An Analysis to the Guitar Lab's gesture acquisition prototype with the aim of improving it.

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Abstract

Our concern in this Thesis is to study gestures in classic guitar, it covers research made in the fields of gestures analysis, sensors, gesture acquisition models and guitar gestures. Recent papers and books along with other Thesis are presented as scientific background for this project which is mainly inspired by the research of Guitar Lab [1], in fact their gesture acquisition model is used as a starting point, with the goals of (1) improving the gesture acquisition system and (2) get a deeper analysis of gestures that could help Guitar Lab's research towards expressivity.

With regard to the gesture acquisition prototype, it is based on capacitive sensors that are able to detect the presence and pressure over a fret of the guitar a brief analysis of the original model is made to demonstrate it's capabilities and its weakness, the capacitive sensors were renewed using new components, an addition to the hardware was made by placing a linear potentiometer that detects the position of the thumb in the back of the neck of the guitar.

The renewed prototype was probed and an deep analysis of the achievements and failures of the model is presented. Towards one of the aims of the Guitar lab to use the prototype for an application different to the gesture analysis, we created an augmented guitar using the sensors as controllers to generate sound and trigger music samples.

[1] GuitarLab is a research team that aims to study of expressiveness through a detection model for left hand fingering based on gesture information via Music Computing and Machine Learning approaches. http://www.iiia.csic.es/guitarLab/

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Introduction

This chapter explains the initial thoughts for starting this project along with the background of the author and his motivations. It also explains how the document is organized and what are the topics concerning each section.

1.1 Motivation and Goals.

I graduated from Electronics Engineering in 2006 with a Thesis in Artificial Neural Networks. After graduating I started working as audio technician in ESPN and in my free time I dedicated my self to develop artistic installations where I was involved in hardware design and programing.

I have always liked Music and Technology, and in my country there are no institutions that make research related to this area. The idea of learning something completely new and related to Music and Technology made me decide to come to Barcelona to take part of this Master.

When I started the course, I didn't know all the different paths that you could take in this field, from signal analysis to cognitive processes and several disciplines that are involved in the use of technology for understanding, describing and generating music. By the time we needed to choose a project for the Master Thesis, all the previous thoughts of a project that I could had before were not clear because of all the new knowledge that I was getting from my first classes, but I was sure about one thing, I wanted to do something that could be touched and seen in the physical world.

When I saw the Guitar Lab project (Guaus, Arcos et al. 2010) [1] and [2], for the first time I felt that I wanted to collaborate in this project due to my knowledge in electronics and my fascination with the guitar, even thought I am not a guitarist, It has always been my favorite instrument.

The Idea to learn about modeling movement and gestures of a guitar player was a strong motivation. I wanted to study the guitar and use my knowledge to develop a tool that could be used to describe the different ways the guitar is played, and the different sounds that you can get by performing with different techniques.

The gesture acquisition prototype done by the Guitar Lab, is one of the first models using sensors with the aim to capture left hand guitar gestures. As we will see in the literature review, most of the gestures analysis use motion capture for retrieving gestures, the model of the Guitar Lab was able to categorize certain positions of the fingers and able to detect some articulations or micro-macro-gestures as they refer in [2](e.g. a Bar, Chromatic Notes, Grace Notes).

Guitar Lab members decided this approach, because it is not intrusive to the player, and also because you can eliminate the finger occlusion problem in [6] (Burns and Wanderley ,2006), a detailed explanation appears in section 2.3.2. The actual problem had to do with the noise generated by the crosstalk effect explained in [2].

Goals

Therefore the first goal of this dissertation is to improve the performance of the prototype. It is vital to do a research in sensors, as materials and different fabrication of sensors are improving everyday.
The second goal will be to continue the research of the Guitar Lab in gesture analysis, and be capable of describing with the model more gestures performed by the left hand.

1.2. Outline

This dissertation is divided in 6 chapters, the first chapter introduce the context in which this work has been developed, and the path to follow with the goals established, the second chapter is also introductory, it includes a collection of relevant information related to our topic.
Chapter 3 reviews the prototype of the Guitar Lab explaining its operation and is tested by different guitarists in order to attain our first results. Chapter 4 explains the modification and additions made to the prototype.
Chapter 5 is an analysis of the experimentation with the model, it explains the reason why we decided to do an application with the prototype, instead of continuing the gesture analysis. This chapter ends with the description of the mapping for using our sensors as sound controllers.
Chapter 6 identify the problems and mistakes committed in the evolution of this project and presents the contributions and future work that this dissertation leaves for further projects related to this thesis.

Literature Review

Our concern in this Thesis is to work in a gesture acquisition model for classic guitar, this review will explain the background and previous work in the gesture acquisition for musical instruments, and sensors applied for gesture acquisition and augmented instruments.

2.1 General concepts

The most important concept to make clear in this dissertation is "*the gesture*", in this section the concept of *gesture* will be explained with a musical orientation, in other words, this section is focused on gestures that are generated during a music performance, gestures in music could be analyzed from different disciplines due to the information that can be extracted, in order to acquire this information, sensors are going to be used, therefore the sensors are a central topic in this dissertation.

2.1.1 Gestures and Music

The definition of gesture is something that has not been conveyed, as it is a big research field studied by different communities, therefore it is important to delimit the boundaries of our study and focus on the work related to musical gestures. C.Cadoz and M. Wanderley (2000)[8] expose and analyze the definitions of the term gesture; the definitions are extracted from different literature on human-human, human-computer interaction and musical domain; Some of those definitions will be presented along this section.

Gestures contain intrinsic information that is perceived in different forms, visual information can be gathered just by observing the movements of a musician and the interaction with his instrument; audible information is also perceived, and sometimes has a direct link with what we see, other internal processes occur at the same time, emotions emerge and cognition processes are happening while witnessing a live performance.

One of the most interesting definitions respecting musical gestures [8] is shown below:

" *There is a diversified set of objects spanning the gap between the lowest-level musical intention (cognition, psychology, musicology) and a simple wave form (physics). These objects will be referred to as musical gestures and they should be seen as the features based on which musical intentions will eventually be recovered through some decision-making. ... The gestures that are fed to the instrument are of a physical nature (fingering, pressure, energy, etc.) whereas the gestures resulting from our auditory perception are not. However, both present the ability to communicate musical intentions at a higher level than an audio wave form. The similarity of their level of abstraction motivated the author to label them both as Musical Gestures*."

E. Métois. 1996. "Musical Sound Information – Musical Gesture and Embedding Synthesis." PhD thesis, MIT, 1996.

A common classification of gestures is between empty handed gestures, and the ones that involve a tool or an instrument, François Delande created a categorization of gestures related to musical instruments by studying Glen Gould playing technique:

A) Effective Gestures: The ones that produce sound.

B) Accompanist Gestures: Body movements that accompany the performance (moving the head or a foot).

C) Figurative Gestures: Gestures perceived by the listener without a direct correspondence with the movements of the performer. (Note Articulation, Melodic Variations)

The aims of this dissertation lead us to the study of *Effective Gestures and Figurative Gestures*, Claude Cadoz (1988)[13] propose different types of functions related with the instruments:

A) Ergotic: Energy transfer between the hand and the object.

B) Epistremic: Typically involves our capacity and muscular/articulatory perception.

C) Semiotic: The function of meaning or of communicative intent.

This functions take place in the gestural channel, it receives and transmits information, in the case of the guitar the hands are the gestural channel, on the left hand fingers perform pressure on the strings and the fret board, each string opposes the force applied by the fingertips, this gestures along with the plucking of the string with the right hand produces sound, which gives the meaning of the instrumental gesture.

A definition of instrumental gesture, C.Cadoz, M. Wanderley (2000)[8], resume the functions of the gestural channel in music:

Instrumental gesture is defined as a modality specific to the gestural channel, complementary to empty- handed gestures and characterized as follows:

- *It is applied to a material object and there exists physical interaction with it;*
- *In this physical interaction, specific (physical) phenomena are produced, whose forms and dynamic evolution can be mastered by the subject;*
- *These phenomena may then become the support for communicational messages and/or be the basis for the production of a material action.*

2.1.2 Sensors

Gesture acquisition is a task that requires a device that can measure physical activity and extract valuable data from movement, to be able to do this, sensors and transducers are required. From home made and cheap sensors to very delicate and expensive systems are frequently used for this kind of tasks, it is very important to define the differences between a transducer and a sensor, a transducer is an energy converter, a sensor fits in to the definition of a transducer but a sensor transform different types of physical stimulus in merely electrical responses.

Miranda and Wanderley (2006)[14], suggest a classification of sensors presented as follows:

- Direct Sensors: These sensors convert the energy from an input into electric signals in a straight way, without any intermediate process.
- Complex Sensors: It is composed of a chain of transducers that converts the input into electric signals, the last transducer is a direct sensor.
- Passive Sensors: Generate outputs without external energy force (piezoelectric).
- Active Sensors: Need energy from an external feed to do the transduction.
- Absolute Sensors: Output absolute physical scaling independent of the measurements conditions.
- Relative Sensors: Produce signals that relates to some specific case.

