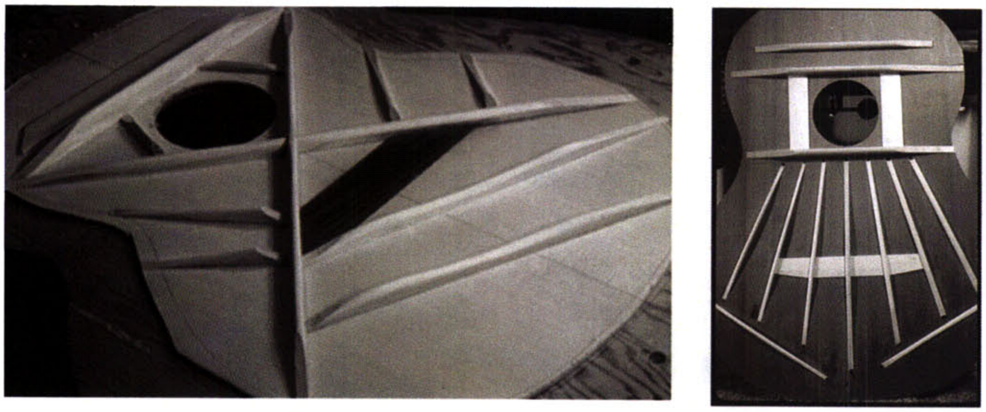

Fig. 83 – Fig. 84 Guitar top plate braces. Steal string guitar (left) and nylon string guitar (right), from [87]

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. The soundboard material qualities and braces are usually responsible for the midrange and higher vibration modes. Other parts are also important: for example, the neck has low frequency interactions with some other major components of the instrument, and its material and type of connection to the body are important.

One of the important jobs of the luthier is to select and prepare the wood, especially for the soundboard. In a guitar, like in the violin family, the top plate is usually made from two quartersawn[21] spruce (or cedar) wood pieces, splinted from the same block in the middle and then glued (see Fig. 85).

Everything said above about guitar design is highly dependent upon a luthier's design and craftsmanship. From the player's perspective, the guitar is a highly expressive instrument, and the player can control the sound by using different excitation methods when using a pick or fingers to pluck the strings. 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 [76, 89]. There are other means of obtaining sound from the instrument by exciting the strings or the body, giving rise to a large range in timbre of the instrument and the number of playing techniques. Together with the special acoustic identities of the wood, the player maintains a unique relationship with the instrument that contributes to the musical style and sound being created.

Fig. 85 Wood's cut, quartersawn cut in the left

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[21] Quartersawn woods are cut in tree's radial direction, in order the have parallel grain pattern with high wood stability.

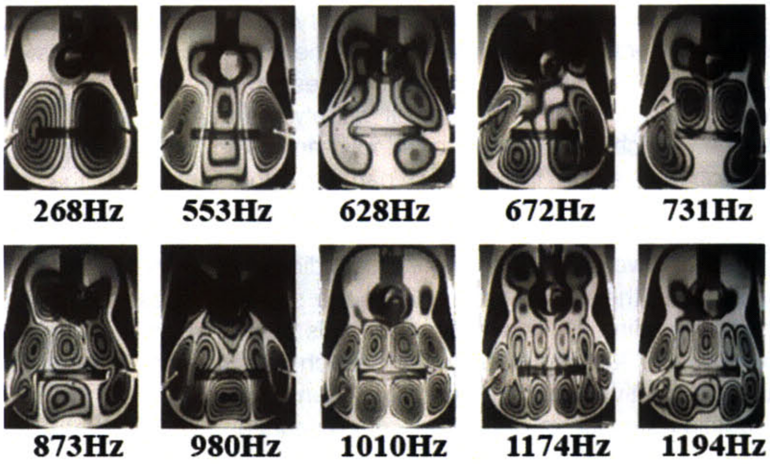

Fig. 86 Acoustic guitar (Martin *D28*) top plate vibration modes (3rd mode, and higher), from [76]

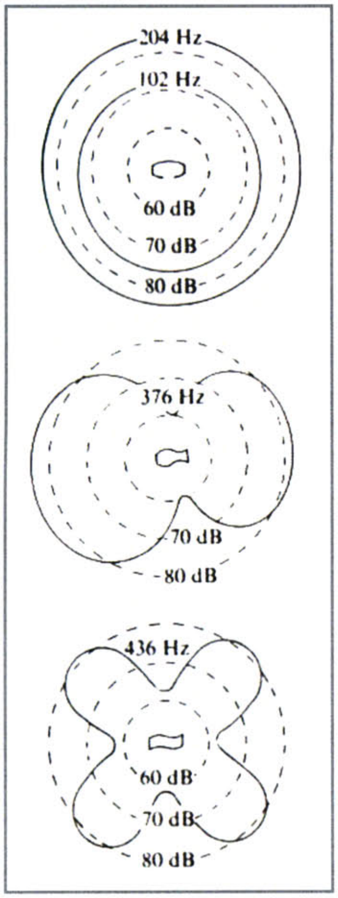

Fig. 87 Sound radiation patterns for four frequencies (Martin D28). From top down: monopole, dipole, quadrapole, from [76]

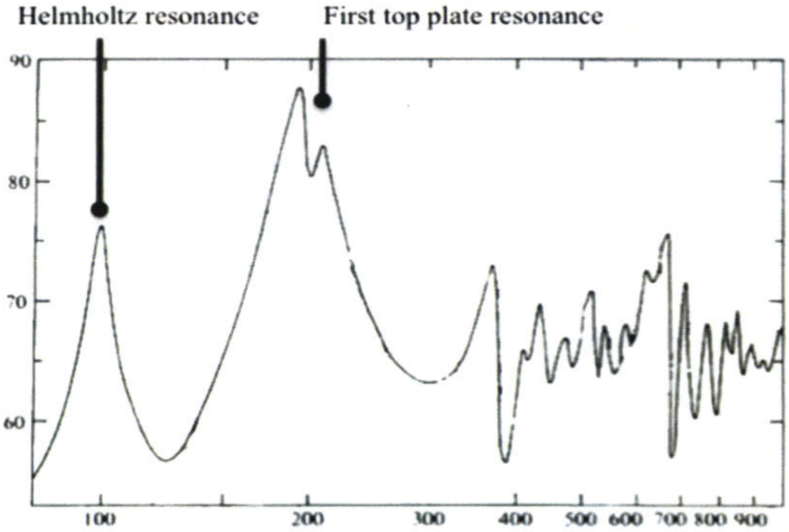

Fig. 88 Sound spectrums 1m in front of martin *D28*, driven by a sinusoidal force of 0.15N applied to the bridge, from [76]

4.4. Introduction to Sensing and Signals

The broad definition of a sensor, according to Jacob Fraden, is a device that receives and responds to a signal or stimulus [90]. This definition includes natural sensors, like those found in living organisms, and man-made sensors. Fraden defines man-made sensors as a device that receives a stimulus and responds with an electrical signal. Any sensor is an energy converter, while the process of sensing is a particular case of information transfer. In musical instruments, the sensed signal could be an audio signal or a control signal. A sensor does not function by itself, and is always a part of a larger system that may include other sensors, signal conditioners, signal processors, memory devices, recording devices and actuators. As an audio signal, the signal can be transferred directly to amplification or be processed by analog or digital processing. As a control signal it will always need to feed a control device, which still needs to supply an audio output. Sometimes control and audio information can be represented by the same signal.

There are two main approaches to audio sensing; the first is based on sensing the acoustic field, while the second is based on sensing the source directly. The first approach is closer to the way we hear – sensing the full acoustic system, which integrates the constructive and destructive waves together with environmental influences (like acoustic reflection or deflection from objects and waves absorbed by the air). This approach is sensitive to environmental noise; when sensing the source itself it is easier to ignore these noises. When we sense the source directly we sample banding or displacement in a specific location of the source's surface; the signal captured in that way may sound different than what we hear.

Sensors may be of two kinds: passive and active. A passive sensor generates an electric signal in response to an external stimulus, and the active sensor requires an external power source for its operation. Another classification, absolute and relative, relates to the scaling of the signal being sensed. In audio sensing, the sensors are usually passive (beside some exceptions) and relative. Popular devices to sense audio are piezoelectric pickups, magnetic pickups and microphones, usually based on magnetic sensors. In that context, a pickup is a sensor that picks up the sound signal.

Magnetic Pickups

According to Faraday's Law, magnetism can be used to produce electricity by moving the magnetic field. This is a fundamental law in electricity generation, and has been used broadly in sensors. The most famous magnetic sensors are electric guitar pickups [93]. The guitar pickup consists of a magnet with many windings (loops) of very fine copper wire around it. When a string, made from iron or steel, moves nearby, it causes a shift in the flux lines of the magnetic field surrounding the magnet, and this induces a voltage in the wire. The voltage pattern that is created is an analog of the string's vibration pattern.

Fig. 89 Guitar magnetic pickups by EMG, from [91]

Piezoelectric Pickups

Piezoelectric pickups are based on the piezoelectric effect: generation of an electric charge by a crystalline material upon subjecting it to stress. This effect exists in natural crystals, such as quartz, in man-made ceramics and in some polymers. To pick up an electric charge, conductive electrodes need to be applied to the crystal at the opposite sides of the cut. The vector of polarization can represent the magnitude of the piezoelectric effect in a simplified form:

Fig. 90 Ceramic piezoelectric sensors, from [92]

$$
\begin{aligned}
P &= P_{xx} + P_{yy} + P_{zz} \\
P_{xx} &= d_{11}\sigma_{xx} + d_{12}\sigma_{yy} + d_{13}\sigma_{zz} \\
P_{yy} &= d_{21}\sigma_{xx} + d_{22}\sigma_{yy} + d_{23}\sigma_{zz} \\
P_{zz} &= d_{31}\sigma_{xx} + d_{32}\sigma_{yy} + d_{33}\sigma_{zz},
\end{aligned}
\qquad \textbf{Eq. 4.10}
$$

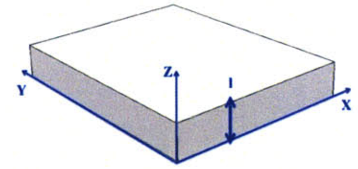

Fig. 91 Piezo material orientation

where x, y, z are the conventional orthogonal system related to the crystal axes, d_{mn} are the piezoelectric coefficients along the orthogonal axes of the crystal and σ is the axial stress. The charge generated by the piezoelectric crystal is proportional to the applied force, for example, in the x direction:

$$Q_x = d_{11}F_x. \qquad \textbf{Eq. 4.11}$$

The voltage V that develops across between the electrodes is:

$$V = \frac{Q_x}{C}, \qquad \textbf{Eq. 4.12}$$

while the capacitance can be represented through the electrode surface area and the crystal thickness l:

$$C = k\varepsilon_0 \frac{a}{l}, \qquad \textbf{Eq. 4.13}$$

where k is the dielectric constant and ε_0 is the permittivity constant.

Fig. 92 Sensor array and the sensed field, sinc plot from [94]

Sensors Array

Using more than one sensor in an array is a good way to determinate the behavior of the sensed field. In acoustic sonar, several sensors, arranged in a discrete array, can give us information about the distance and location of a source and its properties [81]. The detected frequency range depends on the distance between the array's sensors. The field detected at the array is from the form of a *sinc*[22] function; in order to separate the main lobe from the side lobes we need $\lambda > 2\Delta z$, where Δz is the distance between two sensors.

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[22] from the type $sin(q)/q$.

Sound Chain

When the signal captured by a sensor is an audio signal, the process is commonly referred to as the sound (or signal) chain. The signal can be transmitted to different sound processing units, like buffers and filters, audio effects, mixers and finally amplification. To understand the basic concepts of processing and amplifying audio signals, it is important to have some background in analog electronics [95] and signal processing [96].

The field of digital signal processing (DSP) evolved in parallel with the development of digital processing. Today, we can find a huge collection of digital programmable units that allow more control and flexibility in audio signal processing. Although the basic principles of digital signal processing are similar to those of analog signal processing, there are several differences, from new mathematical problems switching to the discrete domain (like Nyquist–Shannon sampling theorem or discrete filtering) to other problems related to technical implementation (such as latency and memory management). The field of digital signal processing opens new opportunities for audio processing, such as flexible digital effects and physical modeling of an acoustic instrument.

Linear Digital Filters

Linear filtering is one of the most important topics in DSP; Julius Smith in *Introduction to Digital Filters* [97] gives a broad background on the field. Let us assume we have two discrete signals, y and x, where y is the filter output and x is the input. The relationship between the input and the output can be defined by moving algebraic windows on both of the signals

$$\sum_{j=0}^{Q} a_n y[n-j] = \sum_{i=0}^{P} b_n x[n-i] \quad . \qquad \textbf{Eq. 4.14}$$

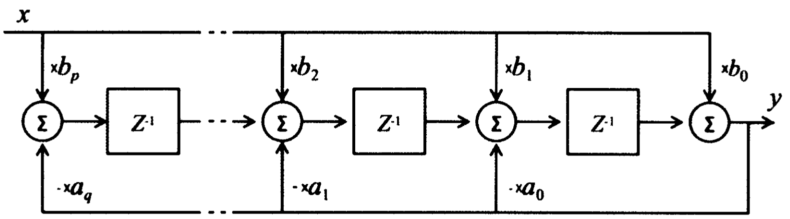

Fig. 93 Digital linear filter

Where x is the filter's input and y is the filter's output, a_n is the filter's feedback coefficient and b_n is the filter's feedforward coefficient. When Q=0, we just have a feedforward part, and we got a finite impulse response filter (FIR). This can be easily implemented by convolving the coefficients with the input signal. When $Q \neq 0$, we have an infinite impulse response (IIR); IIR filters are faster than FIR filters and can be much shorter than FIR filters. This can lead to less calculation power and shorter latency, properties that makes them popular in audio processing. When applying a Fourier transform to Eq. 4.14 and dividing sides, we get:

$$H(z) = \frac{\sum_{i=0}^{P} b_i z^{-i}}{1 + \sum_{j=0}^{Q} a_j z^{-j}} \quad . \qquad \textbf{Eq. 4.15}$$

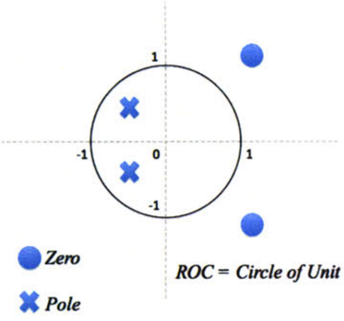

Fig. 94 IIR ROC

The numerator has P roots (the filter's zeros) and the denominator has Q roots (the filter's poles). The zeros and poles are commonly complex. When a linear system has poles with absolute value greater than one, the system oscillates. When the poles are smaller than the region of convergence (ROC) the system is stable. In algebraic terminology, if we implement IIR filter as an operator, the poles correspond to matrix eigenmodes [80]. When using IIR to model a vibrating element, the eigenmodes correspond to the vibration modes.

Kauraniemi, Laakso and Ovaska in [98] analyze different implementation methods for IIR filters, and conclude that regarding quantization errors, *Second-Order Section, Direct-Form II* is the most efficient implementation IIR form. This may be highly important to a fixed-point implementation.

Filter Bank and Parametric Equalizer

A filter bank is a method for easy control of the spectral properties of a signal, without the need to transform it to the spectral domain. The basic idea is to filter the signal with a bank of band-limited filers (IIR or FIR). By precise design of the filter's properties we can get a transparent system; the summation of the filter's impulse response needs to be constant in the entire spectrum and the time envelope delay needs to be equal. When the filter bank itself does not damage the signals, we can apply different manipulations to the different bands in order to get control of the output timbre.

The filter bank, or its more complex version, the parametric equalizer (which also allows the change of the filter's spectral properties) are powerful tools for audio processing, and when being implemented by IIR they can achieve minimal latency and calculation complexity. More than that – by choosing psychoacoustic scales for the bands, like Mel scale [99], we can design the filter bank to fit the way human hear.

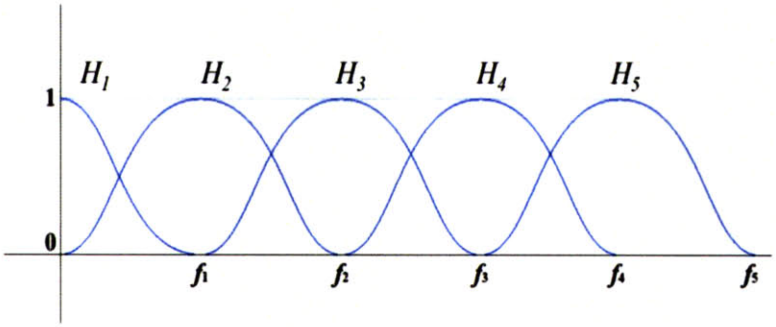

Fig. 95 Filter Bank Spectrum, $\Sigma H_i(f)=1$

Amplification

The common way to amplify an acoustic signal is by analog elements like transistors (*solid-state*) or vacuum tubes. Although vacuum tubes were in use mostly before the transistor's time, they are still popular in audio signal amplification today. In solid-state amplifiers, tube amplifiers or mixed amplifiers, the basic premise is constant: first the audio signal is amplified with a pre-amp to set it to a certain gain level and to transfer the signal from a low impedance signal to higher impedance signal. A second element, the power-amp, sets the signal voltage and impedance to fit the given speaker. The quality of the amplifier depends on several things: the type of the electronic elements in use (especially the tubes or op-amps and power supply), the circuit configuration, the speakers and the speaker's cabinet. One of the most important electronic effects in the late 20th century music, the overdrive (or distortion) was originally created in the amplifier, when it was set to work in extreme condition. The signal saturated the different amplifier elements, mostly the pre-amp, resulting in the desired tone.