The classification of the sensors is useful in order to know how to operate the sensor and to understand its behavior, but each sensor has its own response parameters, even if the sensor does the same physical transduction, Patrick H. Garret (2000)[15], considers that the parameters that better describe a sensor are the following:

- ⇒ Accuracy: The closeness with which a measurement approaches the true value of a measurand, usually expressed as a percent of full-scale output.
- ⇒ Error: The deviation of a measurement from the true value of a measurand also usually expressed as a percent of full-scale output.
- ⇒ Precision: An expression of a measurement over some span described by the number of significant figures available (a precise sensor provides repeatable significant figures).
- ⇒ Resolution: An expression of the smallest quantity to which a quantity can be determined.
- ⇒ Span: An expression of a measurement between any two limits.
- ⇒ Range: An expression of the total extent of possible measurement values.

In general, commercial sensors available in the market, are designed for industrial and medical applications, when we use the same sensors for musical purposes, it is important to match its characteristics with our own drives. The requirements in the musical domain could be less exigent, and sensors with low performance could be still useful.

Koehly, Wanderley et al. (2006)[9], mention the importance of sensors in scientific experiments, and that sometimes the commercial brands limit studies because of the normalized sizes and shapes of them, "*sometimes it necessary to build your own sensors in order to adapt sensor characteristics to your own experiments and interfaces*", they study conductive inks that are used for force/pressure, bend and position sensors, they explain how video tape could be used as linear touch potentiometer. These researchers mention, that in order to analyze the quality of home made sensors for musical performance, you have to take in to consideration a few parameters: linearity, repeatability, resolution, drift and time-response. They show some results of tests applied to different sensors in a special laboratory in Grenoble to observe the evolution of sensors on different circumstances.

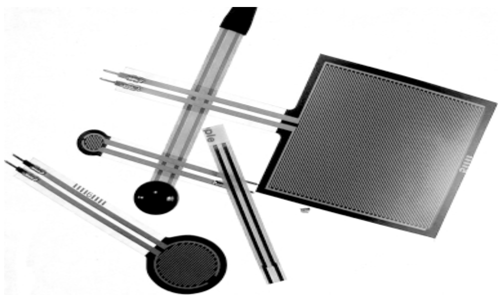
2.1.3 Examples of Sensors

This section will explain some sensors applied in the music field.

Force-Sensitive Resistor

The force-sensitive resistor (FSR) convert mechanical force into electrical resistance. Like any other variable resistor, they generally have two leads. This sensors come in a variety of forms, as shown in Figure 1, but all are generally small and flat.

Figure 1. FSR's variety of shapes and sizes.



FSRs require a firm yet slightly pliable backing to work properly. FSRs are typically designed to sense small amounts of force, such as the force of your finger pressing a button or keypad. The force of your body weight will quickly bring these sensors to their peak reading. This is useful if you only want to use them as a digital input to tell if a person is stepping on them or not (O'Sullivan and Igoe, 2004) [16].

Different retailers and commercialize them(e.g. Digi-Key, Tekscan, Parallax[1]).

Linear Potentiometers

The linear position touch sensor operates according to a similar set of principles as the force-sensitive resistor. It acts as a variable resistor according to the position at which it is touched. A characteristic of the touch sensor is that it only maintains its value for as long as an applied pressure is activating it. When it is inactive, its

[1] FSR's manufacturers and retailers
http://www.digikey.com, http://www.tekscan.com, http://www.parallax.com

resistance value is very high, or infinite. Because of this, the touch position sensor can be used as a kind of valued event trigger. A user might touch it in various places to initiate some process, and at the same instant can provide this process with an initial value depending on the position at which the touch was made.

Figure 2. Soft pots and Thinpots distributed by SpectraSymbol[2]

Strain Gage

A Strain Gage (alternatively: strain gauge) provides an extremely simple and accurate way to measure even slight deformation of a solid surface or object. It is a relatively simple transducer that varies slightly in resistance when compressed or stretched, and can be bonded (using adhesive such as epoxy) to metal, plastic, wood, glass or other solids. The most common gages measure strain only in one direction, but commercial gauges containing more than one sensor on a substrate arranged to measure strain in different axes, are available.

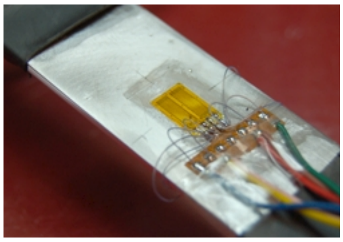


Figure 3. Strain Gage.

IR Sensors and Motion Capture

An infrared sensor is an electronic device that emits and/or detects infrared radiation in order to sense some aspect of its surroundings. Infrared sensors can measure the heat of an object, as well as detect motion. Many of these types of sensors only measure infrared radiation, rather than emitting it, and thus are known as passive infrared (PIR) sensors.

All objects emit some form of thermal radiation, usually in the infrared spectrum. This radiation is invisible to our eyes, but can be detected by an infrared sensor that accepts and interprets it. In a typical infrared sensor like a motion detector, radiation enters the front and reaches the sensor itself at the center of the device. This part may be composed of more than one individual sensor, each of them being made from pyroelectric materials, whether natural or artificial. These are

[2] Different kinds of linear potentiometers are well documented and can be acquired on http://www.spectrasymbol.com

materials that generate an electrical voltage when heated or cooled.

These pyroelectric materials are integrated into a small circuit board. They are wired in such a way so that when the sensor detects an increase in the heat of a small part of its field of view, it will trigger the motion detector's alarm. It is very common for an infrared sensor to be integrated into motion detectors like those used as part of a residential or commercial security system(Hill and Bailey)[17].

2.1.4 Music Instruments and Gestures through Sensors.

Freed(2008)[10], introduces new fiber and malleable materials, including piezo-resistive fabric and conductive heat-shrink tubing, the author show techniques and examples of how they may be used, for rapid prototyping and agile development of musical instrument controllers. Foot-switches with different variants are presented, first, using a FSR with a floor protector for furniture(Figure 3a), then the FSR was replaced by a PCB (Printed Circuit Board) and a patch of piezo-resistive material that changes its resistance according to the compression(Figure 3b), the final variation using the floor protector replaced the PCB with overlapped adhesive copper strips (Figure 3c). Another approach for foot-switches are the Position Sensing Strips or Linear Potentiometers. Freed also mentions the Kalimba controller, as an example of the utility of the sensors reviewed on the paper.

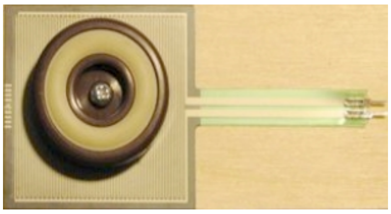


Figure 4a. Round FSR.

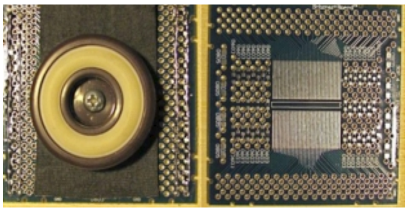


Figure 4b. Fabric and PCB.

Figure 4c. Adhesive copper.

Gauss, Bonada, et al. [3] measured the bow pressing force of a real violin, they used a strain gage that measured the bending on the hairs of the bow, the data was calibrated with a dynamometer in order to map the sensor output in to Newtons.

The same team did another experiment focused on the gestures and movement, this time they used a commercial EMF tracking device[3] [4], with this hardware they were be able to describe the movement of the Bow referenced to the violin position.

Fenza et al. [5], focus their research in the analogies of sound and movement spaces, the motion is recorded by a 3D motion capture system consisting of 6 cameras with IR light strobes, and then it is mapped to a VST in order to have real time interaction between movement and sound.

[3] This is the model of EMF tracking device they used:
http://www.polhemus.com/?page=Motion_Liberty

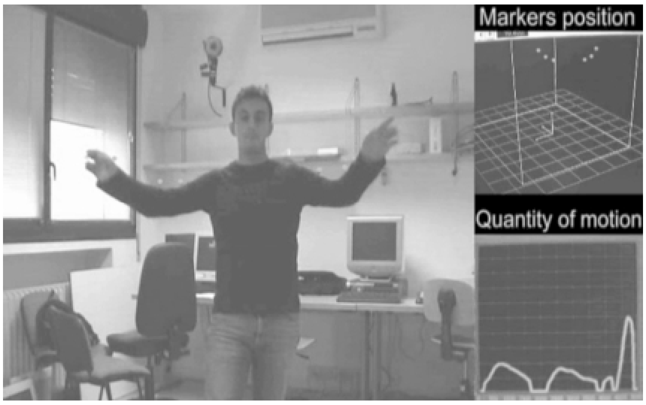


Figure 5. Images from the implemented system. On the left, the subject while testing the system; On the right side, a 3D plot of markers position.

2.2 Gesture Acquisition in Guitar

It was in the middle of the nineteenth century when the classical guitar made major progress towards achieving its potential. Antonio de Torres Jurado considered the father of classical, introduced his model first in Sevilla from 1852-1870 and then from 1871-1893 in Almería, he established the standard of contemporary guitars.

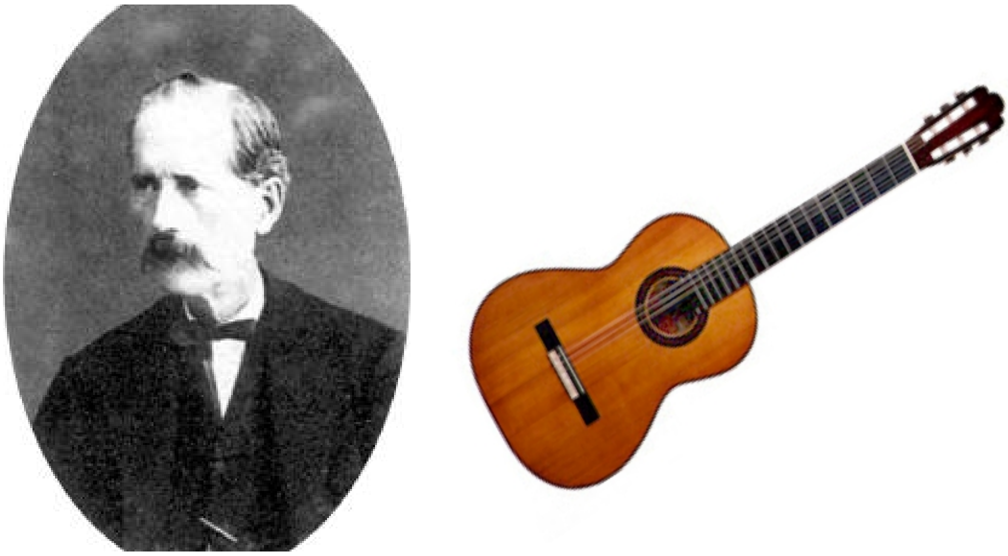


Figure 6. Antonio de Torres and his creation.

Nowadays we have a lot of different guitars, we can classify them in two big categories: Acoustic Guitars and Electric Guitars. Acoustic guitars have different sounds according to their construction; the shape, size, construction material and type of strings determine the resonance that it may produce. On the other side, electric guitars rely their sound on external components more than in construction or shape. As our dissertation is focused on the classical guitar, the study will focus on articulations and gestures that belong to this type of guitar.

2.2.1Principles and Articulations

J.Norton [11], explains that the principles of playing guitar are the same no matter the genres.

- Supporting the instrument
- Left Hand Function
- Right Hand Function

Supporting the Instrument

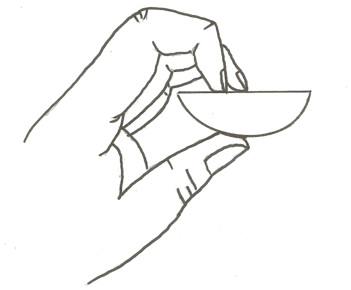
Supporting the instrument has a lot to do with the look of the performer onstage, but Francisco Tárrega, one of the most influents composers and guitarists developed the standardized technique of playing classical guitar.

Figure 7. Francisco Asís Tarrega Eixea

He supports the guitar with the left leg and the chest, his left hand is free to move without carrying the weight of the guitar and his right hand is resting on the body of the guitar.

Left Hand Function

The left hand moves on the fretboard and determines the notes by pressing the strings on the fingerboard. The fingers of the left hand have a specific labeling, the index finger is "1", the middle finger is "2", the ring finger is "3" and the little finger is "4", the thumb could have different notations "p","*"or"+".
The left hand position is shown in Figure 8a, the fingers should be perpendicular to the strings and the thumb aligned with the 2nd finger. The wrist makes a natural angle like the one shown in the Figure 8b; the elbow should be separated from the body, this are suggestions made by Gore in [12].



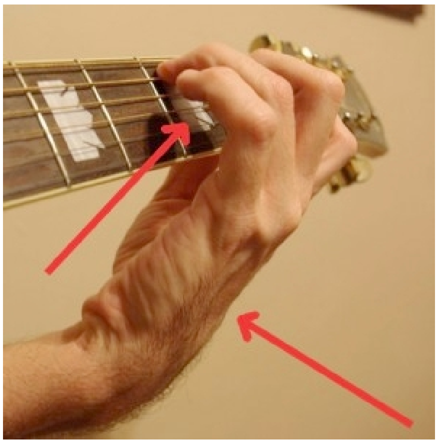


Figure 8a. Fingers Position **Figure 8b**. Angle of the Wrist.

Right Hand Function

The right hand is the one that plucks the strings creating the timbre and notes onsets, the right hand has also its own labeling and it is presented in Figure 9, the letters of each finger come from their name in Spanish, pulgar ="p" indice ="i", medio ="m", anular="a".

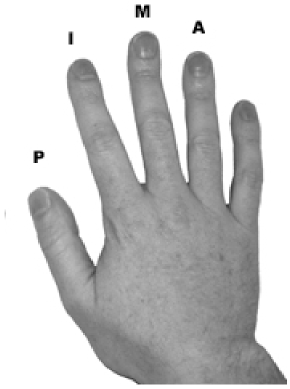


Figure 9. Right Hand Labeling

As this thesis is only focused on the gestures of the left hand, explanation about position and specific functions are not included in this dissertation.

Articulations

The right hand and left hand functions had been categorized by J.Norton [5] as following:

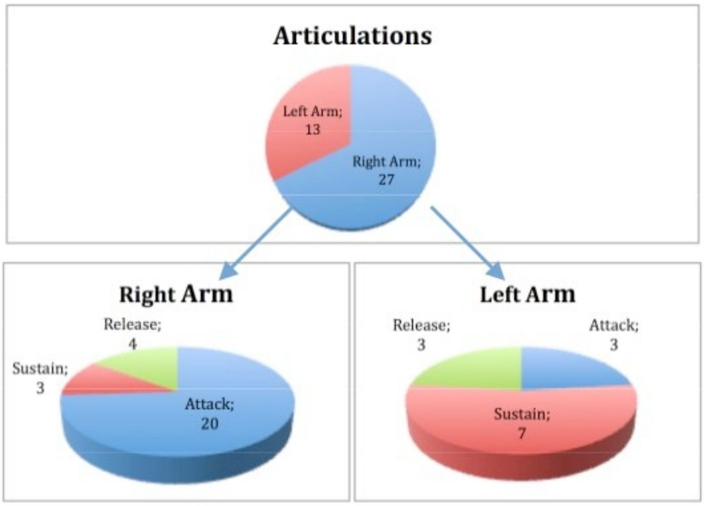


Figure 10. Left Arm and Right Arm Functions.

He defines 3 types of articulations:

Attacks: Articulations involved in originating the sound.
Sustains: Articulations involved in the middle phase of the sound.
Release: Articulations involved in fending the sound.

Including 40 articulations in his classification, most of them are on the Right arm, Figure 11 shows the complete list and Figure 12 indicates the left arm articulations.

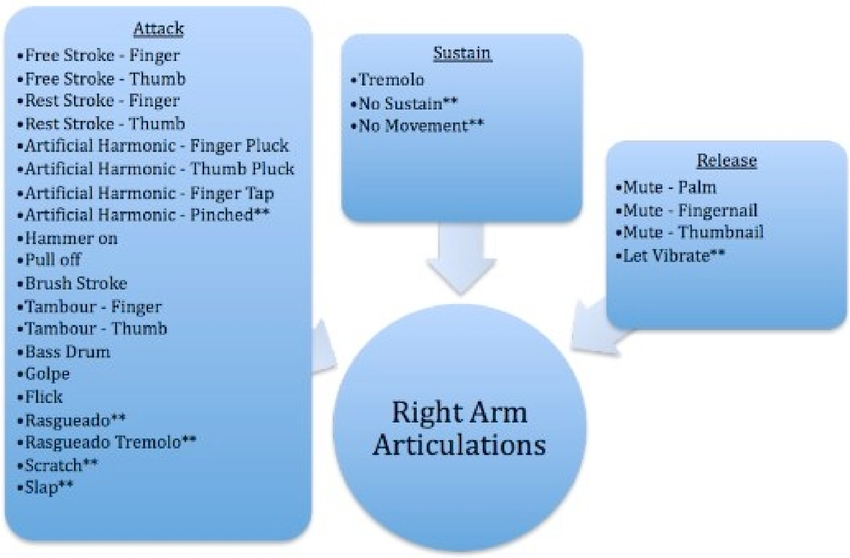


Figure 11. Right Arm Articulations.