4.5. Electric Guitar Technology

The technology of the electric guitars can be easily discussed after presenting that of the acoustic guitars. The strings and the neck of these electric guitars function in a similar way to those of acoustic guitars. The sensors and the bridge are located on a solid plate, with relatively high acoustic impedance. The solid-body guitar does not vibrate at the same amplitude as the acoustic guitar soundboard, and it does not dampen the strings as the acoustic chamber does. In the solid-body guitar, the strings vibrate with higher sustain, while very low acoustic sound is emitted from the body due to the high level of amplitude attenuation in the solid-body. Magnetic pickups, located between the bridge and the fret board, translate the strings' vibrations to a voltage signal. This signal is amplified in an external amplifier.

The Fender string scale is longer than the Gibson Les Paul, which leads to higher string tension. It could also lead to higher sustain, but the thickness of the Les Paul body (and the properties of its materials) leads to a low damping, which keeps the sustain of the Les Paul longer.

The solid body, together with the electromagnetic sensing of a metal string, is the most common electric guitar technology. However, it is not the only technology being use: the hollow body guitars merges electromagnetic pickups with an acoustic chamber, and some electric guitars (such as Parker Fly) are using hexphonic piezoelectric pickups located on the bridge, to sense the string vibration, what allows them to use non-metal strings (such as nylon).

Fig. 96 Electric guitar structure and parts. Jimmy Page's Les Paul guitar, guitar image from [100]

5. Technologies and Implementation

5.1. Overview

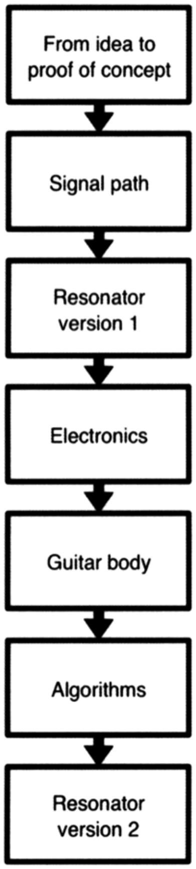

Fig. 97 Chameleon Guitar design stages

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 in this Chapter. In order to fully understand the principles and constraints of the design, the reader should review the background from the previous Chapters.

In this Chapter, I will present all the technical details regarding the Chameleon Guitar design process (Fig. 97). The acoustic principals in Section 5.2 are leading to the search for resonator design guidelines in Section 5.3. In Section 5.4, I will discuss the design process of the guitar itself, based on the shape constraints of the resonators, including the mechanical solution for holding and replacing resonators (the *resonator tray*). Section 5.5 presents the analog electronic design; this is the actual signal path from the sensors to the digital signal-processing unit (*SP unit*). The fabrication process, which ended with a functional guitar, is presented in Section 5.6.

The resonators were made in several cycles; the first resonator prototypes from Section 5.3 were modified to fit the new body. Different fabrication methods were evaluated, as well as different acoustic behaviors. Based on that experience, the digital signal processing algorithms were defined, programmed and checked (Section 5.7). The last stage was to make a new, final resonator collection, correcting problems of previous stages and covering wide acoustic possibilities. This final resonator collection is described in Section 5.8.

The Chameleon Guitar's signal path[23] was the first element of the project to be defined (see Fig. 98). 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 in low frequencies; for instance, the mode influenced by the Helmholtz resonance in an acoustic guitar). Four piezoelectric sensors, located in different places on the resonator, capture different vibration modes. The four sensors' signals are buffered and amplified by the *resonator PCB*, 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, or implementing other digital

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[23] The path of the signal from creation to guitar's output.

audio effects. The output signal is transferred to the output jack[24], and then sent to an acoustic guitar amplifier.

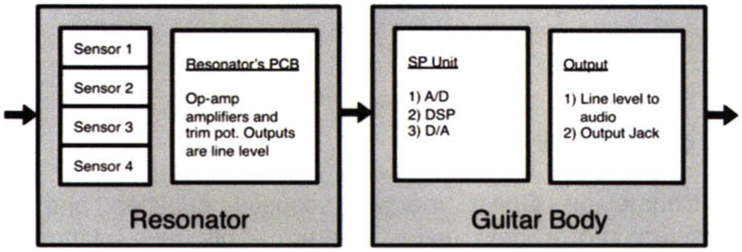

Fig. 98 The Chameleon Guitar's signal path, from sensors to guitar output (the guitar amplifier feed)

After a preliminary prototype was built to validate the concept, and the signal path was defined, the digital Chameleon Guitar was designed in five design stages. In the preliminary analog prototype I started with a given electric guitar. First, I made a cut in the body for the resonator. Then, the shape of the resonator was defined according to the body constraints (and not according to acoustic constraints). This guitar, though it suffered from string action[25] and tension[26] problems, and a lack of low frequencies, proved the Chameleon Guitar concept.

5.2. Acoustics Principles

Important acoustic fundamentals were presented in Section 4.2 and the acoustic guitar's technology was explained in Section 4.3. The main design principle regarding the Chameleon Guitar's acoustic behavior was to shape the guitar and its resonator structure so that the resonator's transverse vibration modes can drive low acoustic frequencies in a harmonically rich spectrum. This design principle relies on the assumption that it is better for a high signal to noise ratio (SNR), to have a harmonically rich spectrum that can be filtered later, instead of creating virtual vibrations in damped frequencies. The goal is to modify the resonator's sound so the output will sound likes a full size guitar without damaging its authentic behavior; the output sound will still represent the resonator's main acoustic properties that relate to the material from which it is made, while the properties that relate to the vibrating system's shape (the chamber's dimensions) will be modified.

An acoustic guitar's behavior depends on its shape and material properties. However, in lower frequencies, when the wavelength is

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[24] With a latency of less then one millisecond.

[25] Action is the height of the strings from the fretboard, which is generally preferred to be low.

[26] In guitar context, string tension is the resistance of the string to picking and bending. When the action is high, more force is needed to push the strings to the fretboard, which lead to a higher tension.

much bigger than the rate of changes in materials (changes in stiffness, density, supportive braces) those properties can be calculated as an average. In other words, the lower vibration modes depend more on shape than on wood patterns, especially the vibrations influenced by the Helmholtz resonance, (usually around 100Hz) and the one related to the soundboard's lowest vibration mode (usually around 200Hz, 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 processing should modify the lower vibration modes and keep the higher ones as natural as possible, in order to achieve the design principle of preserving the wood's authenticity but modeling the output signal to sound like an acoustic guitar (with a controllable chamber size). More than that, as was described in Section 2.5, it makes it difficult to have reliable, digitally modeled, string attacks (transients). As such, the mid-range and high frequencies transient behaviors are preserved and the transient's sound signature is kept as natural as possible.

Each wood resonator has a different acoustic behavior. The sensor locations (Section 5.3) and DSP algorithm (Section 5.7) were defined according to a reference resonator (resonator no. 1 in Section 5.8). This resonator was used to find the optimal sensor locations and to tune the algorithm; all other resonators use these properties.

The Reference Guitar

A Yamaha FG330 acoustic guitar was used as a reference. The actual timbre of the acoustic guitar depends on the acoustic properties of the surrounding environment. In order to capture the superposition of all the acoustic modes of the guitar[27] and to minimize environmental influence, it is better to record it with a microphone or two, located in front of the guitar's bridge [101] in an isolated acoustic environment. The reference acoustic guitar was recorded in the same conditions, using a single MXL USB.008 microphone in a recording studio room.

Impulse Response Tests

A linear system's behavior can be analyzed by its response to an impulse input. Although a guitar is not a linear system, at low amplitudes, its behavior is similar to one. Inta [74] used the method of impulse response to analyze and model a guitar's behavior. In this research, impulse response was imitated by hitting the center of the guitar's bridge with a metal stick coated by plastic. The recorded signal, in the conditions described above, will be treated as the system response.

Finite Element Method

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[27] Regarding to human hearing range, 20-20K Hz

Finite Element Method (FEM) analysis is a numerical way to solve partial differential equations. Eq. 4.6 is an analytic solution for the differential equations of a vibrating plate (Eq. 4.5), but it is unsolvable when the shape is difficult to define and the material has isotropic patterns (like in wood, where the stiffness and density depends on the direction).

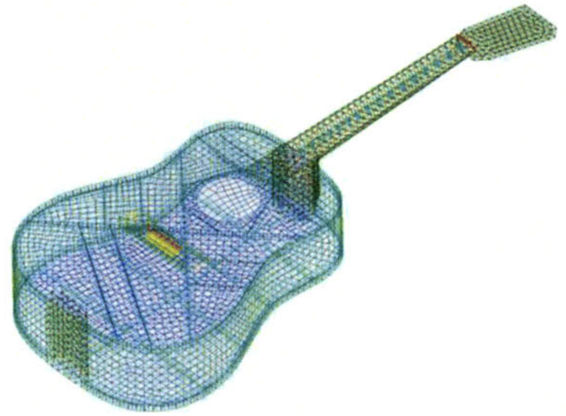

Fig. 99 An example of a mesh model of an acoustic guitar, for FEM, from [102]

The basic principle of FEM, as is being describing in [80], is to solve the differential equation in its weak form; integrating above a range of small differential elements (see Fig. 99) using linear algebraic methods. Comsol Multiphysics and Catia are simulation environments that merge FEM with CAD abilities; a digital 3D model of a physical object can be imported (or directly modeled). After defining all material properties and boundary conditions, a visual FEM simulation can be rendered for a variety of differential equations.

As was mentioned in the beginning of Section 3.2, several researchers suggested the use of FEM for musical instrument design and analysis. In the next Section I will explain how it has been used to design the shape of the Chameleon Guitar's resonator.

5.3. Resonator Design

The resonator's shape was designed in an iterative process using FEM, acoustics tests and mechanical adjustments. Starting with surface area analysis, the reference acoustic guitar's plate was modeled in Rhino 3D, assuming 2.5mm thickness, no bridge, braces or hole and with free boundaries. The vibrating modes (Eq. 4.5) were simulated in Comsol Multiphysics. The wood's properties were defined as [103]:

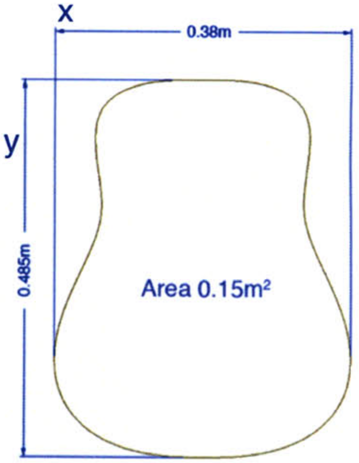

Fig. 100 Acoustic guitar reference, top plate, full surface dimensions

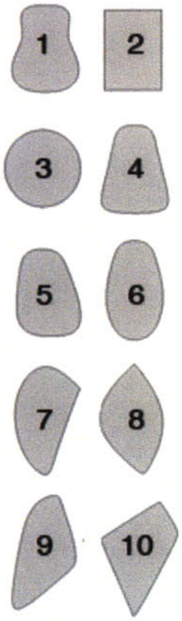

Fig. 101 The ten first simulated shapes

Table 1 Sitka spruce properties

Density	Vxy	Vyz	Vxz	Ex	Ey	Ez	Gxy	Gyz	Gxz
600	.03	.47	.43	.9e9	12e9	.5e9	.7e9	.7e9	.04e9

V_{mn} is Poisson's ratio, E_n is Young's modulus (elasticity) and G_{mn} is the modulus of rigidity. The shape and dimensions are presented in Fig. 100. The first three eigenmodes for different surface areas were simulated. Here are the results for a variety of area sizes:

Table 2 Three first eigenmodes of several plate sizes (in Hertz)

Eigenmodes	Full Size	72.5%	50%	30%	16%	6.25%
1	23.80	33.00	48.50	78.50	148.00	374.00
2	32.70	45.20	66.60	107.80	203.40	516.00
3	56.70	78.44	115.60	187.10	353.40	899.30

The goal was to find an area size that can hold vibrations that are as close as possible to the lower vibration mode of the acoustic guitar (around 100Hz, see Fig. 88 in page 53), but at the same time, to minimize the surface area. In free boundary conditions, a surface size of 25% of the original guitar top plate seemed to be enough.

The next step was to choose the resonator's shape, using similar criteria as in the previous simulation. Ten different shapes (Fig. 101), all with the same area size, were simulated. The goal was to find shapes that give the lowest vibration modes in a relative dense spectrum. Here are the results for these 10 shapes and their first 5 eigenmodes:

Table 3 five first eigenmodes of ten different shapes (in Hertz)

Eigenmodes	1	2	3	4	5	6	7	8	9	10
1	93.00	84.00	93.00	96.00	105.00	96.00	112.00	100.00	82.00	95.00
2	127.00	129.00	105.00	125.00	148.00	130.00	129.00	143.00	142.00	114.00
3	221.00	213.00	231.00	207.50	212.00	224.00	209.00	187.00	194.00	198.00
4	266.00	249.00	238.00	300.00	292.00	274.00	284.00	289.00	257.00	250.00
5	291.00	298.00	325.00	303.00	294.50	300.00	306.00	297.50	301.00	281.00

Shapes 5, 6, 7 and 8 were rejected (first vibrating mode is too high). The next step involved a practical consideration: adding four[28] rigid points to the boundaries in search for a way to hold the resonator in place. Those points were selected according to the previous simulation (Fig. 102). A candidate for a rigid point was location on the boundary that has a minimal displacement in the lower vibrating mode. This design process proceeded in several iterations, started

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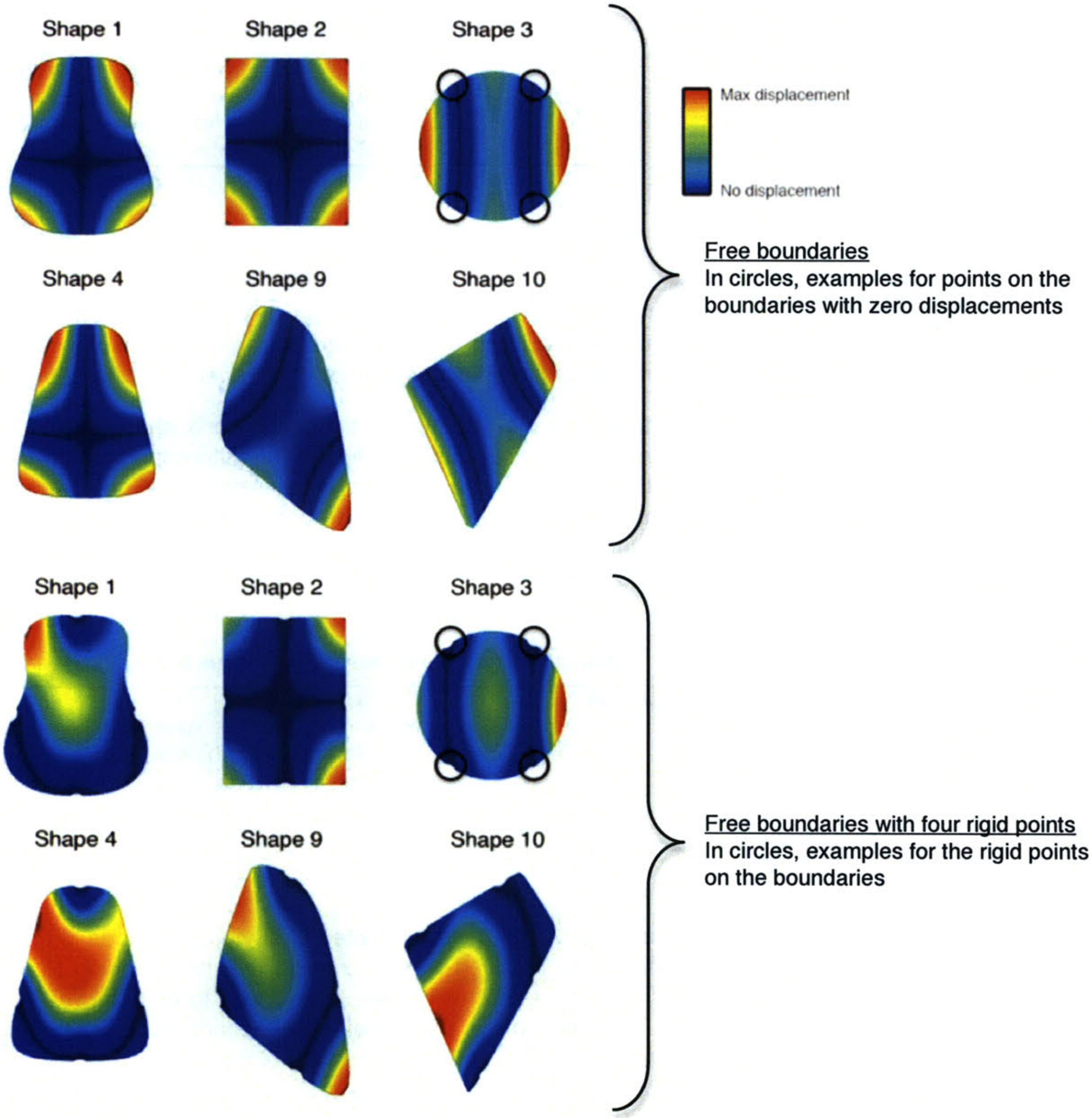
[28] In looking for the minimal rigid points to add to the shape, four was the minimal number that would keep the resonator stable for flipping. After modifying those points physically, I was able to produce resonates with just three supported points.

with four rigid points on the boundaries and converged on a pseudo optimal shape, with just three simply-supportive points (see Fig. 102 and Fig. 107).