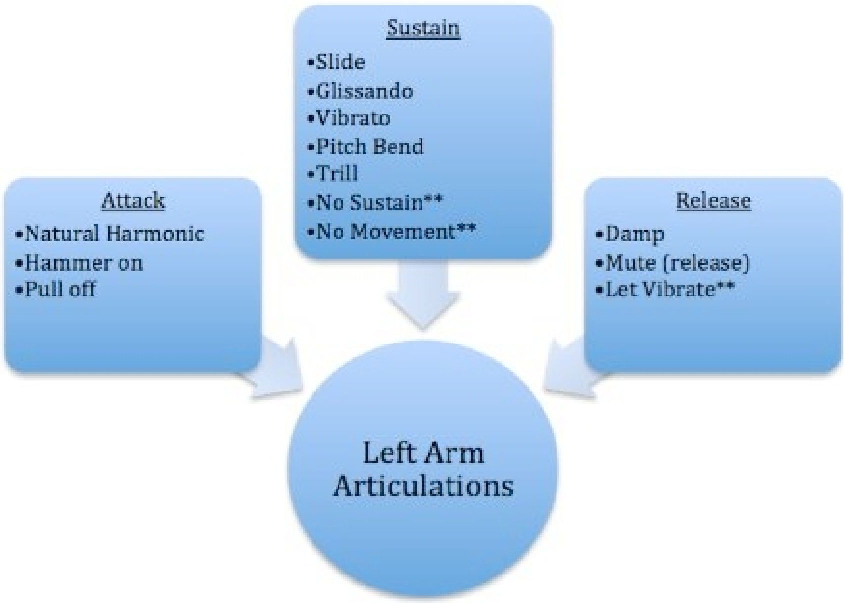


Figure 12. Left Arm and Right Arm Articulations.

Description of the left hand gestures:

Attacks

Natural Harmonic: Fret a note lightly on a node and pluck the string with the right hand and then release.
Hammer on: Firmly hit a fret a note while plucking with the right hand.
Pull off: After fretting a note the same finger plucks the string with an upward motion.

Sustains

Slide: Slide into the start of the note.
Glissando: Slide into a new note without lifting the finger.
Vibrato: Moving the finger back and forth while depressing a string.
Pitch Bend: Push or pull the string without bending during a note.
Trill: A rapid continuous sequence between hammer-ons and pull-offs.

Releases

Damp: Terminating the sound by releasing the pressure on the string.
Mute: Terminating the sound by muting the string.
Let Vibrate: Let the string decay naturally.

2.2.2 Different approaches of gesture analysis in guitar

Burns and Wanderley, 2006[6], use a visual system with low-cost cameras that is able to recognize fingering gestures of a left-hand guitarist. The system apply fingertip detection using the circular Hough transform algorithm, this algorithm allows detection of linearity in a group of pixels, creating lines; these lines are then grouped by proximity in order to determine the position of the six strings and of the frets. This prototype was able to recognize chords and a series of notes successfully, in the first five frets of the guitar, this disadvantage made the analysis simpler but limited, other problem that they had was the finger occlusion, 2 fingers in a same fret were not detected by the system.

Reboursière, Anderson et al. [7] sustain their research, on how new music technologies would help, to extend the way the guitar is played nowadays, they built an augmented guitar with a particular design, they created a toolbox for augmented guitar performances for PD and MAX/MSP. Our interest in this paper is the Gestural control, they add pressure sensors to the back of an electric guitar, these sensors control parameters of the sound, using the natural movement of the guitarist, although their sensors were more sensitive than necessary, they managed to map the center pressure to the frequency, and the total preassure to Q parameter of a bandpass filter.

Guaus, Arcos et al. [1][2], created a prototype model that extracts the fingering pressing, fret position and the pressure of the fingers on each string, capacitive sensors are used for this aim, the benefit of using this kind of sensors is that they are not intrusive to the player.
One of the problems of the prototype described in [2], is the crosstalk, although the system takes advantage of this effect (for measuring distance between the finger and the fret), undesirable capacitance is extended to non pressed frets on the sides. They could capture 75 different finger combinations for different strings and frets positions, that were sort in 22 different categories, their data showed that there is no difference between changing from one fret to another with the same string combination, they had some troubles in some categorizations because the system was not able to differentiate between categories. For classification they use 1/22=4.54% using by its simplicity the K-nearest neighbors classifier with k=3, the study of this model is very important because this dissertation is a continuation of their job.

Analyzing Guitar Lab model

This chapter shows the functioning of the original model, it explains the hardware and software components that make possible the gesture captioning.

3.1 Understanding the original model

The model built by Guaus, Arcos et al. [1][2], is based on capacitive sensors that are able to detect the presence of a finger either approaching to the fret or pressing the fret, as Badger explains in [18], the capSense library turns two or more microcontroller pins into capacitive readers, which can sense the electrical capacitance of the human body, the capSense method inside the library, toggles a microcontroller send pin to a new state and then waits for the receive pin to change to the same state as the send pin. A variable is incremented inside a while loop to time the receive pin's state change. The method then reports the variable's value, which is in arbitrary units.

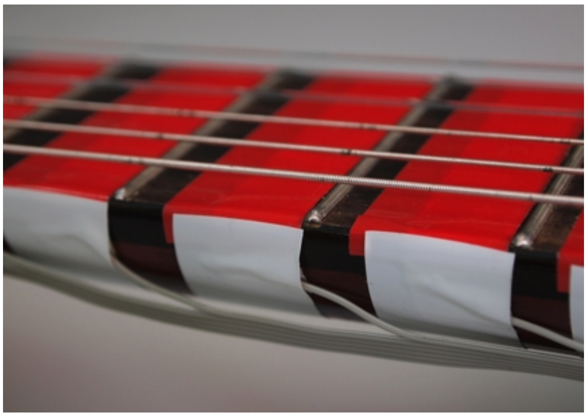


Figure 13. Individual sensors for each fret and its connections

The sensors used in this prototype are home made, foil paper covered with Isolating tape, each sensor foil paper has a wire connection that goes to the microcontroller. The choice of having this sensors had to do with the availability of commercial sensors that could detect either short distance and force, as these sensors were designed for the guitar, the size is not a problem because the design is made so that it fits on each fret.

The hardware to drive the sensors and communicate with a computer was the Arduino Duemilanove microcontroller; this open hardware device, is a tool very commonly used in science, professional and amateur projects and art installations.

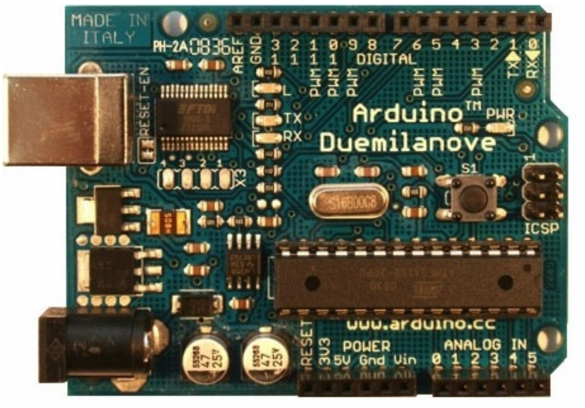


Figure 14. Arduino Duemilanove

The characteristics of the Arduino are shown in the table 1.

Microcontroller	**ATmega168**
Operating Voltage	5V
Input Voltage (recommended)	7-12V
Input Voltage (limits)	6-20V
Digital I/O	Pins14 (of which 6 provide PWM output)
Analog Input Pins	6
DC Current per I/O Pin	40 mA
DC Current for 3.3V Pin	50 mA
Flash Memory	16 KB of which 2 KB used by bootloader
SRAM	1 KB
EEPROM	512 bytes
Clock Speed	16 MHz

Table 1. Characteristics of the Arduino

The program made in the Arduino's IDE[4] uses the C++ library CapSense [18] and the data received by the sensors is allocated in a pitch bend format, the idea of using pitch bend format is due to the resolution that it can give, the pitch bend message includes two data bytes to specify the pitch bend value.

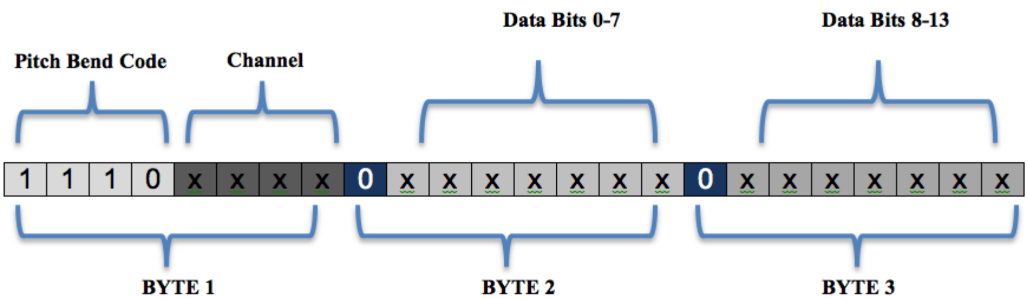


Figure 15. Pitch Bend Bytes Distribution

[4]IDE or Integrated Development Environment, is a software application that provides comprehensive facilities to computer programmers for software development.

With the help of the FTDI[5] chip, the Arduino uses the usb port as a virtual serial port and through it, Arduino's IDE is capable to send and receive data in different formats. To communicate the Arduino's IDE with any audio software , Serial to Midi Converter[6] was used, it is a software that creates a virtual midi port, and allows you to send and receive data through serial protocol.

Graphics in figure 16 show two tests of the prototype capturing single fingering Bars and a Chromatic scale, this examples were taken from [2].

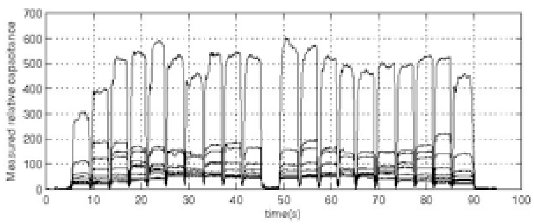


Figure 16a. Finger Bars.