A prototype guitar structure was built to test the resonator's acoustics and to make sure it stayed stable on three support points under string pressure, and to modify the bridge position. The impulse responses of six bridge locations were checked (Fig. 103-105). I discovered that the third position gave the closest spectral image to the reference example.



Free boundaries
In circles, examples for points on the boundaries with zero displacements

Free boundaries with four rigid points
In circles, examples for the rigid points on the boundaries

Fig. 102 Best 6 shapes; with free boundaries and with fixed points on the boundaries. The black circles demonstrate how zero displacement points were selected to be the fixed locations

The number of sensors and their locations were defined next. FEM simulation was used to analyze the first 20 vibration modes for a 2.5mm Sitka spruce plate with boundary and support as described above (and in Fig. 105), including the bridge. The vibration modes were plotted and analyzed visually (Fig. 106). Piezoelectric sensors are good for sensing surface vibration; however, they are sensitive to surface bending (derivative of the displacement). Based on that and the cross-section of the first 20 vibration modes (Fig. 107), four locations for the sensors were chosen.

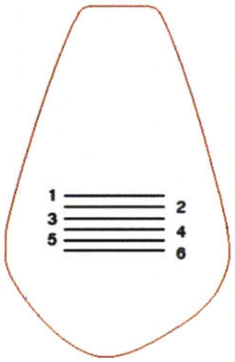


Fig. 104 The six optional positions for the bridge

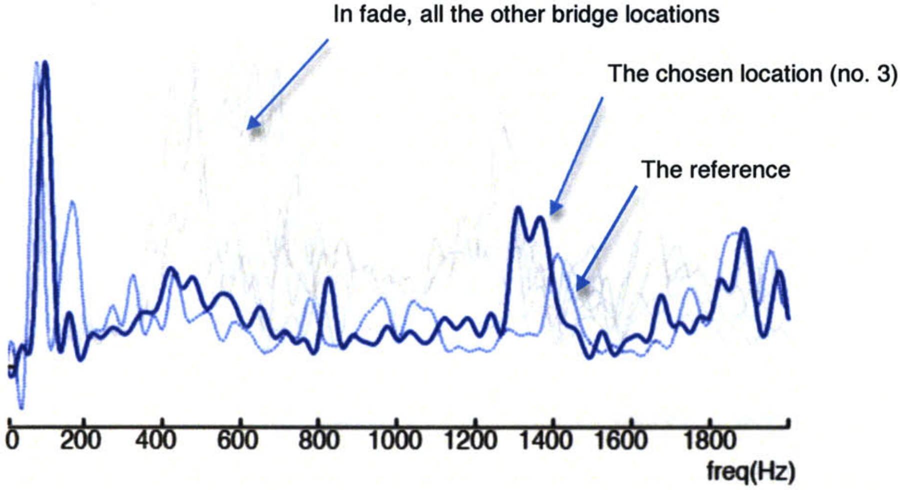


Fig. 103 Impulse response for three of the six bridge optional locations. The chosen location is in dark blue (no. 3 in Fig. 104), the acoustic guitar reference is in light blue. The fade gray represents all other bridge locations

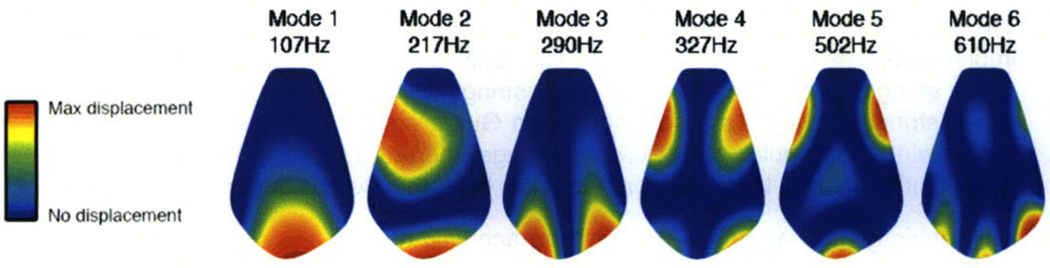


Fig. 105 Six first vibration modes of the chosen resonator, with supports as in Fig. 107

Alternatively, the sensor locations could be defined by solving an optimization criterion with FEM. Due to the high complexity of the problem and the need to involve physical tests the experimental iterative approach was used instead.

The resonator's design process depended on the criteria that were defined. It does not guarantee that other resonators, from different types of wood and with different support or structure will behave the same.

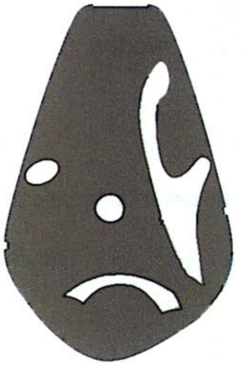


Fig. 106 Cross-section of vibration modes

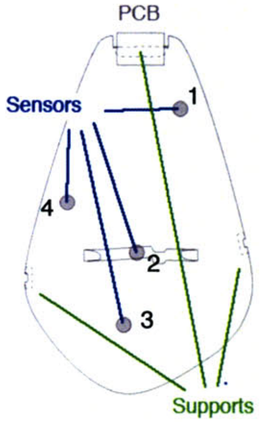


Fig. 107 Final resonator design

5.4. Design of the Guitar Body

The resonators defined constraints for the body design. The guitar's body should be able to embed the resonator inside it and still be strong and ergonomic. Several elements are important for guitar ergonomics: weight, stability[29], body size, thickness and string tension. The strings' sustain, which needs to be as high as possible, depends on the tension. Most of the references for this Section are based on interviews with instrument-makers, such as Marco Coppiardi, Ken Parker and Aaron Green [7, 27, 104]. Useful references for acoustic and electric guitar-making are [4, 105].

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

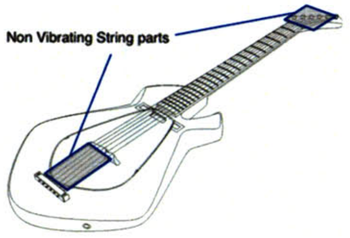


Fig. 108 Non-vibrating string parts

An electric guitar has better sustain than acoustic guitars; the solid-body minimizes the strings' energy loss on 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 can cause high-tension problems, like resistance to bending. Those problems can be minimized by making the non-vibrating parts of the strings longer (from neck to tailpiece and net to tuners, see Fig. 108). These factors influenced the design

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[29] In this context, guitar stability means that the guitar won't flip to one direction when stabilized on the leg.

of the neck's head and the tailpiece location.

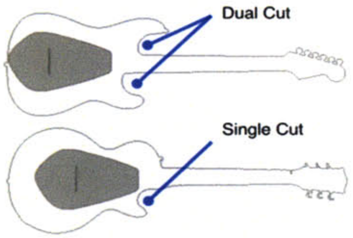

Fig. 109 Resonator shape inside Stratocaster (top) and Les Paul outlines

Although a long scale length is usually associated with Fender Stratocaster (or similar models), a Les Paul body was selected, due to the resonator's shape constraints on the body (see Fig. 109). The single cut solution of the Les Paul gives more stability to the connection with the neck. The neck designed to be glued to the main body frame, unlike the Stratocaster's screws connection.

Several 2D and 3D sketches were made (Fig. 110) in an iterative design process, before defining the final shape. A 3D model of the guitar was then built in Rhino3D (Fig. 111). Design efforts were made to fit the aesthetic look of the Chameleon Guitar into the current popular electric guitars family, without making it too similar to existing models, and while focusing the viewers' look to the resonator. A turquoise color was chosen to contrast with the warm resonator colors, which were expected to be brown wood tones.

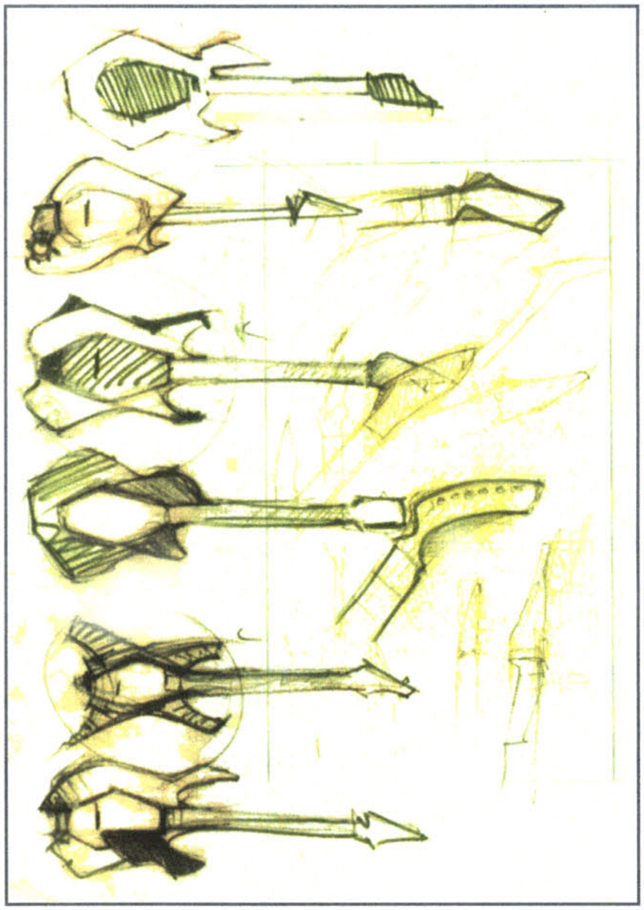

Fig. 110 Chameleon Guitar sketches

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 guitar's materials. The mechanism for the resonator replacement, called the *resonator tray* (Fig. 112-113), was designed in Rhino3D, with a constraint of no more than ten seconds replacement time. Aluminum and delrin have a low friction coefficient, which makes them good candidates for sliding elements. The tray itself was designed from aluminum, while the rails and the lockers were made from delrin.

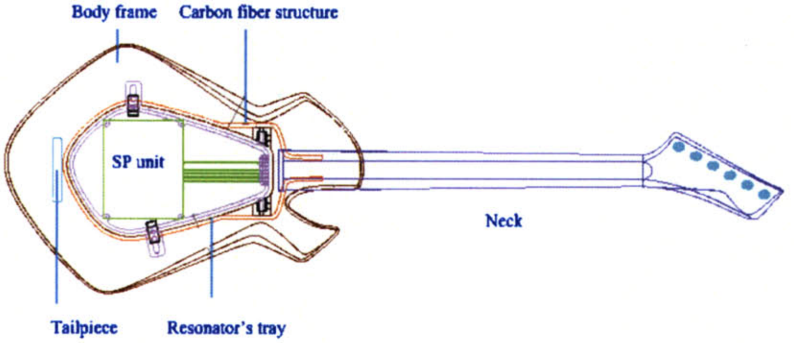

Fig. 111 Chameleon Guitar parts, Rhino3D model, top view

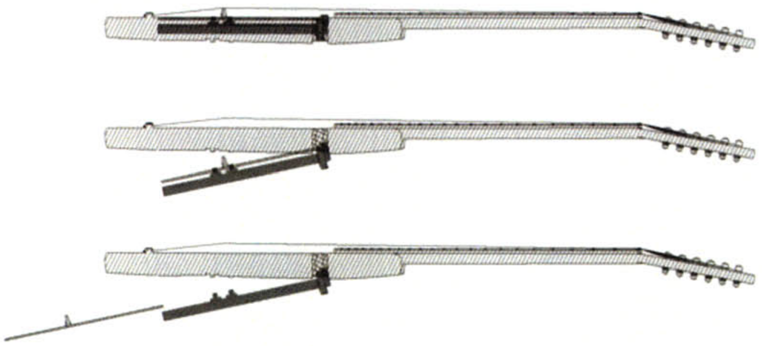

Fig. 112 Replacing the resonator by opening the *resonator tray*, guitar's side view

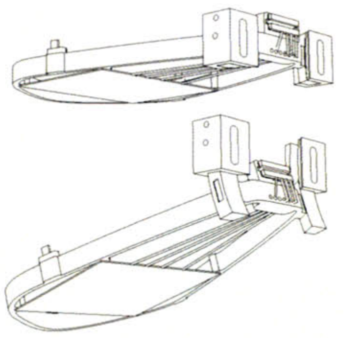

Fig. 113 *Resonator tray*, closed and open

The last design stage was to choose the woods for the guitar parts. Mahogany, which is better than maple[30] for vibrating at low frequencies, 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 fiber structure is located inside the poplar body frame to add stiffness.

5.5. Electronics

The signal starts it's path with the piezoelectric sensors, amplified at the *resonator PCB* and processed in the *SP unit*, as was

---

[30] Mahogany and Maple are the most popular woods for electric guitar necks. Mahogany is used for the Gibson Les Paul, while Fender made Maple a choice popular with the Stratocaster.

demonstrated in Fig. 98. Fig. 114 shows how those elements are embedded in the guitar's design. The sensors are ceramic piezoelectric disks (common for musical uses) with a resonant pick at 7000Hz (± 600Hz), 9.9mm diameter and 0.12 mm thickness. A small disk size was preferred in order to minimize the affected resonator surface. Voltage fluctuations (the sensed signal) develop on the sensors when a vibration field is applied, and are transmitted to the *resonator PCB* with thin coax wires.

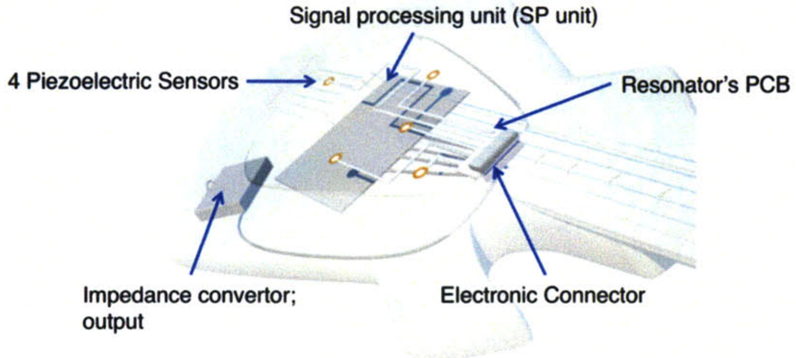

Fig. 114 Signal's path in the Chameleon Guitar design

The *resonator PCB* circuit is described in Fig. 115-116; it was designed for five channels, although just four would have been enough. In order to change the piezoelectric voltage signals from high to low impedance, they need to be buffered with an op-amp. The piezoelectric sensors have an electric capacitance that can be used with a resistor to implement a high-pass filter. The lowest standard note of the guitar is the E note (80Hz). The sensor capacitance, 10nF, is calculated from Eq. 4.13 (page 55); when the resistor value is 0.5MΩ the filter cutoff (f_{3db}) is:

$$f_{3db} = \frac{1}{2\pi RC} = 31.831\ Hz.$$

This guarantees that the guitar's relevant spectrum will not be filtered out. The transform function of the filter is less relevant here; it will be taken into consideration in the DSP algorithm (Section 5.7). The signals are biased to 2.5V; the PCB outputs are all line level signals. The PCB is powered from the *SP unit*, a LED power indicator is included, and grounded by the *resonator tray*, such 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 to the guitar.

The *SP unit* that was chosen is the Freescale's *Symphony™ SoundBite Development Kit* (Fig. 117) with Freescale's *Symphony™*

DSP56371 (192 MHz, 24bits fixed point processor). The unit has 8 audio line level, inputs and outputs. The unit's sampling rate is 48Khz with 16bit quantization levels. The analog to digital sampler includes an anti-aliasing filter.

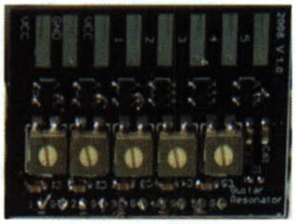

Fig. 115 *Resonator PCB*, top view

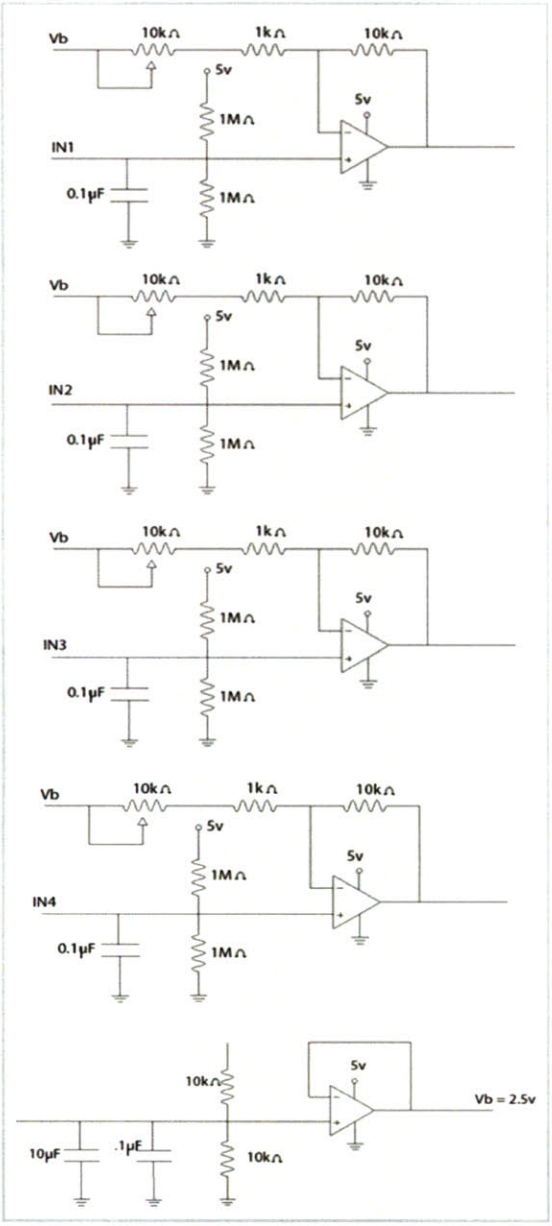

Fig. 116 The SP unit schematic (the capacitor to ground are used to filter noises)

Four line level inputs are transferred from the *resonator tray* connector to the inputs of the *SP unit* by coax wires. After processing, the output signal is transferred from a line level to an audio level (in other words, a high impedance signal changed to a low impedance one) and then to the guitar output jack.

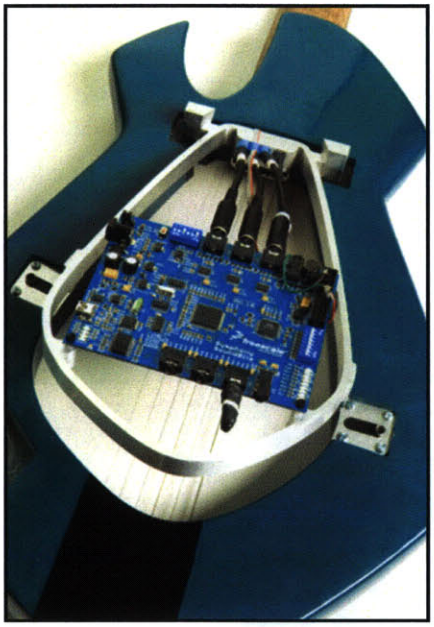

Fig. 117 The *SP unit* inside the *resonator tray*

5.6. Fabrication

The fabrication of the Chameleon Guitar body was done in two stages, similar to that of the design of the resonators discussed in Section 5.7: digital fabrication, based on computer modeling of the guitar, and hand-made modification: sanding, gluing, adjustment and varnishing.

The guitar's neck and body frame were milled separately by a Shopbot CNC machine (Fig. 118-120). The carbon Fiber structure, made by Clear Carbon and Components, was glued inside the body with epoxy (Fig. 123). The fretboard was made by hand; adjusting its dimensions, then inserting, trimming and sanding the frets wire. After inserting the truss rod into the neck[31] the fretboard was glued to the neck. Then the neck was adjusted and glued to the body with epoxy (Fig. 124-127).

The guitar was sanded, varnished and polished over a ten-day process (Fig. 128). The tailpiece, output jack, net and tuners were assembled. The *resonator tray* (Fig. 129), which was made in a CNC process by Ramco Machine shop, was the last element to be assembled.

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[31] The Truss Rod is a long metal screw that adds stability to the guitar neck; it is a standard in electric guitars.

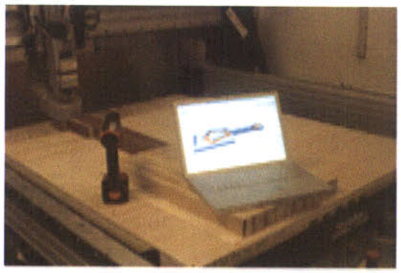

Fig. 118 Digital Fabrication, from the computer to the machine (left)

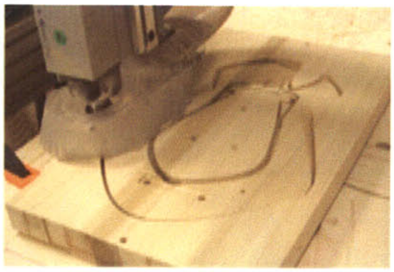

Fig. 119 Milling the body frame (right)

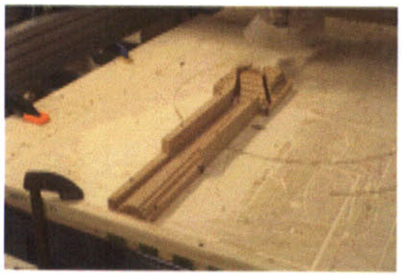

Fig. 120 Milling the neck (left)

Fig. 121 Sanding the neck (right)

Fig. 122 Preparing the body frame (left)

Fig. 123 Gluing the carbon fiber structure (right)

Fig. 124 Preparing the neck for the truss rod (left)

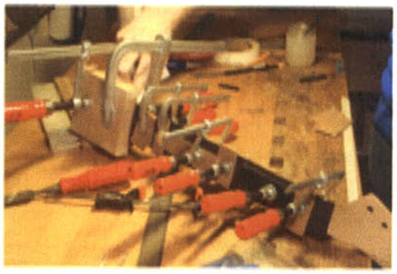

Fig. 125 Gluing the fingerboard to the neck (right)

Fig. 126 Inserting the frets (left)

Fig. 127 Gluing the neck to the body frame (right)

Fig. 128 Painting the guitar (left)

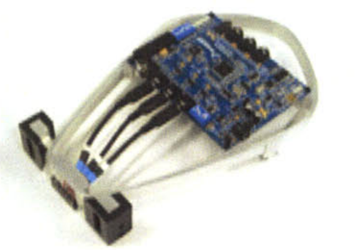

Fig. 129 Assembling the *resonator tray* and adding the SP unit (right)

5.7. Signal Processing

The signal-processing algorithm was developed and tested using Matlab and was implemented in the above-mentioned *SP unit* in C code, using the Freescale's *Symphony™ Studio Development Tools* and based on Freescale's *Eight-channel-C-template* C code software[32]. 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 is to implement a virtual chamber based on the physical resonator, i.e., to manipulate at least one resonator's signals (resonator no. 1 at page 81) and re-construct them to minimize the difference D between the Chameleon Guitar's output (captured by a microphone, 20cm in front of an Acoustic AG15 15W 1x8 Guitar Combo Amplifier) and the reference guitar:

$$D = S_r - \sum_{i=1}^{4} \sum_{j=0}^{N} c_{ij} (S_i * h_j). \qquad \text{Eq. 5.1}$$

S_r is the reference guitar's signal, S_is are the four sensors' signals, c_{ij} is the band coefficients per signal channel and h_is are the filters. D value can be minimized by a good filter bank design (h_j values) and correct coefficients (c_{ij}) choice. First, each of the signals has a filter bank with its bands tuned according to the reference guitar's eigen-frequencies. The best candidates per band (that minimize D) were selected. Each band was multiplied (its amplitude and decay rate) to achieve the required reference level. However, when more than one signal was a good candidate for a specific band, the one with the higher SNR was chosen. After tuning the algorithm of the guitar to minimize that difference, tuning it to a sound like a smaller or bigger guitar chamber was relatively easy.

The resonance mode relates to the spectral amplitude and decay rate of the relevant frequency. As the acoustic waves in the guitar are closer to its resonance modes, the decay rate is slower. In Section 2.4 the IIR filters were presented. IIR can imitate such a behavior coherently; the resonance behavior of the IIR can be tuned by the distance of the filter's poles from the ROC (see Fig. 94). The IIR can add a slower decay rate to the transferred band, i.e., by tuning the filter bank's IIRs, we can fit artificial reverberation to selected bands. Practically, the filter bank was implemented by a *Second Order Section Direct Form II* filter.

An iterative, sequential[33] implementation for an IIR in Matlab is presented here:

---

[32] This software package integrates my C function with 8 channels of inputs and outputs drivers (48KHz 16bit, one sampling cycle latency).

[33] The default implementation for linear filtering in Matlab is more efficient but isn't equivalent to the C implementation. The code that presented here can be transferred to C easily, with minor syntax changes.

```
% ------------------------------------------------------------
function Out=IIR(In, Hd)

% SOS Direct Form II IIR
% This part was replaced by the sampling management
% in the C implementation
% In:    input signal
% Out:   output signal
% Hd:     IIR filter parameters

SOS = Hd.sosMatrix;
% SOS:   L-by-6 matrix that contains the coefficients
%        of each second-order section in its rows

G = Hd.ScaleValues;
% G: gain for each section

global X;
X = zeros(length(G),3);

for n=1:length(In),
    Out(n)=IIR_d(In(n),SOS,G);
end

% ------------------------------------------------------------

function Out=IIR_d(In, SOS, G)

% SOS Direct Form II IIR, one sample
% This part was implemented in C code

global X;

X(:,2:3)=X(:,1:2);
X(1,1)=In;

for i=2:length(G),
    X(i,1)=G(i-1)*(SOS(i-1,1)*X(i-1,1)...
           +SOS(i-1,3)*X(i-1,3))...
           -SOS(i-1,5)*X(i,2)-SOS(i-1,6)*X(i,3);
end

Out=G(end)*X(end,1);

% ------------------------------------------------------------
```

The filter bank implementation is simple, and is based on summing and amplifying the relevant signal bands. Actual Values of a_is and Hd_is are attached in the Appendix. The signal source per band was selected based according to Eq. 5.1.

```
% ------------------------------------------------------------

% Hd1-Hd13 are the IIR filters structures
% a1-a13 are the bands coefficients (0s were optimized out)
% s1-s4 are the four channels signals

S = ...
a1*IIR(Hd1,s2)   +  a2*IIR(Hd2,s2)   +  a3*IIR(Hd3,s1)   +...
a4*IIR(Hd4,s4)   +  a5*IIR(Hd5,s4)   +  a6*IIR(Hd6,s4)   +...
a7*IIR(Hd7,s2)   +  a8*IIR(Hd8,s4)   +  a9*IIR(Hd9,s2)   +...
a10*IIR(Hd10,s1) + a11*IIR(Hd11,s4)  +  a12*IIR(Hd12,s4) +...
a13*IIR(Hd13,s4) + a14*IIR(Hd14,s4);

% ------------------------------------------------------------
```

The impulse response of resonator no. 1 (from Section 5.8) was used for tuning the filter banks (see the example in Fig. 131). The IIR coefficients were optimized in Matlab's FDAtool using a brute-force process. The results of the impulse response after being processed are presented in Fig. 130. This Matlab system required 14 bands and mainly processed resonance modes below 1KHz. It was implemented on the guitar with fewer bands (starting at seven and leading down to four), depending upon the amplifier's volume; morphing between the guitar's acoustic sound and the amplifier's output tends to give interesting overall results when the digital processing contributes mainly to the lower modes

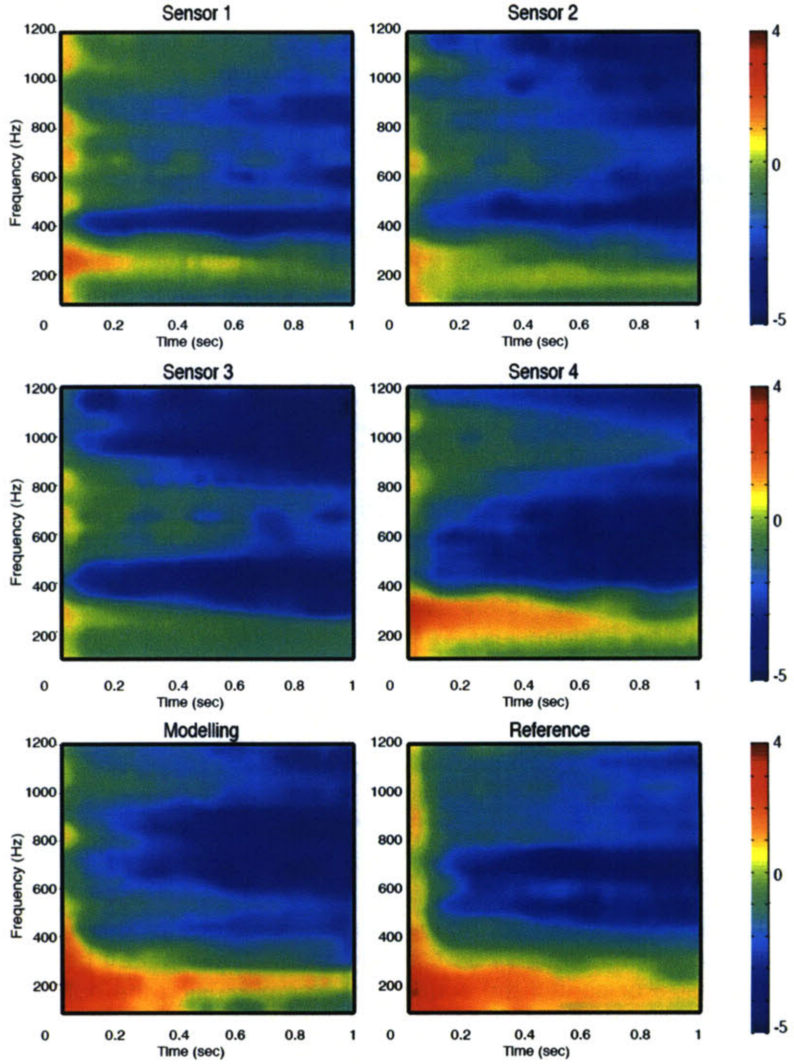

Fig. 130 Impulse responses' logarithmic, smoothed spectrograms of the sensors, the modeled output and the reference

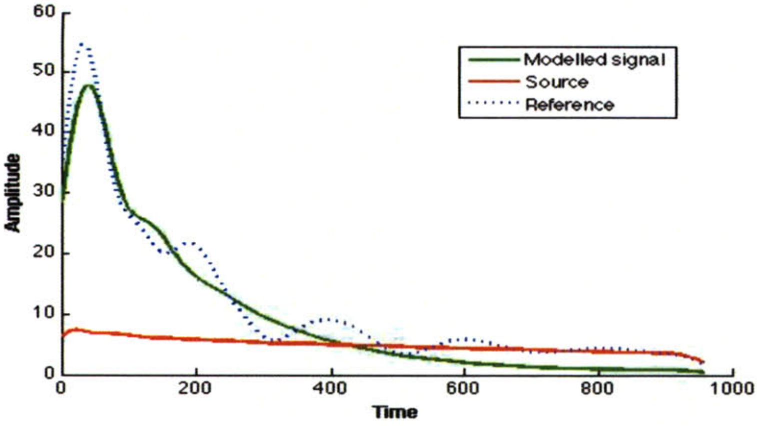

Fig. 131 Three band-limited signals (180-220Hz). The source's decay rate was changed with an IIR to fit the reference's decay rate

Alternative Algorithms

The algorithm described above is a suggested implementation for the virtual chamber. However, the use of a DSP enables implementation of a variety of sound processing standards and synthesized algorithms. Lazzarini, Timoney and Lysaght [106] describe adaptive frequency modulation synthesis based on an acoustic oscillator (instead of electrical oscillator). Julius O. Smith III in *Physical Audio Signal Processing* [107] 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. Each of those signals is a different superposition of the resonator's vibration modes (with phase difference that can be ignored for low frequencies). The distance between the signals can be represented as D_{nm}:

$$D_{nm} = \sum_{j=0}^{N} c_{nj}(S_n * h_j) - \sum_{j=0}^{N} c_{mj}(S_m * h_j) \qquad \textbf{Eq. 5.2}$$

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.

```
% ------------------------------------------------------------

% Hd14 is the IIR filter structure
% b1-b3 are the bands coefficients (0s were optimized out)
% s2-s4 are three of the four channels signals

S = s4*sin( b1*IIR(s2,Hd14)+b2*s3 ) + b3*s2;

% ------------------------------------------------------------
```

A suggestion for such processing is described in the above Matlab code. This version is a combination of phase modulation with a distortion effect, depending on the b_i coefficients 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, gives a natural signal. In case of a resonator that allows easy, non-coupled manipulation of s_4 (like resonator no. 6 in Section 5.8), an interesting overall effect is given.