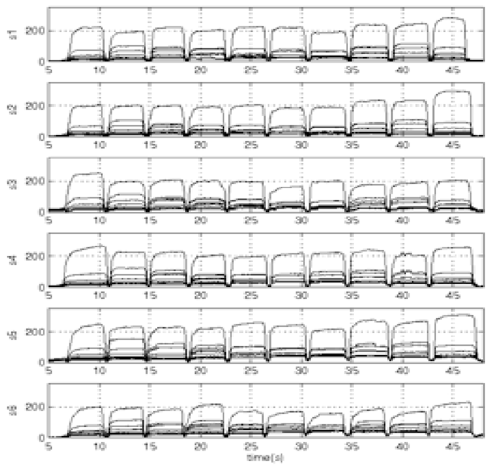


Figure 16b. Chromatic Scales.

In Figure 16a, all strings are pressed by a finger, starting at the first fret; then, ascending fret by fret until the 10th fret; next a pause of a beat; and finally, going down to the first fret. The change of fret occurs every 4 beats at 60[bpm] and in Figure 16b, It has been performed a chromatic scales, one for each string, starting with the open string and playing an ascending scale until the 10th. fret. The change of fret occurs every 4 beats at 60[bpm].

[5]Future Technology Devices International (FTDI) is a semiconductor device company. It develops, manufactures, and supports devices and their related software drivers for converting RS-232 or TTL serial transmissions to USB signals. http://www.ftdichip.com/

[6] Serial to Midi Converter is a free software that is explained and can be downloaded in the following link: http://www.spikenzielabs.com/SpikenzieLabs/Serial_MIDI.html

3.2 Recordings and preliminary results

A recording with the original model was made at ESMUC, the recording was made with the purpose of compare how different persons perform the same score and obtain valuable data from the sensors to be able to correlate the sound with the gestures.
The music pieces were *Corcovado* by Antonio Carlos Jobim and *Cello Suite no. 1 (i-Prelude) by* Johann Sebastian Bach, there were three guitar players.

Benjamin Abad   John O'Connell   Stelios Togias

Figure 17. Photographs of each player.

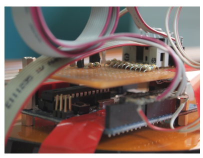
3.2.1.Recording Utilities

Audio Recording

- Vocal and Instrument microphone AKG P3S[7]

- Computer Audio Interface: Tascam US-122[8], this was the bridge between the microphone and the software used for the recording. (Logic Express 9)

Data Acquisition



- Capacitive sensors and Arduino microcontroller.
- Software: Serial-Midi Converter and Logic Express.

Serial Midi-Converter sent the pitch-bend midi format through USB-Serial protocol, Logic Express can read pitch-bend midi, so two tracks were recorded into Logic, one with the Audio and the other with the sensor info in pitch-bend midi format.

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[7] Specs of the microphone:
http://www.akg.com/site/products/powerslave,id,1157,pid,1157,nodeid,2, language,EN.html
[8] Specs of the Audio Interface:
http://tascam.com/product/us-122/specifications/

3.2.2. Recording analysis

The analysis was done offline, using Matlab and some Midi Scripts[9], the values obtained from the sensor vary from 0-16384, in this case we are measuring the variation of capacitance, using the pitch-bend resolution, the units of the measurement will be labeled as relative capacitance units (rcu), the same way that is done in [1]and[2].

The first guitarist, Benjamin, recorded Corcovado in three different ways, Melody, Chords and Melody and Chords together.

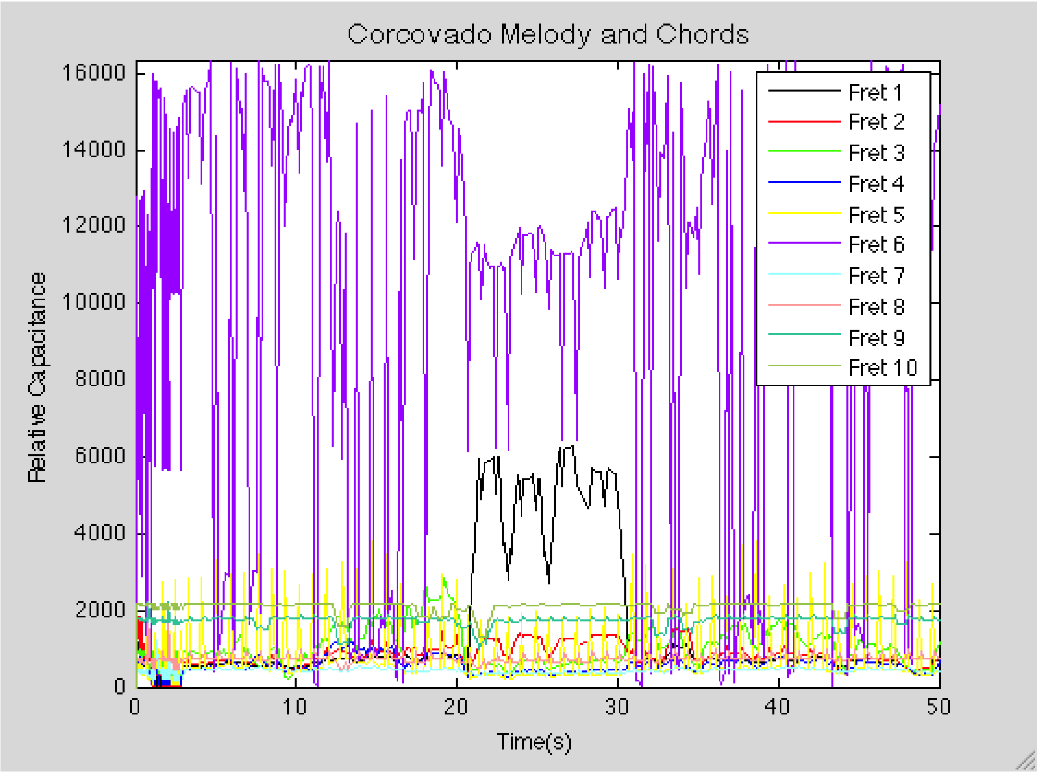


Figure 18. Relative Capacitance values in a sample of 50 seconds, each fret is a midi-channel with pitch-bend format.

Figure 18, shows the capacitance values obtained from the sensors, while Benjamin Abad was playing Corcovado, as we can see there is an out standing midi channel (fret 6), this fret was discarded for the analysis, its values are completely different from the range of values obtained by the other sensors.

In Figure 19 we have more or less the same patterns, the fret 6 out stands and the other channels remain in lower values. If we try to make a relationship between what is played and what is shown by the plots of the sensors, it is necessary to check notes played on the guitar, with the purpose of reviewing the capacity values on the frets that are active during the score.

9 The midi Scripts where these analysis are based can be found at http://www.kenschutte.com/midi - Notes it includes basic midi functions.

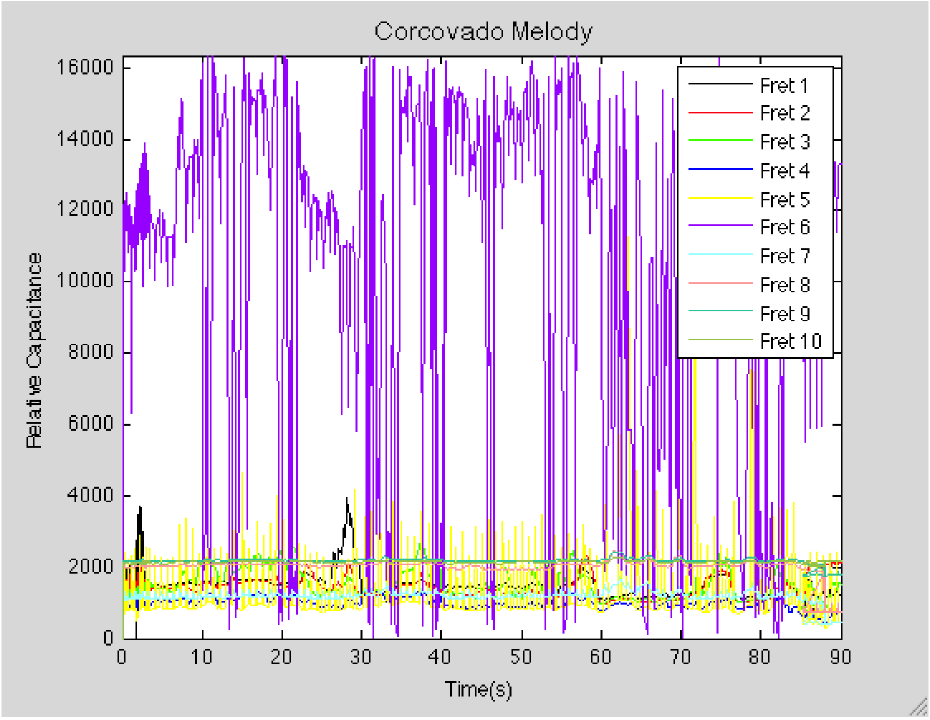


Figure 19. Corcovado's Melody sample of 90 seconds.