5.8. Resonators

The resonator's design was a long process of trial and error. In this Section I will present the final collection of resonators, based on the experiences acquired during the process. Some of the resonators are conservative in designs, while others implement more experimental concepts.

All resonators in this Section have four piezoelectric sensors located in the same x_i and y_i (see Fig. 107). 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. The last four resonators test different ideas – embedding springs, a 3D printed chamber, screws or complex boundaries and connections. Different players, as discussed in Chapter 6, have tested all of these resonators.

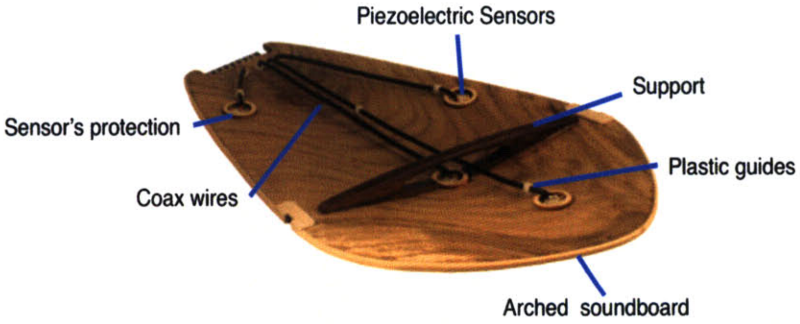

Fig. 132 Resonator's back: sensors and support

Making the Resonators

Based on Section 5.2, 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 (Fig. 133), where the wood-cuts and grain direction were selected in a traditional way (see Section 2.3). Then, the resonator's shape were milled using Shopbot CNC machine and cut with Universal Laser Cut machine. The bridges were made in a similar way, and glued with epoxy glue to the resonators after location adjustment.

All the resonators were hand-finished, first sanded or trimmed with a scraper[34], then varnished using different techniques[35] for protection and aesthetics. Different combinations of oil varnish, water based lacquer, watercolors, shellac or wax were applied. The *resonator PCBs* were glued to the resonator with epoxy glue. The sensors were glued with special ethyl cyanoacrylate adhesive, and were protected with a thin balsa ring (see Fig. 132). Coax 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. 133 Preparing acoustic joint block for soundboard (left to right)

Spectral and amplitude plots of impulse responses of the resonators, as was captured from the four sensors and *resonator PCB* are presented in Fig. 143-144. Here we can see the change in decay rate and spectral behavior between resonators, and the change in modes coverage between sensors. A performance evaluation will be described in Chapter 6.

Fig. 134 Snapshot of the varnishing process

---

[34] A sharp steal plate, used for trimming wood surfaces.

[35] Marco Coppiardi was mainly responsible to the varnish process. The process was based on traditional wood varnishing techniques for musical instruments.

Resonator No. 1

Fig. 135
Resonator no. 1

The first resonator is the simplest one; the soundboard was made from 3mm thick Sitka spruce, with a single support from flat mahogany in the back. The bridge was made from an ebony base and a bone top. The orientation and size of the support[36] were defined after several modifications, in order to add stability to the resonator with a minimal surface. This is the only resonator that wasn't arched in the milling process; the soundboard and the support, both flat, were glued in an arched mold. After the glue dried, the wood stayed arched and resisted string pressure[37]. It was then finished and varnished to look modern and clean.

Resonator No. 2

Fig. 136
Resonator no. 2

The second resonator was made from 4mm thick western red cedar. Unlike the first one, it was arched in the milling process. The support was oriented like the previous resonator, but instead of one glued wooden strip, here I glued two sculptured bars in order to test different support approaches. The lower part was made from ebony (to add stiffness). The bridge base was also made from ebony and the top was made out of bone. It was varnished in a heavier style, to give it a more traditional look.

Resonator No. 3

Fig. 137
Resonator no. 3

The third resonator was made from 4mm thick spruce, taken from an old[38], broken bridge in Vermont. This resonator was also arched in the milling process. The supports were designed in a different orientation than the previous resonators; one was made from rosewood and located underneath the bridge, while the other was sculpted from the resonator wood itself. The bridge was made entirely out of ebony. It was varnished to give an old, used, "antique" look.

Resonator No. 4

Fig. 138
Resonator no. 4

This resonator was made from oak wood, 3mm thick, and it is the only one that wasn't quartersawn (see Section 2.3). It was also arched in the milling process. Because oak is much stiffer than spruce or cedar, it was enough to use a single support from rosewood underneath the bridge. The bridge was also made from rosewood. It was varnished in light style, to keep the original beauty of the wood.

---

[36] The Appendix includes images of all resonators from the back, including supports and sensors.

[37] This process, called wood lamination, is a common technique in furniture making.

[38] Estimated to be older than 150 years.

Resonator No. 5

This resonator was made from 4.5mm padouk wood. Padouk is very soft and rarely used for guitar-making. It was arched in the milling process, but unlike the previous resonators, here I use the laser cutter to create circular holes to be used as screw holders. The screws add mass and influence the vibration modes. They can also behave as a free element that vibrate and create noisy patterns that sound similar to the acoustic distortion of a clipped signal. By modifying the locations of the screws the user can tune the acoustic sound. The bridge was made from an ebony base with a bone top. It was varnished in a light style, to keep the original beauty of the wood.

Fig. 139
Resonator no. 5

Resonator No. 6

This resonator was made from 4mm thickness purpleheart wood and western red cedar. The purpleheart is very stiff, does not need support, and was arched in a milling process. Part of the purpleheart surface was replaced with a free hanging cedar plate, connected with a cedar arm underneath the surface. The acoustic vibration patterns on the cedar plate, which contains a sensor, are expected to be different than in the case of a joint resonator. This plate can be easily manipulated by the player's hand to get interesting sound effects. The bridge was made from an ebony base with a bone top. It was varnished in light style to keep the original beauty of the wood.

Fig. 140
Resonator no. 6

Resonator No. 7

This resonator was made from 3mm thick mahogany. The top was milled arched, and has a single support made from mahogany and ebony. Two spring systems underneath the bridge add their physical resonance to the soundboard, causing a metallic, high frequency sound. The bridge was made from ebony alone. It was varnished in heavier style, to give it an old, used look.

Fig. 141
Resonator no. 7

Resonator No. 8

This resonator was made from 3mm thick walnut, and a 3D printed plastic chamber. The chamber can be filled with liquids (water, oil) or other materials, such as sand or rice. Rice will create a crunchy sound when shaking the instrument and will add noisy acoustic patterns to the sound ("acoustic distortion"). The bridge was made from rosewood alone. It was varnished with wax and oil to give it a simple natural look.

Fig. 142
Resonator no. 8

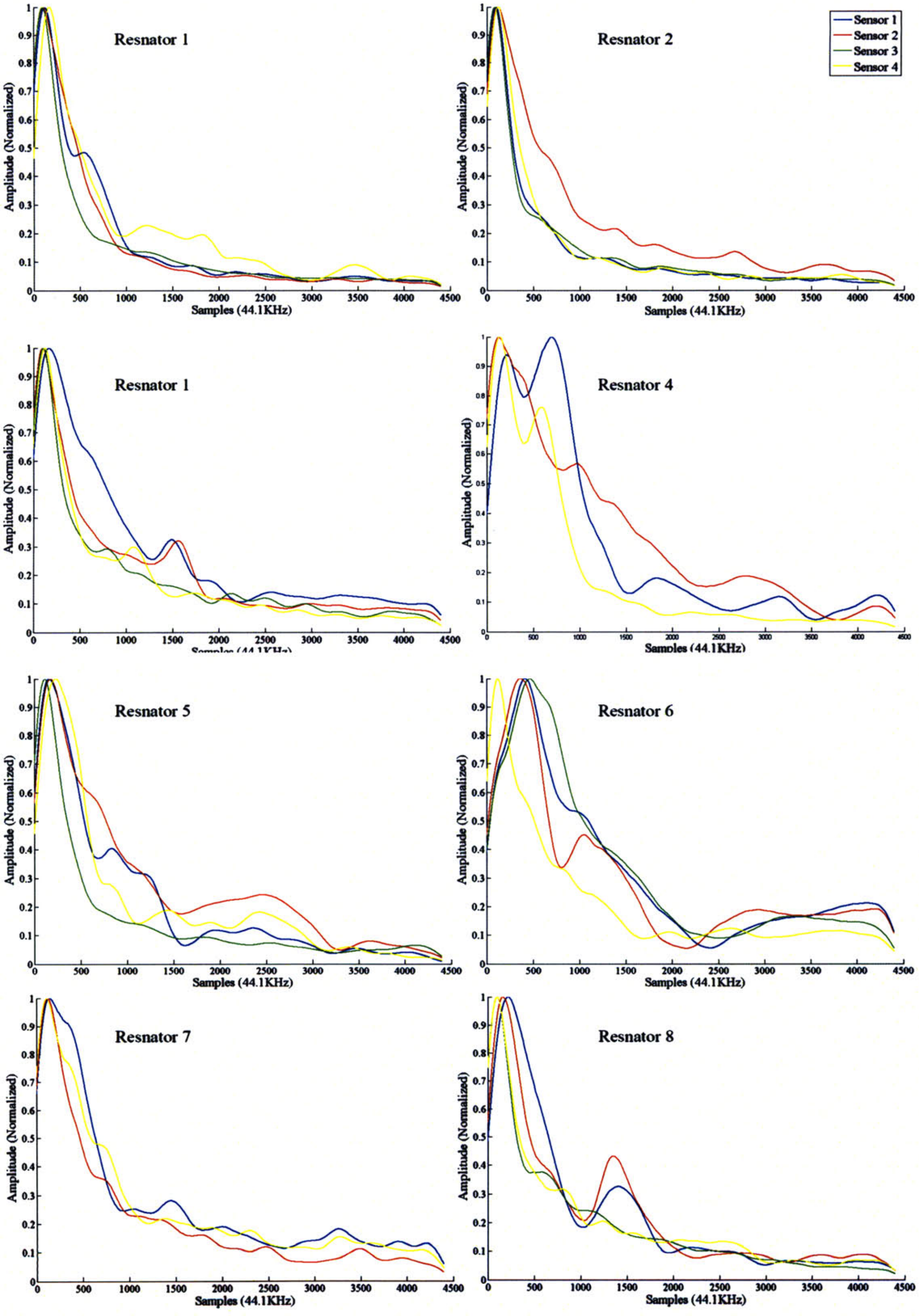

Fig. 143 Resonator impulse responses: four sensors output's envelopes

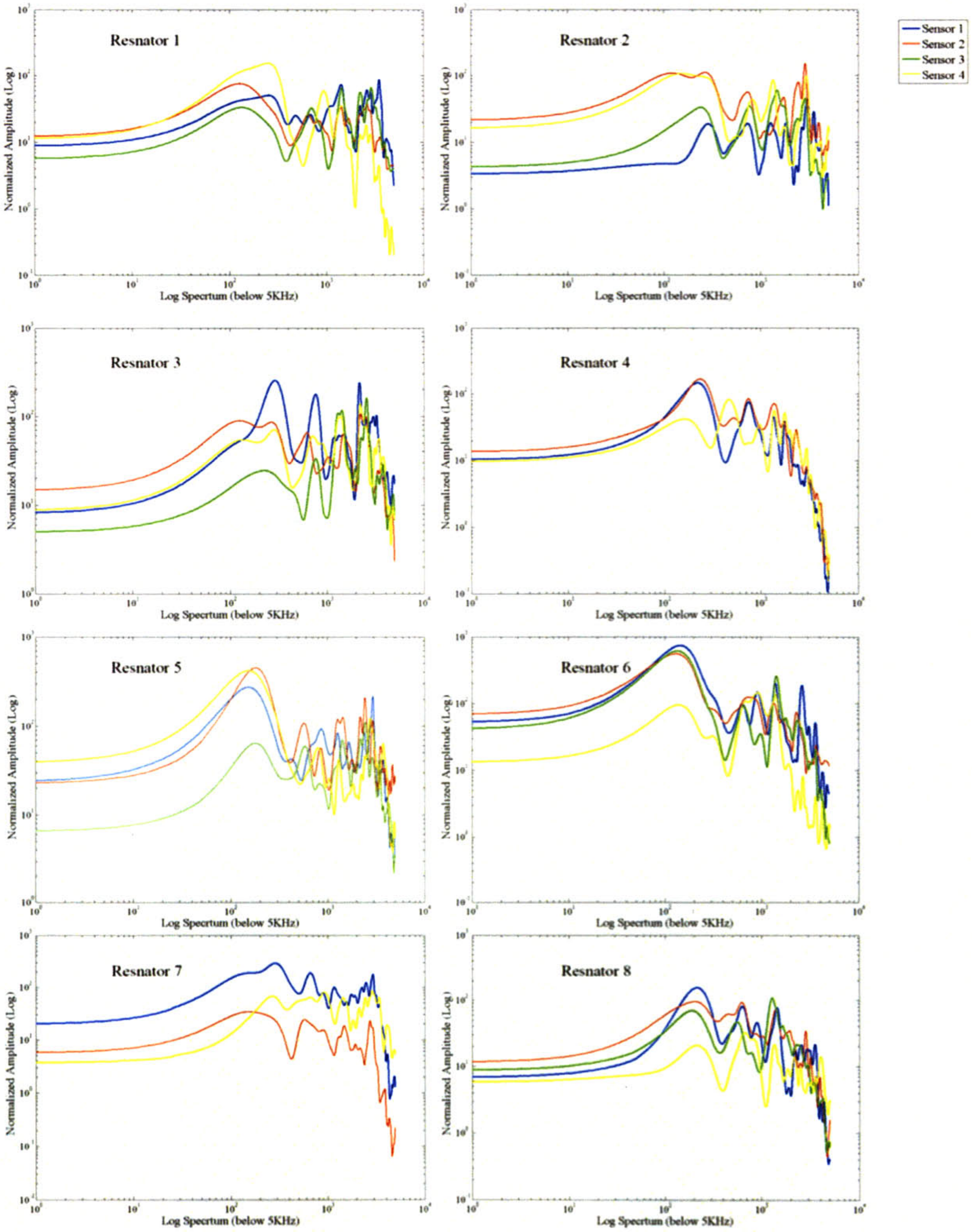

Fig. 144 Resonator impulse responses: four sensors output's logarithmic spectrums

6. Evaluation and Future Work

6.1. Overview

In this Chapter, I will discuss the evaluation of the Chameleon Guitar by both guitar players and instrument-makers. After that, I will discuss the results and propose future plans. In Section 6.2, *Players Evaluation*, I will explain the evaluation method and present the results. In Section 6.3, *Instrument-makers Evaluation*, I will discuss the conversations with different guitar- and violin-makers, and their feedback. Section 6.4 describes the issues discussed in these evaluations, analyzing and summarizing them, and presenting future plans.

6.2. Players Evaluation

Participants

Fifteen guitar players took part in the evaluation of the project. The players varied in their weekly playing time, from 0.1 hour to 17 hours per week. The average playing time was 4.3 hours. The players were asked about their favorite music style and the type of guitars they normally use (Fig. 145).

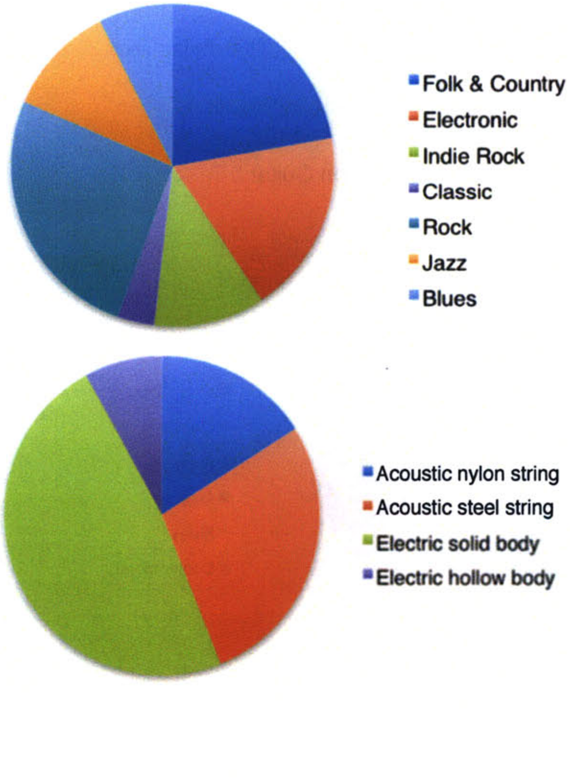

Fig. 145 Favorite musical style (top) and preferred guitar (bottom) of participants

Evaluation Method

Each of the players used the guitar for an hour in an acoustic recording studio. Several reference guitars were available: an acoustic guitar, a classical nylon-strings guitar, a Gibson Les Paul electric guitar and an Ibanez EDR470 electric guitar.

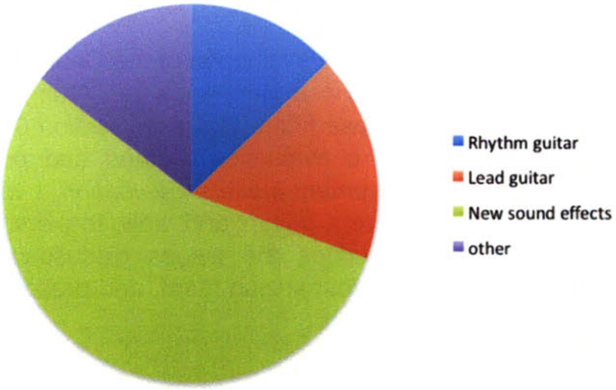

Fig. 146 The most important property of the Chameleon Guitar

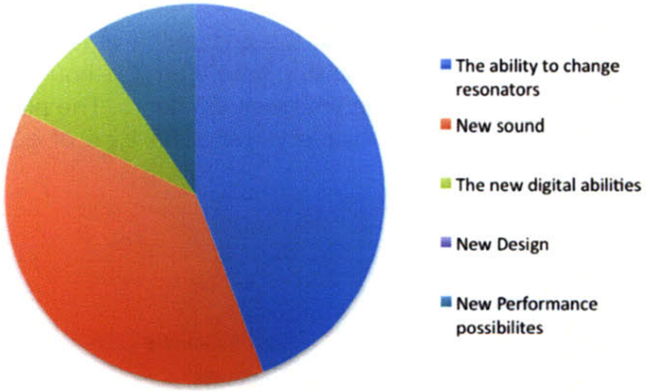

Fig. 147 What role best fits the Chameleon Guitar

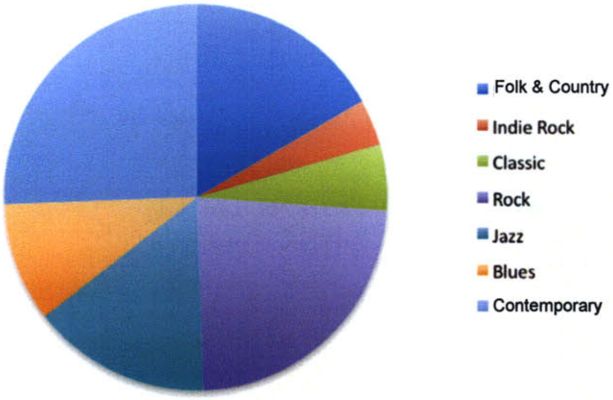

Fig. 148 What musical style best fits the Chameleon Guitar

After presenting 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 processing, small chamber processing and a digital effect (see Section 5.7 for technical details). Each participant played in his or her preferred musical style[39]. The participants were asked to replace at least one resonator by themselves and to examine the tangible qualities of the resonators.

In the last part of the evaluation, the participants filled out a survey with several questions regarding their experience with the guitar. The answers were analyzed and are presented in the next Sections.

Concept and Contribution

The first question the participants were asked was if they would like to have a Chameleon Guitar. Answers were rated on a scale from one to seven[40]. 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 (see Fig. 146), the role that best fits the guitar (Fig. 147), and the musical style that best fits the guitar (Fig. 148).

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 sound possibilities (with less synthesizer involved), more acoustic properties that do not exist in an electric guitar; and new expressive ways to play the guitar (together with new sound effects). Several people 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 resonators. Some said this could lead to new sound revolution and to a new collecting culture (when a player collect unique resonators, each represents different values). From that, some participants said, new big hits and iconic original sounds could appear.

Playability and Ergonomics

The participants were asked to give feedback on the playability aspects of the guitar. Here the answers varied widely. While some of the issues were matters of personal preference (string type and action, guitar weight, frets type, neck radius), it seems that there are several issues that bother the majority of players. Overall, the guitar was easy to hold and to play, and received positive feedback. It fitted best for players that are more used to electric guitars (especially long scale necks, such as Fender Stratocaster) and were using the

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[39] Sound examples were recorded and can be checked in the project's website; check the sound section in www.thechameleonguitar.com

[40] One represents "no" and seven represents "definitely"

Chameleon Guitar for playing music originally written for acoustic instruments.

The main consistent negative issue was that the guitar does not stay in tune after replacing a resonator; it continues to lose tuning and, depending on the resonator, has some general intonation problems. The Steinberger tuners have a limited tuning range. More than once the tuner could not pull the string any more even though the string was not tuned yet. Some participants recommend considering using an auto tuner system (see Gibson Robot, Section 2.5).

The high expressivity of the Chameleon Guitar's resonators, together with the piezoelectric sensors' behavior, leads to a strong impulse-like sound when hitting the resonator directly. While some players liked it, due to the high degree of control this adds to the instrument, the majority of players claimed this effect needs to be softened. Several players suggest considering resonator protectors, such as a pick guard (see Fig. 80-81).

The participants were asked if it is easy to replace a resonator, on a scale from one to seven[41]. The averages answer were 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 fifteen seconds. 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.

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 acoustic tangible interface, such as in resonator no. 6, seems to be very compelling to the majority of players. Some of them wrote that it allows them to expand the playing experience. Several participants believed the expressive control of digital effect from the resonator can serve as an interesting alternative to guitar pedals.

For a few of the participants, the digital abilities suggested a big potential to create new sounds. However, some of them said 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 is not developed enough. There are some disadvantages of using a computer for sound processing and one participant was not sure about the argument of using the computer instead of an analog circuit.

Resonators

The participants were asked how many resonators they felt they might use. The average answer was 4.2, with standard deviation of 2.6. Then they were asking to choose the preferred three resonators (from the evaluated resonators list, see Section 5.8) and to explain their selections. The results are presented in Fig. 149 and in Table 4.

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[41] One represents "no" and seven represents "definitely".

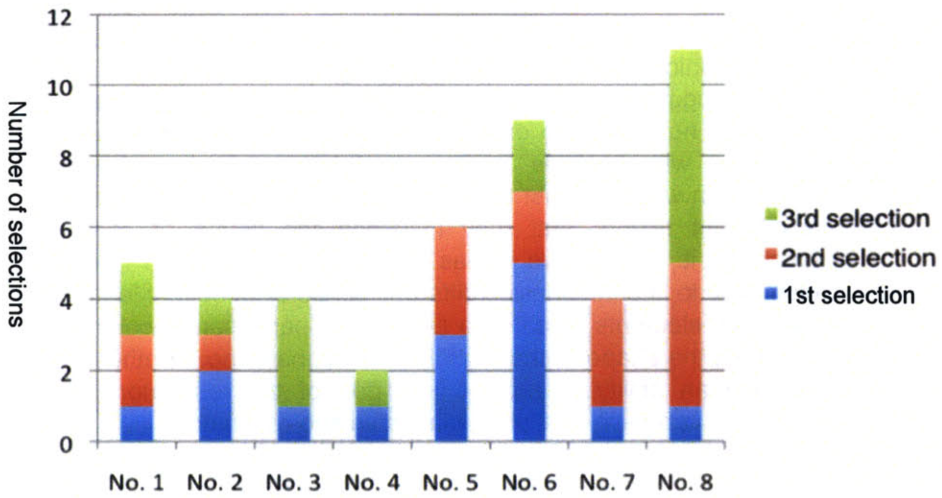

Fig. 149 Three preferred resonators

Table 4 Participants resonators selections and arguments

Popularity	Resonator	Participants' Arguments
1 High popularity	No. 8	It has highly experimental property. Several players claim it is the most novel, unusual resonator
2	No. 6	Well-balanced, nice sound; It stayed in tune and it has a very interesting, highly sensitive expressive abilities with its loose piece; very different (than normal guitar) with a lot of potential
3	No. 5	It has great bass and full sound and an interesting distorted sound due to the vibrating screw; it stayed in tune; it looks good; it has an ability to adjust a lot of parameters
4	No. 1	It has a nice balanced tone, most similar to normal acoustic guitar
5	No. 2	It has a nice big acoustic sound, similar to a classical guitar and very responsive
6	No. 7	It has an un-predictable sound, while the spring allows different effect
7	No. 3	It is the most beautiful, with a great texture and a nice full sound. One participant mentioned the wood's narrative that reflects from its look
8 Low popularity	No. 4	It has unique and rich tone and a beautiful wood

After evaluating the resonators, the participants were asked to suggest a design for a new resonator. The ideas varied from alternative materials (such as glass, steel, fabrics and compositions) to mechanical elements, including motors and wheels. Several players suggested to develop further the idea of the free plate (as in resonator no. 6) and to examine possibilities of combining separate elements with multiple springs and wires. Another interesting suggestion was to adjust the resonators surface friction, by applying a different texture that may influence the sound of chafing or touching it. Alternative ideas include adding more electronic elements to the resonator (different sensors, speakers and visual feedback elements, such as a LCD). One participant recommended adjusting the shape of the chamber in resonator no. 6; other offered to have an ability to replace just part of the resonator, so one resonator can have multiple replaceable sub-resonators.

6.3. Instrument-makers Evaluation

Instrument-makers qualitatively evaluated the Chameleon Guitar. The guitar was presented to individual guitar-makers (the New England Luthiers[42] [108] and Ken Parker [27]) and to violin-makers (Marco Coppiardi [7], Kevin Kelly and Paul Crowley [109]). The guitar-makers gave an inside perspective, while the violin-makers gave an un-biased point of view. Gibson's CEO and Gibson's engineers [9] gave the perspective of a big manufactured in the field. The project was discussed freely, regarding its concept, technical issues and optional contributions.

All instrument-makers agreed it is difficult to predict the success of new instruments, but it is certain that the quality of materials and shape have a high impact on the guitar's success ("*It is not always about the sound*" – John Svizzero). The majority of instrument-makers said they would be willing to developed resonators if the market would demand it. Ken Parker suggested to keep on improving the sound quality, and to have at least one resonator that is acoustically optimized.

Some suggested making as many resonators as possible, which would vary just a little from each other, and then to try them acoustically on the guitar, without electronics sensors and processing. By this method it would be possible to speed the resonator evolution process and learn about the influence of small details on the acoustic behavior. Such resonators could be made from different wood types, composite types, or other materials, such as carbon fiber.

The instrument-makers had a deep interest in the contribution to the fabrication process, where the fast resonator replacement can serve as an easy way to evaluate and design acoustic behaviors. In that context, the digital fabrication abilities (such as using 3D digital

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[42] A group of instrument makers (mostly guitars) from New England area: Steve Spodaryk, John Svizzero, Jeb Hooker, Alan Carruth, DJ Parsons, Donald Lambe, Thomas Knatt and Daniel Wangerin.

design and CNC milling machines) seem to interest makers more than the digital abilities of sound processing. Here, the digital technologies can be used to improve qualities while keeping prices low by optimizing the process for small-scale resonator production.

> *"The thing that I find most interesting is distilling the instrument down to its most important component (the soundboard) and then having this USB key ability to plug it in anywhere and feel like it's your very own instrument."*
>
> – Steve Spodaryk

6.4. Discussion

Overview

The Digital 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 digital simulation. While fifteen players evaluated it, at least fifteen more players tried it in a total period of ten weeks. During that time, two groups of resonators were made and fifteen different resonators were tested (including the final group of eight resonators from Section 4.8) and the *resonator tray* was opened at least three hundred times. The project was discussed with designers and engineers, demoed multiple times and received significant press coverage. Two professors from Berklee College of Music, specializing in teaching guitar techniques, Garrison Fewell and Jon Finn, also took part in the discussion [110-111].

General

The concept seems to be compelling to the majority of the participants. Players from different musical styles as well as instrument-makers understood the idea and its potential well, as can be seen from their answers in the *Concept and Contribution* (Section 6.2). 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 of the domains.

> *"To me, the instrument "Electric Guitar" begins at the guitar and ends at the speaker. Everything connected in-between is considered part of that instrument.*
>
> *- Acoustic Guitar ends at the guitar. If it is connected to a speaker, it is "sound re-enforcement" and not "tone production".*
>
> *- The differences in definitions mean that amplifier design or function will be very different for each application.*
>
> *- So far, I have not yet found an "amplified acoustic guitar" that sounds close to the real thing.*

> *It sounds like your instrument might be completely away from that whole approach. That makes it interesting! I have found that the vast majority of "one size fits all" instruments tend to be a series of compromises that make them "jack of all trades/master of none." To me an instrument that really carved its own niche would be really interesting."*
>
> – Jon Finn

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 will be appropriate for. The players that liked the guitar less are generally players who are not used to this guitar interface (such as nylon strings players). It seems that hollow body guitar and electric guitar players enjoyed the Chameleon Guitar more.

After analyzing the survey forms, no correlation was found between the participant's favorite musical styles and the role they saw for the Chameleon Guitar. While the most important property of the guitar according to the players is 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).

Guitar Body

Physically, the Chameleon Guitar functioned well. The body was stable, with good support for low frequencies. The guitar was stable on the legs of the player when the player played while sitting. However, some modification will be need for a future development. Also, in the current design, regular high quality tuners should replace the Steinberger tuners that have limited tuning range.

For a new design of the guitar, a more unique aesthetic identity is needed. The resonator needs to be better distinguished from the surrounding body. This can be done by a bigger gap between the resonator and the guitar body, and by using a black color for the guitar itself. The surface development of the guitar should be more stylized, with a better fine-tuning of the shape. The shape needs to be modified in order to have a place for the *SP unit* in the body frame itself, and not in the *resonator tray*. The use of auto-tuners should be considered.

From the user evaluations, I can see that it is not easy enough to replace a resonator. The participants gave it an average score of 4.6 out of seven. It is hard to close the *resonator tray* under the pressure of the strings, and a better mechanical solution is needed. However, relying the sliding elements on delrin and aluminum has proved a reliable solution.

Sound and Digital Processing

The participants referred to the new sonic possibilities as one of the most important contributions of the 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 the digital abilities are important, they mostly felt that it contributed as a sound effect and not as 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 abilities. The question of how to control the software, by tangible interfaces on the resonator themselves or by electronic controllers on the guitar, still need to be tackled. When considering the high degree of complexity the 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 maximized with digital sound design.

Resonators

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 choose resonators from the collection that they have 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 analyzing the popularity of the resonators I learn that the second group of resonators (no. 5 – no. 8, the more experimental resonators), were preferred. Here, the most popular resonators are no. 6 and no. 8, and the main argument relies in their unexpected behavior (although sometimes this behavior is actually produced by the digital effects), higher expressivity, and experimental options. Loose elements and embedded chambers have a lot of potential. It can be interesting to combine these with other mechanical elements (such as wheels or wires) and to redesign the use of the spring (resonator no. 7).

The first group of resonators (no. 1 – 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, for sound and craft modification experiments. In general, sonic qualities, interface issues, narrative properties, and aesthetic qualities were related to the resonators, more than to the guitar.

7. Design Potential

7.1. Overview

Up to this point, the presentation of the Chameleon Guitar project focused on the musical context, describing its musical motivation, goals and technologies. However, the project was inspired by many different fields, such as the fields of fiction, product design and human-computer interaction (HCI), and it was intended to also contribute in those areas.

In this Chapter, I will discuss and analyze the Chameleon Guitar's inspirations (other than the musical ones), the development of related concepts, and contributions to the HCI and design fields. I will cover topics such as the relationship between objects and narratives, the virtual vs. physical aspects of those narratives, interface issues, concept design and related design approaches.

In Section 7.2 of this Chapter, I will present an introduction to narratives in object design, describing the image of a hybrid object and related fictional inspirations, discussing interfaces and contents in object design and suggesting a perspective for the relationship between virtual and physical elements in object design. In 7.3 *Hybrid Narratives and The Chameleon Guitar* I will explain the Chameleon Guitar in relation to the discussion in Chapter 7.2, and present design potential that benefit from its unique properties. In Section 7.4 *The Resonators: Narrative and Design Potential* I will present different design approaches to resonators, inspirations and visions and discuss examples. In the last Section, 7.5, I will discuss general design potential and possible contributions of the project to other fields, such as design, economics and entertainment.

7.2. Design and Narratives

Narratives, cultural rituals, technologies, practical considerations and much more, influence the field of object design. In this Section I will discuss relevant topics that contribute to the way we communicate with objects around as.

Introduction to Narratives in Object Design

Alongside the development of technology, natural and man-made objects reflect the narratives and meaningful stories of their users. Man-made objects play more than merely a practical role in our lives. From stories painted on ancient bowls to god-like sculptures to an alchemist's tools, objects hold a cultural, if not a spiritual, place in society.

Different narratives are usually associated with different iconic objects. As people impose their perspective on the objects they use, the life cycle of an artificial element sometimes grows into a deeper narrative than its practical uses. For example, the Japanese *Wabi Sabi* is an art form focused on "*finding beauty in imperfection and profundity in nature, of accepting the natural cycle of growth, decay, and death*" [112]. According to Wabi Sabi, the history of the object is a part of its beauty. Another example is wedding rings passing from generation to generation. This ring will not only hold its original purpose and aesthetics but also an added narrative that creates a stronger emotional connection to the object.