The chords played in Corcovado are shown in the figure 20. This figure shows the first phrases of the introduction of the song, and with the help of this figure we know which frets are pressed and which fingers are pressing the fret.

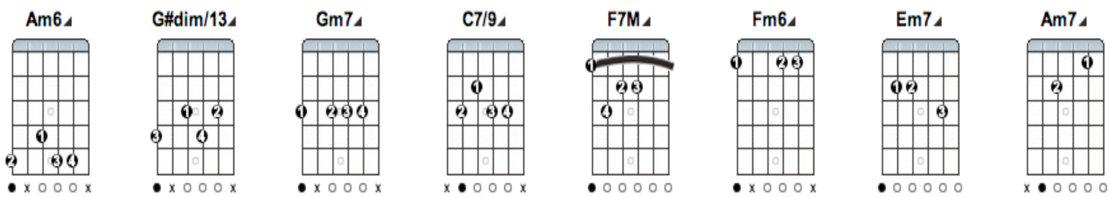


Figure 20. Chords played in Corcovado

The next task was to find each of the chords in the plots made by MATLAB, according to the introducing chords, Am6 should manifest the activation of frets 4 and 5, if we see the plot in figure 21, the plot of fret 4 in the first 5 seconds is bellow frets 8,9 and 10 which are not activated, fret 5 is having a weird behavior, it seems that is activated periodically as you can see in the yellow peak hence it does not represent the behavior of the sensors along the score.

If we move to the 3rd chord that represents a Bar in fret 3, It should have a higher capacitance than all of the other frets, this articulation was captured, if we see the plot of fret 3, it increases its value from the second 10 till the 15, and this is the time where this chord was played, the data displayed by the sensors is not consistent, fret 5 and 6 were not working properly and the others sensors seem to be imprecise in the measurements.

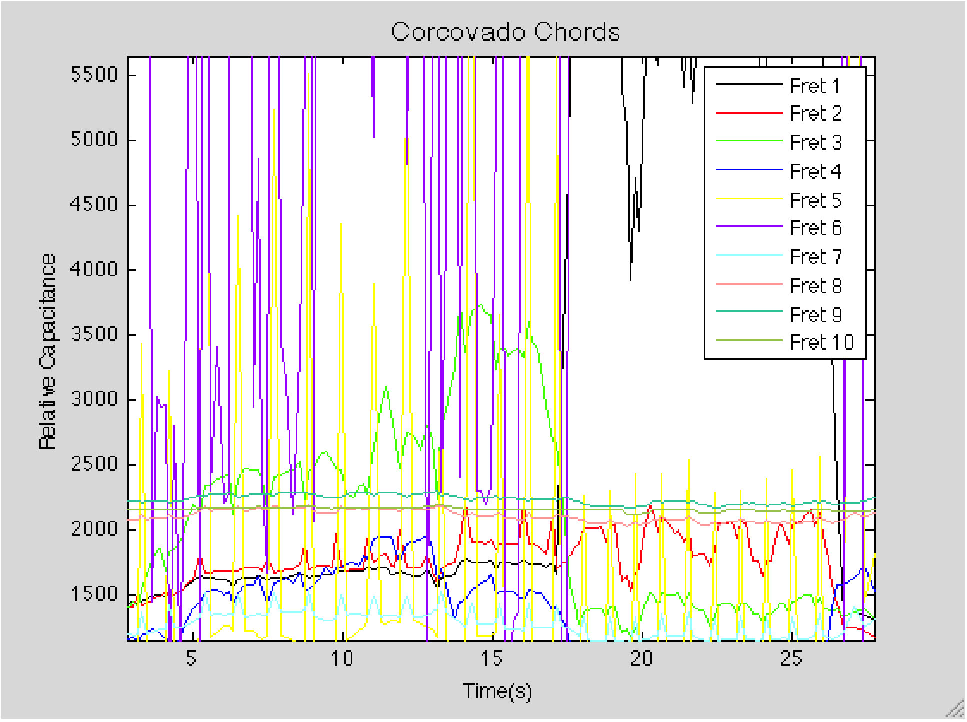


Figure 21. Plot of the fret values in Corcovado Chords

The next recording was *Cello Suite no. 1 (i-Prelude) by* Johann Sebastian Bach, here the objective was to compare different players performing the same song, with the previous analysis we can infer that the values obtained from this recording will not be reliable, figure 22 represent the behavior of the sensors in Johns and Stelios performance which seem to be very similar.

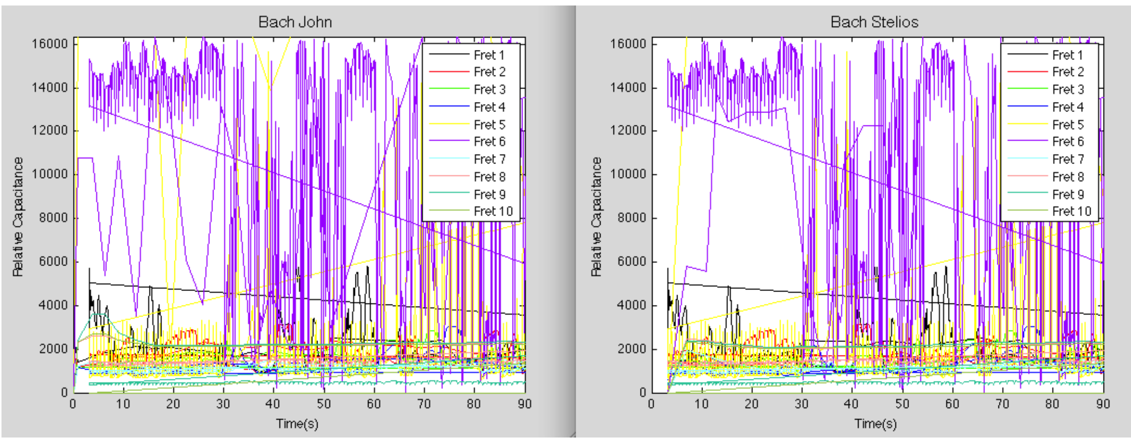


Figure 22. Bach performed by John and Stelios

In order to continue and improve the prototype some changes were needed, the prototype was built in the beginnings of 2010, by the time we were doing this recordings it has passed more than a year, it was necessary to renew the components and these results made it evident.

Renewing the Acquisition Model

According to the previous results in the data Acquisition, there was a lot of noise induced by some channels, improvements were made to the model with the intention of get better results with less noise induced by the uncovered cable terminals.
The analysis made on the recordings was offline, so it was difficult to observe what was happening in real-time, as the Midi Monitor[10] displayed the values as a stream, and it is not easy to monitor the activity of all the frets and compare them, so a software interface needed to be implemented in order to support real time data.

4.1 Implementation and New Features

New connections were made from the Arduino to the shield that connects to the guitar.

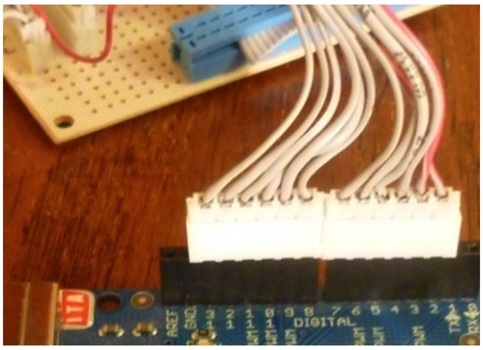


Figure 23. New Connectors to avoid contact between Cables

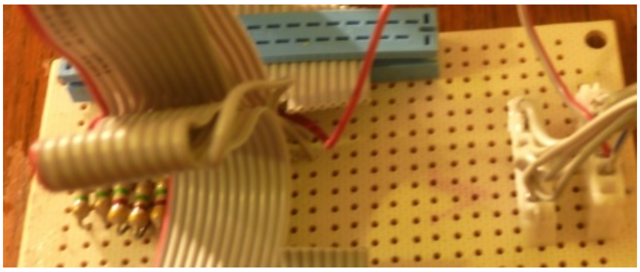


Figure 24. New Connectors and Shield from Arduino to the Guitar.

The old connections produced malfunction, as the cables were very close they generate noise between neighboring frets, the new connections are very well Isolated and also are easy to connect and disconnect from the Arduino Board.

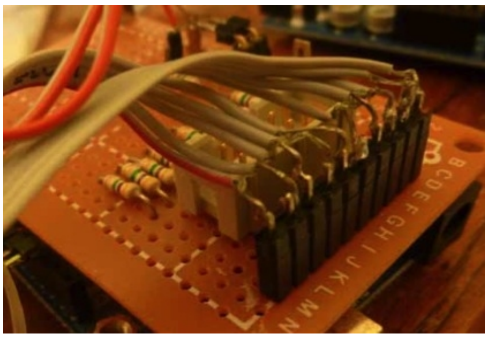


Figure 25. Old Connections from the Guitar to the Resistors.