While the manual fabrication process reflects any unique events that occurred while the object was being produced, mass production methods are designed to efficiently repeat the same manufacturing methods, ending with a high similarity between artifacts. However, after using them for a long enough time, even mass-produced objects differ from each other by marks and symbols, which are usually unique and define the specific connection between the user, the object and their shared experience.

Hybrid Objects

The image of a hybrid object existed in ancient cultures and mythologies. From the Greek Gorgon god, who had a squat nose, bulging eyes and a grimacing mouth with a boar's tusks [113] to Mary Shelley's Frankenstein [114], the vision of a creature that combines elements from several different creatures was always fascinating to the human imagination. Modern graphics gave the hybrid object's visual aspects a new strong drive, producing new combinations and narratives: from Steve Austin, Darth Vader or the Terminator [115-117], our culture is full of visual symbols of part-machine part-human figures. Sometimes the organic matter is covering mechanical structure and sometimes the machine enlarges the abilities of the limited human body.

Fig. 150 The Greek Gorgon, from [113]

Fig. 151 Leonardo Da Vinci's flying machine, from [118]

The vision of a hybrid object is much more than fiction. Inventors and engineers have worked on enhancing human abilities, from Leonardo da Vinci's flying machine [118] to the modern bicycle. The *Biomechatronics* group at the MIT Media Lab, for example, focuses on "*How technology can be used to enhance human physical capability*" [119] by developing new prosthetics to artificially compensate human disabilities.

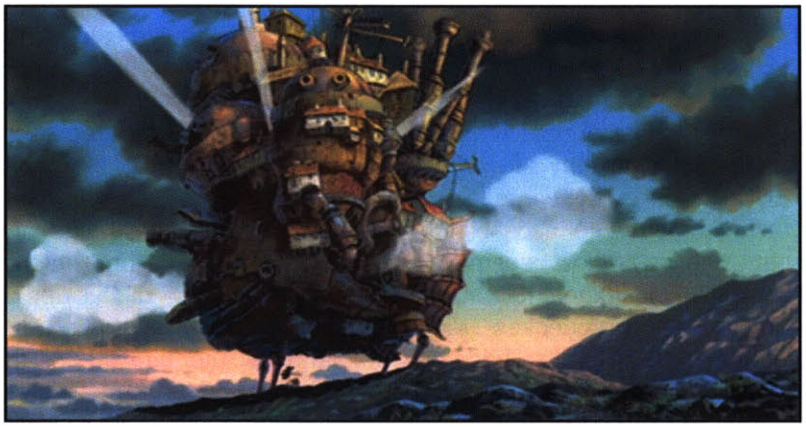

Fig. 152 Howl's Moving Castle, from the movie [120]

As the imaginary hybrid connections of the past become more realistic and practical today, writers and designers are always motivated to deliver new concepts of unique connections between the machine and the organic matter. In *Howl's Moving Castle*, Howl is a wizard living in an enchanted moving castle [120]. A flame in the fireplace drives the castle, which is Howl's heart itself. This is a vision of a machine and human sharing the same source of energy and control.

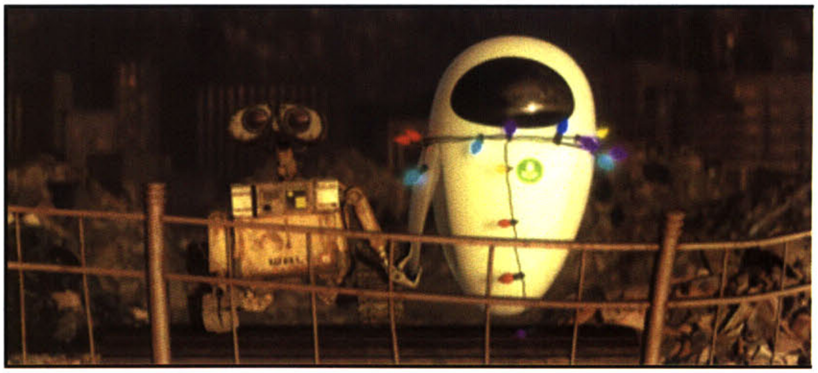

Fig. 153 Wall-E and Eve, from Wall-E [121]

In *Wall-E*, a robot named Eve is built to find plants on a futuristic Earth [121]. When a plant is found, Eve inserts it into a specific storage place in her body and changes her operation mode from searching to protecting and delivering. While the plant is stored inside of her, Eve has a visual symbol of a green plant in her breast, associated with the symbol of the heart. Eve is a machine that changes its functionality, depending on an organic heart.

The Virtual Domain

The idea of merging artificial and natural properties has existed since the beginning of technology. The advent of the digital environment introduced the virtual world, which enabled a new type of experience. Suddenly, physical objects in a digital environment do not represent just themselves; they are an interface, a gateway, to a new world. This new world, cyberspace, contains huge amounts of information that was never so accessible. Modeling physical constraints and simulating scenarios became a popular way to imitate and enlarge the real world experience. Communication changed, digital design and fabrication processes were created and a new field was born. The physical controller becomes the tangible interface [1] for the virtual domain.

All of this has changed the way we see physical objects. The properties of today's objects, such as its uses and life cycle, are divided into physical and digital aspects. The physical interface has a limited degree of freedom; while the digital one is usually more flexible. The life cycle of a product is now divided into its physical package and the digital contents or information. We can upgrade the software without changing the physical package. Conversely we can also replace the package and save the digital information. Suddenly, we have multiple narratives: the narrative the physical object represents, and the narrative its digital content carries. In Wabi Sabi, old objects gain historical value and tell their life story with the physical marks they carry. In the digital tool, the content can be easily refreshed and fixed. While the old approach appreciates the object's tradition, the new technologies prefer progress.

The main disadvantages of the digital domain are lack of authenticity and uniqueness. A digital element cannot represent an individual narrative, since it can be easily copied and transmitted. Because it can be manipulated without regard to physical domain constrains, the details of a digital body are not as appreciable as a physical elements.

Digital technology enables a new type of hybrid objects: objects that combine physical properties with digital ones. This allows new concepts, such as building a body that exists partially in the physical domain and partially in the virtual one. Unlike the tangible interface, the computer can be used to actually read the information naturally embedded in the physical object, and enlarge that physical experience in the computer.

Fig. 154 Virtual-real hybrid human figure. digital art by David Searson, from [122]

Interface and Content in Object's Design

A simple distinction can be made between the user interface and the functional or psychological contents of an object. Mostly the user interface can be treated as a superficial layer that comes between the object's content and the human. The contents the object carries with it can be divided into technical contents and abstract contents. The former are the object's technical designation, its mechanical, electronic and digital mechanisms, the types of materials it is made of, its energy consumption and more. The abstract contents are those that affect the object's image in the eyes of the user. Such contents are subjective and can be interpreted in different ways by different users (Its aesthetic aspects, the cultural contexts, historical memory, feelings the objects brings up by the manner of its operation). All these affect the image the object creates with the user. Mostly these contents are interwoven to make up the essence of the object.

The Chameleon Guitar concept (A Physical Heart in a Digital Instrument) and the technology[43] presented in this thesis, enable a detachment between the interface and some of the object's contents. This detachment enables replacement, change and adjustment of the object's contents as well as the manner of its operation. The interface layer, the object shell, remains unchanged. This can be compared somewhat to a change in digital content, without changing the physical box. However, if a change in digital contents usually enables only a change in the information of the object, our approach enables control and change of fundamental contents, which concerns the object's essence while leaving the interface

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[43] In this context, the Chameleon Guitar digital unit is used for implementing a virtual chamber.

unchanged. The principles of the approach are based on modeling of a virtual shape, imitating a physical object's behavior, when only a sample of the physical object exists[44].

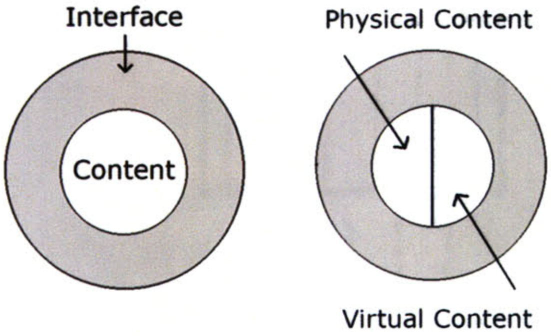

Fig. 155 Interface and content layers

Physical and Virtual Contents

A digital environment enables convenient and safe control without costs – there is no material price for a changing virtual figure's size in a computer game. Physical objects do not enjoy such freedom. Constraints such as price, physical forces, construction costs, safety considerations, space and an inability to correct mistakes places limitations on the creative freedom of expression. These difficulties encourage creation in virtual environments – exciting computer games can be created which use huge virtual spaces and shapes without a price limit or physical constraints. Shapes can be copied and delivered very rapidly. These objects can carry different and extreme values – from images of ancient cultures to science fiction and fantasy, mundane layouts for imaginary situations. As the virtual shapes' simulation ability is perfected, the virtual technology and culture becomes more common.

In essence, virtual culture is a material-free culture. As discussed before, materials have an effect on the object's behavior, and inhomogeneous materials (such as wood) are hard to simulate with reliable quality. In addition, the inhomogeneous properties of the material and the quality of work create unique objects, in which no object is identical to on other. There are many objects where the material, the texture and the experience of touch are a central part of the user experience. The assembly and handling quality of hand-made and craft products, from acoustic musical instruments to jewelry, furniture and ceramics, are of critical importance for the characterization of the object's contents and the image it creates. Objects made of inhomogeneous materials or hand-made works mostly carry values that are different than objects that are manufactured in complete uniformity. A violin is an acoustic

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[44] Metaphorically, the physical sample can be treated as the physical DNA of the element we model.

instrument that depends on the wood of which it is made and the quality of the assembly for the creation of sound. Since no two pieces of wood are completely the same and good violins are hand-made, no two identical violins can be found. This fact, instead of being an obstacle, makes the price of good violins rise and creates a luxurious and rare image for the quality of material and work, which cannot exist in a virtual object.

Like the texture rendering process in a modeling program, where we provide an image as a tile and the whole relevant shape is tiled by it, the chameleon guitar allows a physical material to enter a digital environment. In a way it is manipulation of boundary conditions. Boundary conditions are an important part of any physical system's definitions. The manner in which an object behaves under any physical field (gravity, radiation or various types of pressures) depends on the material and its borders (see Section 4.2). The idea presented can be physically characterized as manipulation of boundary conditions while keeping the material's properties. If we have compared the sample to the object's DNA, the boundary conditions define the object's shape. This concept presented in this thesis tries to benefit from both environments – the physical and the virtual – maximizing the content experience from the object.

In the guitar prototype, the virtual model and the material sample are both replaceable, under an interface that remains the same. Such a hybrid object can read digital information from a disk and physical information from a piece of wood, rock or hand-painted fabric, so a different behavior is simulated yet is unique and cannot be copied.

It can be argued that the importance of the physical sample is doubtful. Digitally modeling inhomogeneous materials may be improved in the future. However, I believe that it will not change the need for use of a physical sample, since that need stems from the knowledge that this sample is unique and may carry a historical memory of meaning to its owners. Once the sample can be virtually copied, it will automatically lose its uniqueness (the same way it sometimes now gets lost in the mass production process), which is a significant tier of the connection between the user and the object.

7.3. Hybrid Narratives and The Chameleon Guitar

In Section 2.7 *The Electric Guitar*, I presented recent developments in guitars and digital technologies. Interesting developments are also occurring from the HCI point of view. Some guitar manufacturers, such as Sims Custom Shop [123], embed LED lights in the guitar's neck. Fret Light is a company that uses an external computer to control the LEDs on the neck. It is used mainly for educational purposes [124].

It is expected that the above technologies will merge with the virtual abilities of products such as Guitar Hero. This combination will connect the real playing experience[45] to the digital domain, where the

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[45] In the Guitar Hero computer game, the user isn't creating music; the user is hitting recorded notes of known pieces.

music being played is monitored and controlled from the computer. The player can get new visual feedback from the neck but also, similar to Guitar Hero, take part in a virtual experience.

Fig. 156 Fret Line's LED neck. From manufacture's website

The major problem in this vision is the lack of authenticity. The digital guitar is more flexible but less authentic then the regular electric guitar (see Sections 2.5, 2.6 and 4.5). Guitar Hero is not a guitar but a computer game. Any narrative correlated with it depends on the chosen virtual representation. Beyond that, it does not relate to the traditional acoustic experience: if an acoustic guitar's sound identity correlates with its aesthetic (wood patterns and quality), in digital guitars, the object is just an interface, and it fully depends on the software. The life cycle narrative, which is highly important to the unique connection between a player and his instrument, does not exist.

Earlier, I discussed the object's narratives, both physical and digital. The Chameleon Guitar presents an object with multiple narratives. The interface, the guitar itself, is a modern digital package that can be made in mass production, can connect to a digital network and can handle digital information. The resonator, however, is the heart of the system. Making the resonator by a traditional acoustic method we preserve the traditional musical instrument narratives and merge it with modern technology. The third narrative is the hybrid chamber, where the material's properties are being taken from the resonator and then the boundary conditions are being manipulated digitally. By applying virtual shape to a physical sample of material, the digital-physical hybridization creates a complete object. The physical resonator is the heart of the guitar, while the digital processing is the freedom, a link to imaginary possibilities.

While the guitar can have authentic hybrid representation, it can be linked to known virtual experiences, such as computer gaming, animation or storytelling. In an imaginary acoustic environment, a user can simulate shapes of guitars that are not practical to build in the physical world or can take an iconic shape (such as to merchandise), download it to the guitar and let it be simulated as an acoustic body, relying on the resonator's material properties to preserve the authentic acoustic qualities (see Fig. 157-160 for visual examples).

Fig. 157 Concept design: flying balloon-guitars and amplifiers. Figure drawings by Jasmine Florentine

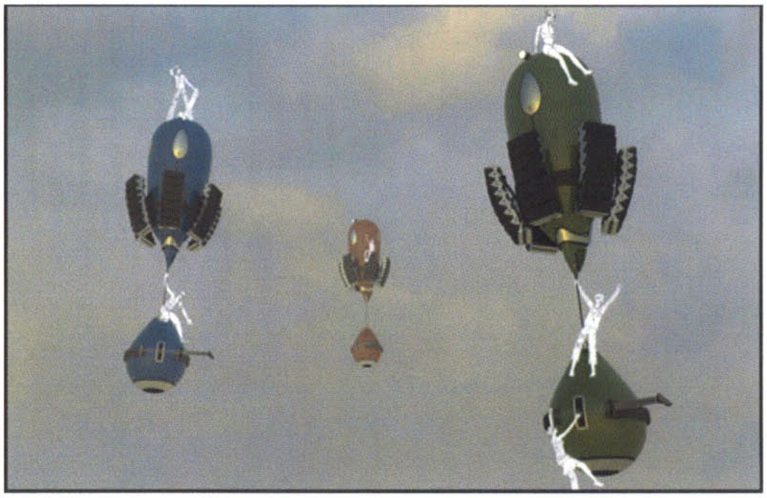


Fig. 158 Concept design: a huge bubble-like guitar

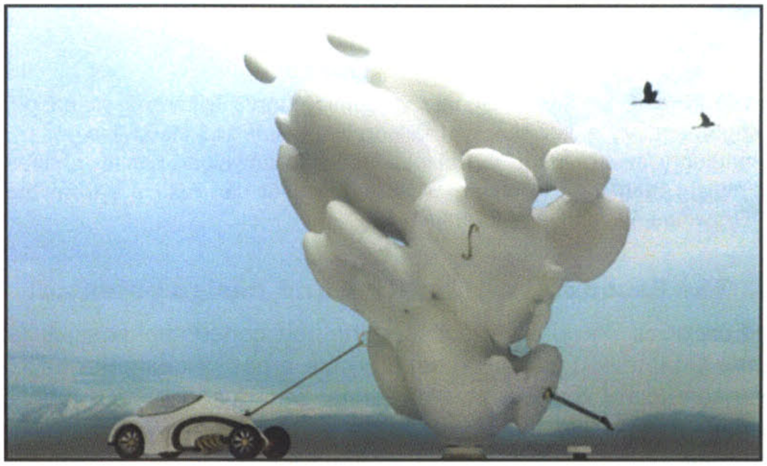
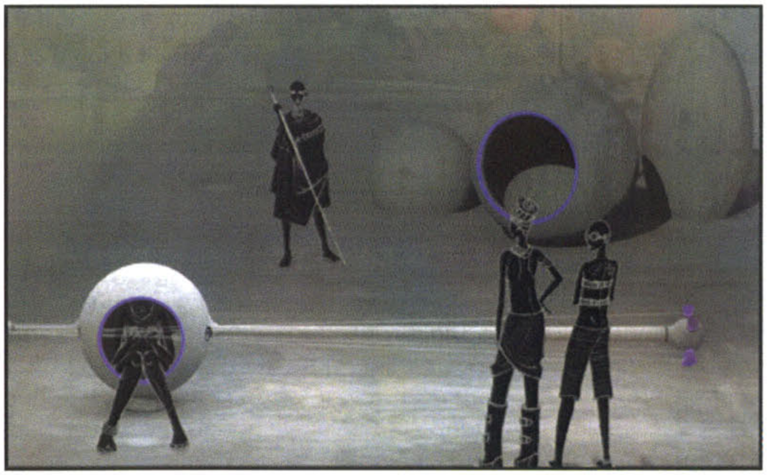


Fig. 159 Concept design: the concert krar. Figure drawings by Jasmine Florentine



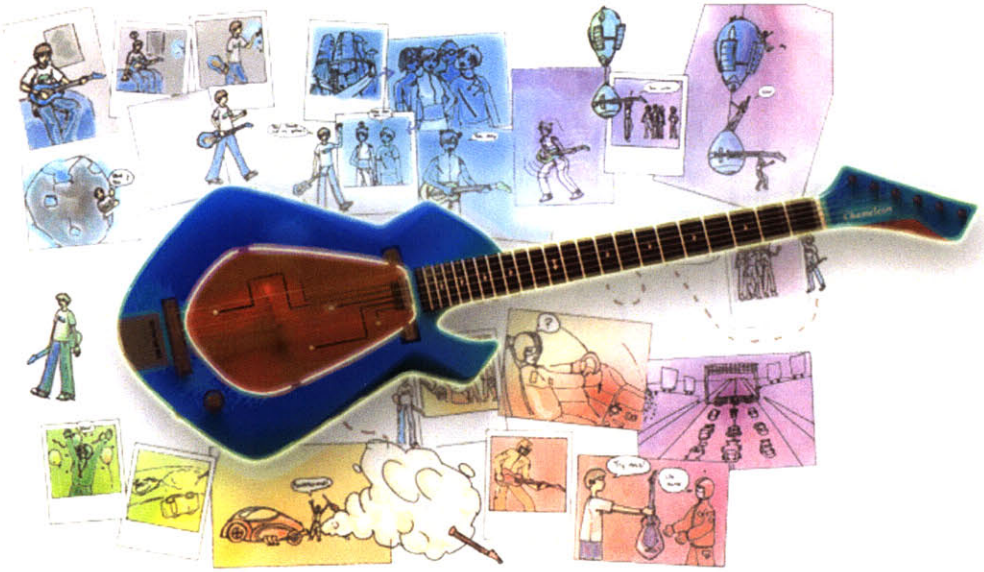


Fig. 160 The Chameleon Guitar: a comic story. Different scenarios, involving imaginary guitar shapes (balloon like guitar and cloud like guitar). The imaginary environment can inspire users to download similar shapes and simulate them on the guitar. By this, the user can take a part in the story. Drawings by Jasmine Florentine

7.4. The Resonators: Narrative and Design potential

In the previous Sections, I discussed the new conceptual possibilities that the Chameleon Guitar presents in the areas of design and HCI. The resonator of the Chameleon Guitar introduced a new type of experience: flexibility in choosing the acoustic heart of a musical instrument.

Sometimes musicians and instrument-makers are not willing to take risks and try innovative approaches, due to the dominant influence of tradition. Good acoustic instruments are not easily made, and the unique interface and sound quality they present defines the relationship with the player. For a user that is used to his instrument, it is not easy to replace or change the well-known tool.

The Chameleon Guitar resonator can be replaced without changing the main interface of the guitar. Each resonator has its tangible abilities, but the guitar structure does not change. It enables risk-taking. An instrument-maker can try different materials and concepts without using many resources. Similar to fashion (see Fig. 161-162), the user can replace his preferred resonator once in a while without replacing the whole instrument. Moreover, although the guitar body can be mass-produced and uses digital technology for sound processing, the instrument's heart can preserve uniqueness and be made by individual experts or amateurs. The resonator can have high-end quality or be made by an amateur player.

Fig. 161 Resonator designs: hand-drawn sketches

Fig. 162 Resonator designs: digital sketches

For example, resonator no. 3 (Section 4.8) has been made from the remains of an old covered bridge from Vermont. The bridge is estimated to have been built from Sitka spruce in the first half of the 19th century, which is a good choice for an instrument's top plate. The piece that was found was too small to make a violin or guitar, but it was big enough for a Chameleon Guitar resonator. The wood was processed in the traditional methods and then varnished to give it an antique used look. This resonator's narrative relies on its aesthetic values, its sound and its story. All of those values that traditionally relate to full-scale instruments are now part of the hybrid machine, in which the computer's output will reflect the properties of the resonator.

Fig. 163 Covered bridge in Vermont, from [125]

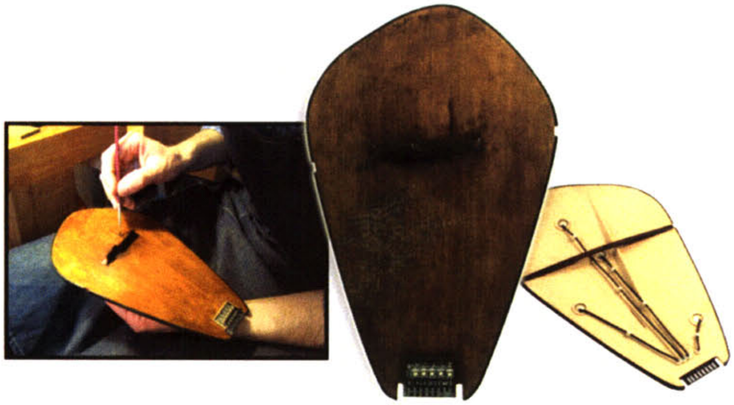


Fig. 164 Resonator no. 3, front and back (at the right). At the left, applying antique-like elements to the resonator's front

Another example is work that has been done by Melodie Kao in the MIT Media Lab. Kao developed a design process for a resonator reflecting environmental values (Fig. 166). The resonator was made from an old broken acoustic guitar (Fig. 167). The wire shapes developed from the outline of the mahogany wood, from which the resonator was made (Fig. 165). In this resonator, as well as in the previous one, the design process reflected historical narratives and was inspired by the unique material.

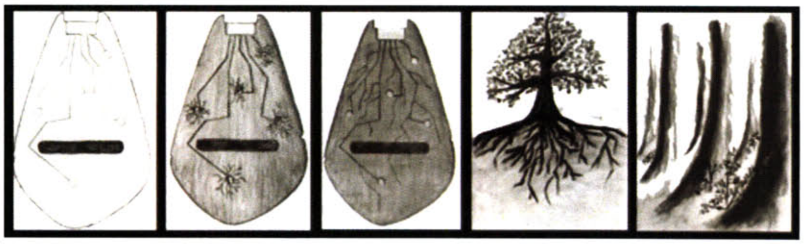


Fig. 165 From right to left: Kao's design process

Fig. 166 Kao's resonator inside the Chameleon Guitar

Fig. 167 An old guitar's back (mahogany wood), used for Kao's resonator

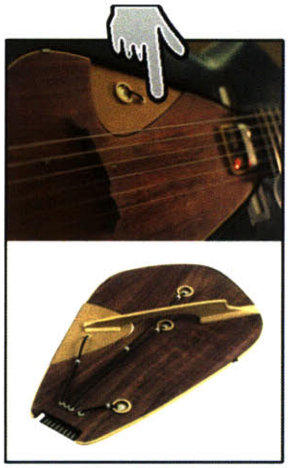


Fig. 168 Resonator no. 6 with the control plate, front and back

There are three different approaches to designing and developing a resonator and the related user experience. The *Complete* approach is when the resonator and the virtual shape's simulation together create a hybrid chamber. Then we can sample materials or craft qualities and "clone" their properties to a virtual shape. This was the basis for the Chameleon Guitar design and the previous discussions.

A second design approach, the *Tangible* approach, treats the resonator as an interface for digital processing. For example, in resonator no. 6 (see Section 5.8) the surface is divided into two wooden plates, where both of the plates are covered with sensors. The smaller plate is hanging on a cantilever arm (see Fig. 168); it is very sensitive to any physical manipulations. When applying non-linear processing taking benefits from the difference between signals and using the small plate's signal as a controller (see last part of Section 4.7), we can create an acoustic controller for the algorithm.

The third approach, the *Acoustic Effect,* handles the resonator as an acoustic effect. Here the digital unit is used only for filtering or amplification, but the resonator itself can have additional mechanical elements beside the acoustic plate. As an example, it can use free elements, springs, wires, small chambers with liquids, pipes and more, similar to Bart Hopkin's work (see Section 2.2). In resonators no. 5, 7 and 8, several similar ideas were implemented and tested. Resonator no. 8 is a good example of embedding a small chamber in the resonator itself, which can be filled with liquids, for instance. Based on conclusions from a preliminary resonator with the same idea, this resonator is made from hard wood and a 3D printed chamber, and two of the sensors are located on the chamber. This adds a high degree of control to the guitar; by shaking it or changing its angle we get new sound effects.

A significant part of the resonator's design concept is to enable alternative evolutions of resonators. Anyone can develop a resonator, which reflects new acoustic ideas, aesthetic values and control options. For instance, Adam Kumpf from the MIT Media Lab investigated conceptual ideas to embed liquid chambers and pipes in a resonator. This work evolved from resonator no. 8.

Fig. 169 Resonator no. 8, with a chamber

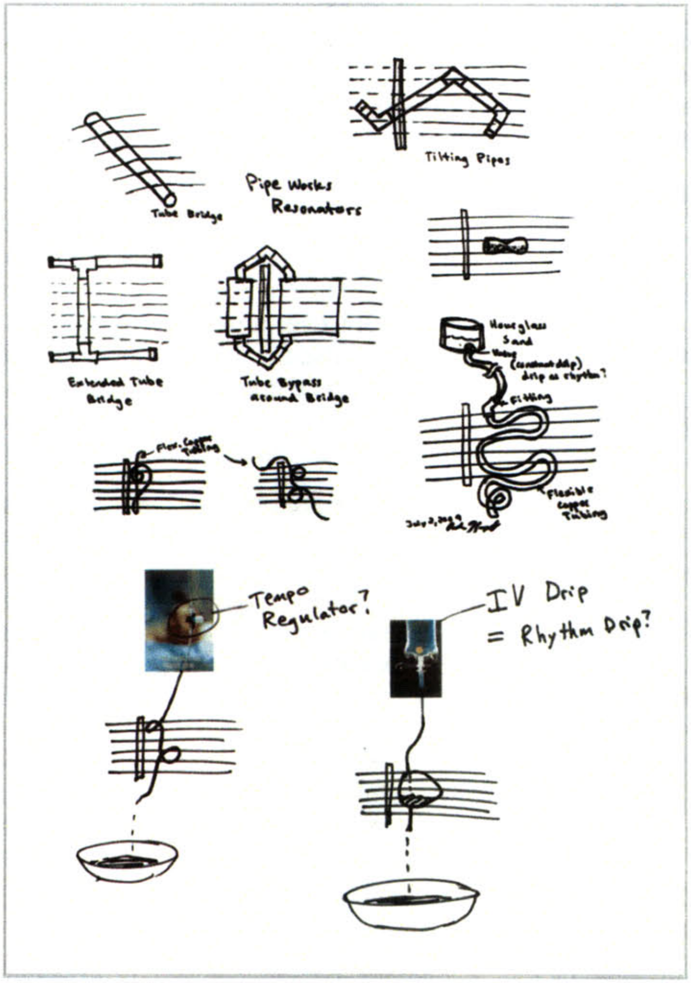


Fig. 170 Adam Kumpf conceptual sketches for resonator with embedded pipes and chambers

7.5. Design Vision

In the Chameleon Guitar, I aimed to develop new platforms linking the virtual to the physical environment in order to create an innovative hybrid instrument. This concept has a broader design contribution than just to musical instruments. For instance, in architecture, materials have a fundamental function in defining the structure, but some parts of the shape are mostly used for aesthetics. The possibility of preserving a material's behavior and applying virtual shapes to structures in places where a physical existence is not required may be interesting. Since the material sample is replaceable, one can create a dome made of fabric or paper and change its height and size virtually. The system can then simulate the dome's behavior under various weather conditions using physical measurements taken from the sample under the same conditions. The possibilities latent in the approach are vast, and create ways to connect worlds both functionally and aesthetically in a way that did not exist until now.

Any object, tool or instrument can be defined as a set of properties, such as color, size, function and context. I wish to see how these properties can be adopted and optimized in their natural environments. Each environment, physical or virtual, has its own benefits. A significant property of the virtual environment is freedom. We can create visual effects that cannot exist in reality. We can create music that no instrument can make and we can take a part in a fantasy. However, a weaker property of the virtual environment can be a stronger one within the physical environment, and vice versa. For example, take the property of authenticity: the behavior of living creatures, hand-crafted objects, sensation of the wind blowing, the feel of a grain of sand are all too complex to be modeled accurately by computers. By linking the two environments, we can create a platform that benefits from the best properties of each domain. We can envision how a story, a computer game, or a music piece can simultaneously exist in the virtual and physical domain.

Creating an object, instrument or tool that combines the authentic property of the physical environment with the freedom of the virtual one is a research and design challenge. For example, the handcrafting process relies on the expertise of the maker, while the industrial object is designed for mass production. Digital elements can easily be embedded in an industrial product when all the physical properties can be precisely defined. Furthermore, integrating digital properties into physical objects creates a design problem: which one of the environments represents the true image of the object?

Conceptually, by embedding traditional, hand-made or "natural" elements in digital objects, we can create a link between two extremes. While a traditionally fabricated object is linked to cultural roots and rituals, a digital environment offers unlimited information and flexible interfaces. Both have their advantages, but often we see more mass production process than craft, more synthetic materials than natural ones. Increasingly, we see how digital interfaces and controls are simply replacing rather than coexisting with manual ones. In a majority of applications, this process makes sense, due to efficiency, reliability and flexibility of new technologies. However, it is also reasonable to preserve traditional values that do not go hand in hand with these new methods. New technologies can damage the uniqueness and authenticity of traditional products that give the object deep cultural context and a long life cycle. Merging the benefits from both environments, the uniqueness with the flexible, the synthetic with the natural, and the machined with the crafted can create an improved concept for a product with better awareness of historical, cultural, and environmental context for new technologies.

Within an economic context, we note that modern society faces huge challenges. In the future, economical, energy and environmental crises will influence the consumer market and industries even more. Digital technology can play a major role in a reality of limited materials and expensive energy while allowing cultural expression and maximum flexibility of a product. I believe that we will see more integration of high technology, new media, and digital information with natural materials, hand-made objects and energy preserving processes. The process of merging small scale, individually fabricated parts with high-tech objects could be a stabilizing force for the market. Mass production processes will depend more on smaller organizations that rely on their craft qualities. Based on the right designs, this can lead to better use of energy and materials – by localization of the fabrication processes using local materials and canceling long distance shipping.

We can see that the challenge of hybrid design for a product is deep as well as broad. While good practical application requires innovative solutions from both physical design and technological aspects, the opportunities that such research creates can be inspirational to other fields, such as economics, the environment and entertainment.

8 Conclusions

The Chameleon Guitar is the product of a year and a half of development, taking inspiration from both the digital and the physical musical landscapes. The new approach to designing guitars was tested successfully and proved itself over time. The guitar and its resonators functioned well, were evaluated by fifteen 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 the project was to merge traditional values and digital abilities. Based on the evaluation results, I can say that it was fairly successful. In addition to this success, the process of experimentation and risk in the design of resonators resulted in innovative expressive abilities. It seems that the community of instrument-makers felt more attached to the traditional approach, while the guitar players were more excited by the experimental approach. I believe that both of these approaches need to continue being developed together, combining traditional values in experimental solutions. As a quality criterion it is important to have at least one resonator that sounds like a good acoustic guitar, and more work, acoustically and digitally, needs to be done to accomplish this criterion.

The guitar design reflected the image of an object that functions in the two domains, the digital and physical. It still needs more design identity development, since the guitar body is too similar to electric guitar rather than reminding the observer that it is a hybrid package.

The instrument's digital abilities have a huge potential that interests users, especially because of its potential to enlarge the resonator's unique physical properties. However, richer digital processing options still need to be investigated. A visual feedback and control is also needed, dependent on the guitar design.

More generally, the approach could be easily implemented in other string instruments, such as the violin family, and with a bit more effort could be developed into a piano solution. More conceptual and technical work needs to be done to apply a similar hybrid approach to other design fields beside music. Here, sampling properties of the physical material (a metaphoric DNA) and "cloning" it to a virtual model opens a door for new discussion in HCI and design. New qualities of authenticity and random behavior approaches can be introduced to the digital domain; new, flexible control options can be applied to physical objects.

The external computer interface for modifying the digital content of the instrument is a different topic that requires more research. The potential is huge: we connect an object to virtual environments in a way that has never been done before. This connection can demonstrate how physical objects can enjoy the same media influences 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 environments, opening up a new future for hybrid design of objects.

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All audio and video files, including selected recorded files that from the evaluation, can be found in the projects website:

www.thechameleonguitar.com

Matlab's *mat.* Files, containing filters' coefficients, can be download from

http://www.thechameleonguitar.com/Chameleon_Guitar/Digital_Processing.html

More pictures of the resonators can be found in:

http://www.thechameleonguitar.com/Chameleon_Guitar/Resonators.html