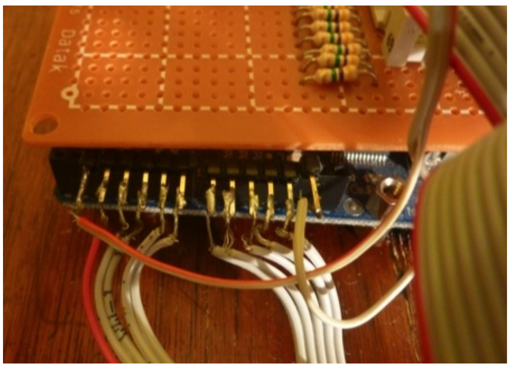


Figure 26. Resistor to Arduino old Connections.

[10] The midi monitor is a tool very convenient for detecting incoming midi messages. http://www.snoize.com/MIDIMonitor/

The fret board was built with the same architecture and materials than the previous: home made sensors, with foil paper acting as a capacitive sensor, the sensor connections were done by adhesive isolating tape, because of the difficulty of soldering aluminium foil, the setup includes a 4.6 megohm resistor between the send pin (pin2 of Arduino duemilaenove) and the receive (sensor) pins (3 to 13 in Arduino). The next diagram in figure 27 shows the connections, where the capacitors represent the sensors mounted on the guitar for each fret.

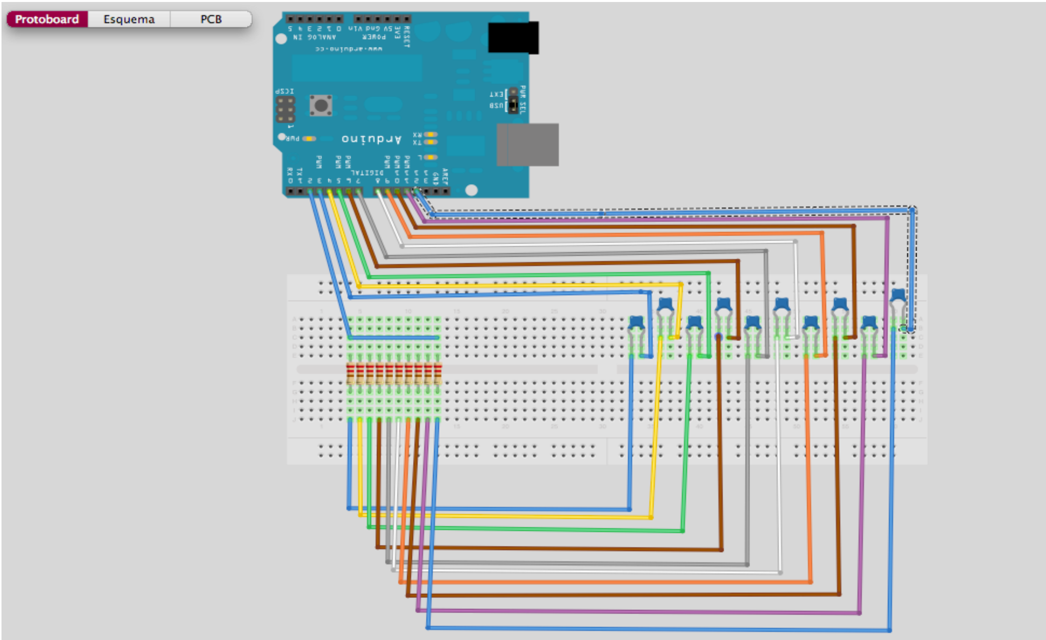


Figure 27. Connection scheme

Another sensor was added to the prototype in order to detect the position of the thumb in the back of the guitar, New Thin Pot sensor spectrasymbol[11] was installed in the back of the neck of the guitar (see figure 29), the capacitive sensors were replaced by new ones(figure28).

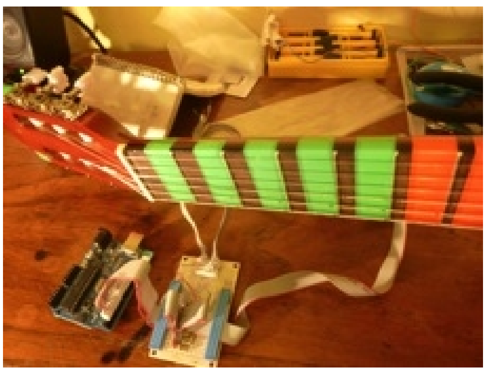


Figure 28 New Capacitive Sensors.

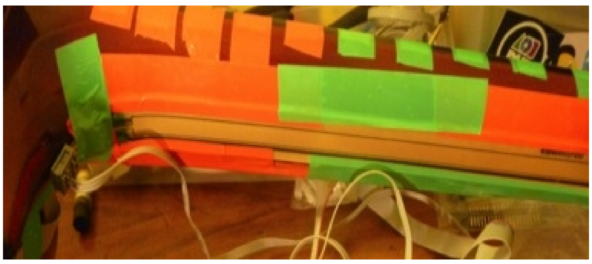


Figure 29. FSR implemented on the back of the neck.

[11] All the specs and data sheet about the sensor is documented in this webpage http://www.spectrasymbol.com/thinpot

The sensor was connected to the first analog pin (pin 0 analog) in the Arduino.
All the values were mapped as midi pitch-bend bytes and were streamed to MAX/MSP via Serial 2 Midi.

4.2 Mapping

The first choice to map the values coming from the prototype was Pure Data, because its capability to work with real time data, and all the support that it has for sound, also it gives the possibility to develop a graphical interface.
PD has an object called [bendin] that read pitch bend midi format, the values obtained were mapped directly to GEM[12] .

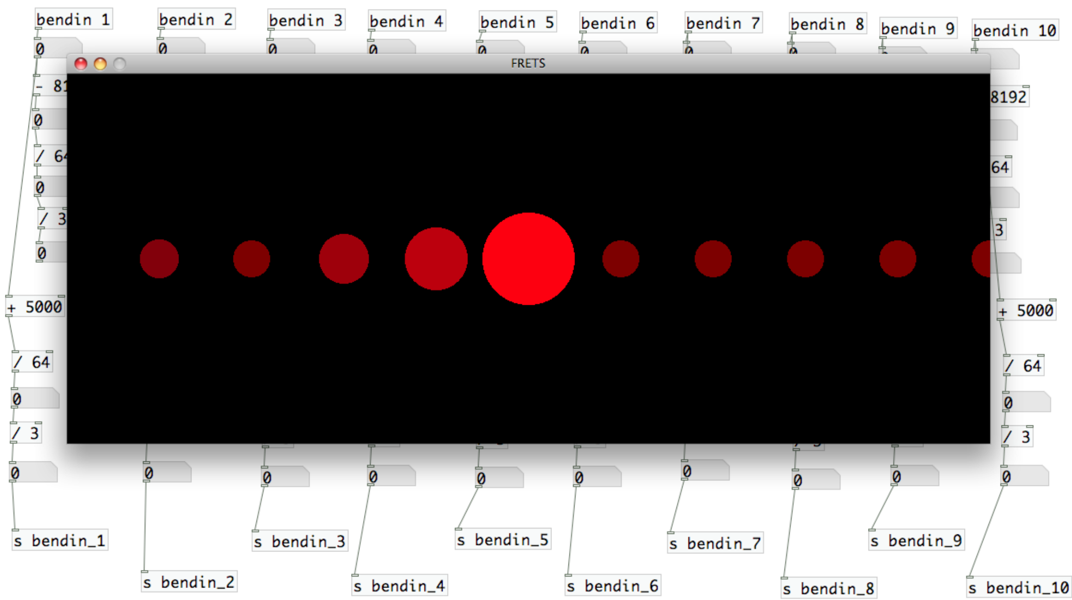


Figure 30. First Mapping with PD.

The Patch allowed us to visualize activity coming from the frets, each circle represented one fret and it grew according to the pressure applied.

After doing some tests with similar objects in MAX/MSP, the guitar interface was moved to Max, the decision was made mainly because of the friendlier environment that Max offers, providing a broad documentation of each object and a lot of basic tutorials that allows to understand and learn quickly how to program.
In Max there are two objects that can read pitch-bend data [bendin] and [x bendin], the object [x bendin] was selected because it preserves the resolution of the pitch bend byte (2^14 bits).

The visual interface is very simple, it has only 3 variables that need to be configured to calibrate the system, the first one is the value of the "Gate Threshold to avoid Noise", this parameter has to be adjusted with the intention of eliminating the capacitance values captured due to the prototype environment conditions,

[12] GEM stands for Graphical Environment for Multimedia, and it is an External Plug In of Pure Data that allows you to create graphical interfaces. http://gem.iem.at/

this sets the floor to any incoming gesture capturing in the visualizer, when this value is in "0", trivial activation can be detected, according to the conditions the value must be incremented to set a floor for visualizing only relevant data. The second is the midi input selection that allows us to read midi streams from different sources, and finally,the toggle for turning on or off audio;in the first steps of the visualizer, the amount of pressure was sonified with the purpose to have audible feedback.
The Figure 30, shows the visualizer and the configurable options mentioned above, the visualization is very abstract but it displays the changes on the frets in real time and that was the goal of doing it. The first row are single green vertical slider objects from Max that show instantaneous activity, while the orange vertical multi-sliders represent the changes of activity over the fret along the time. The visualizer displays a Bar articulation applied on fret 1, the values of the capacitance are not showed on the visualization because the number analysis is meant to be offline and the visualizer is just meant to be a reference for performer.
The long Horizontal slider at the bottom of the window is a slider that moves according to the position of the thumb finger; the FSR on the back of the neck of the guitar is 40 cm long but it was segmented to only 30 cm long so the divisions that you can see on the horizontal slider represents 1 cm each one.

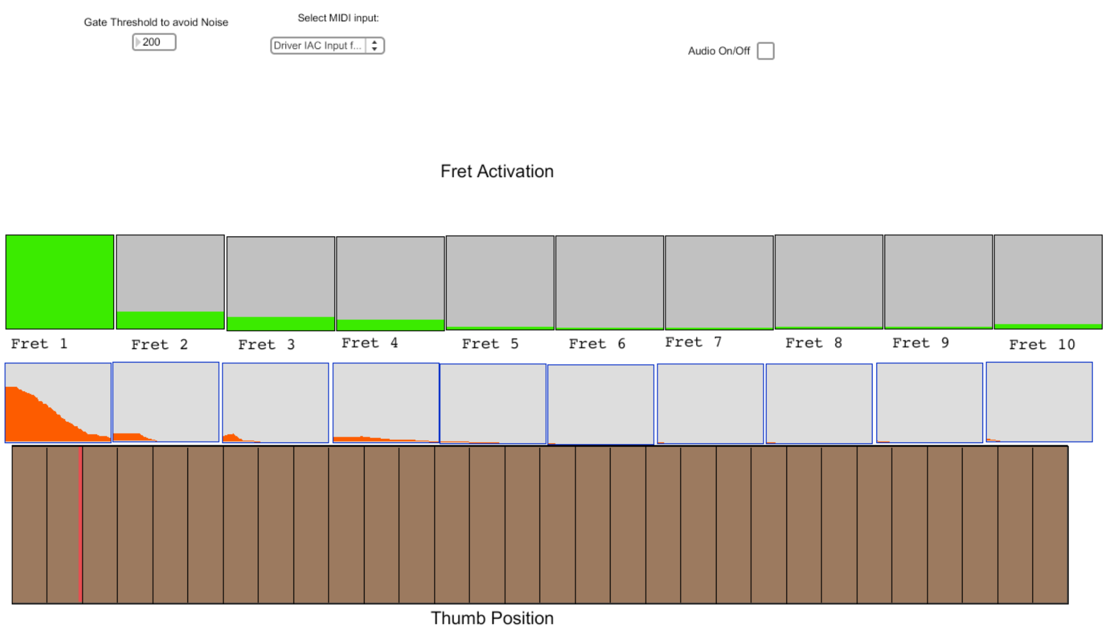


Figure 31. A Bar articulation on Fret 1 with the thumb 2 cm away from the nut.

The figure 31 shows significant but undesirable activity in neighboring frets (fret 2,3,4) in this case this frets were not pressed, the analysis of this phenomena will be shown in the next section.

With the modeled renewed and a new interface, the first tests are provided in this chapter, the evaluation of the model threw unexpected results, and they made us rethink about our initial goals.

5.2 Evaluation of the model

The model was analyzed according to some of the evaluations done by the Guitar Lab in [2], to start the evaluation of the model let's look at the Table 2, it shows the percentage of undesirable capacitance induced in neighboring frets.

Art	**Measured**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Bars	fret +1	11.3%	55%	54%	6.4%	12%	15%	14.8%	19.5%
Bars	fret -1	8.3%	60%	42%	7%	13.5%	15.2%	12.8%	16.9%
s6	fret +1	44.5%	58%	13.7%	32.9%	38.1%	14%	50.5%	14.9%
s6	fret -1	62%	19%	21.8%	51.7%	50.5%	79%	35.8%	17%
s1	fret +1	46.60%	33.3%	23%	44.7%	15.8%	61%	50%	30.1%
s1	fret -1	27.6%	38%	16%	44.7%	19.5%	43%	55%	15.9%

Table 2. Percentages of relative capacitance measured from fret 2 to 9 while preforming a bar and a single finger string pressing.

On the first columns we can see the articulation performed (all the Bar articulations were performed with the index finger, and the single finger string pressing s1 and s6 were done with the medium finger), the percentages measured are the value of the capacitance induced to the previous and forthcoming frets in the bar articulations.

Art	**Measured**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Bars	fret +1	48.0%	35.9%	31.1%	29.2%	27.7%	31.6%	32.9%	30.6%
Bars	fret -1	31.9%	28.9%	27.9%	27.3%	30.3%	28.9%	28.3%	34.3%
s6	fret +1	60.5%	53.1%	53.1%	51.9%	54.8%	51.8%	59.6%	51.2%
s6	fret -1	39.2%	46.3%	43.2%	46.9%	47.3%	43.5%	46.6%	56.7%
s1	fret +1	52.0%	42.0%	41.6%	36.9%	30.0%	36.3%	39.5%	36.6%
s1	fret -1	36.4%	37.4%	38.9%	37.2%	34.8%	34.1%	37.0%	46.9%

Table 3. Guitar Lab Noise Measures

Comparing table 2 and table 3, both have very high percentages of undesirable capacitance, both have lower percentages on the Bar articulations than in s6 and s1, in table 2 the percentages are more variable but lower in quantity in most of the cases, particularly in the Bar articulations. In order to understand better the data on the tables and make a deeper analysis on the output from the sensors lets take a look at Table 4.

Articulation	Fret 1	Fret 2	Fret 3	Fret 4	Fret 5
Bar	1354	**9966**	973	579	398
s6	1583	**5721**	**2667**	682	394
s1	1332	**2131**	950	659	452

Table 4. Each row of data represents one sample of the values from fret 1 to fret 5, obtained while performing 3 different articulations in fret 2.

Table 4 shows 3 events in fret 2, a Bar and the values measured in relative capacitance units, a finger pressing on string 6 and finally a finger pressing on string 1, all of the 3 events present values of contiguous frets in the same measure, the prototype is able to detect each of the 3 events, as it is seen on the column of fret 2.

Let's take a look at the blue fonts, the event of pressing the string 6 and string 1 should throw very similar values, and there is more than a 50% difference between them. The explanation for this is that when you press a s1, your finger has just the tip over the fret, and when you press s6 not only the tip is over the fret, the whole finger is covering the area unless it is not touching the board. This proximity effect creates a considerable difference in the values.

If we look at the yellow cells we can see that the noise induced in fret 3 has a higher value than the detection of pressing s1 in fret 2, the noise induced could create a misunderstanding of events in an eventual classification algorithm. Repeatability[13] tests shown that, the variation of measurements have the same behavior as the percentages of noise induced in Table 2, both are very unstable.

In section 3.1, the figure 16a shows an ascending and descending Bar articulation in the 10 frets, a similar analysis was made with the renewed prototype to continue the evaluations.

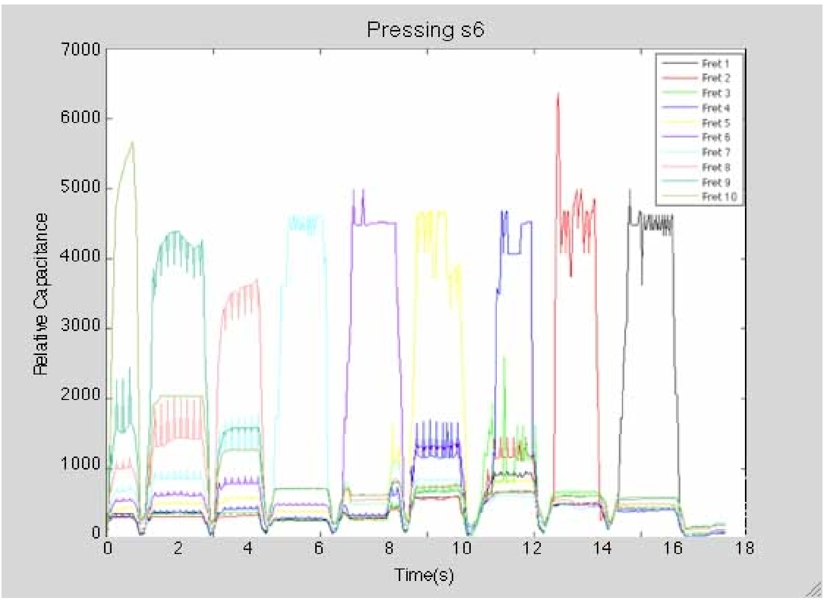


Figure 32. Descending fret positions pressing the sixth string.

13 Repeatability: The closeness of short-term successive results obtained using the same method and conditions.

In figure 32 the plot displays the values of relative capacitance obtained while pressing string 6 from fret 10 to 1, it is evident which frets are pressed, in this case the prototype has a very good performance showing accuracy in determining which fret has more activity.

From this analysis, we can conclude that the persistence of noise, is a big obstacle for any further gesture analysis. The system does not provide a good response in terms of repeatability and reproducibility[14] ,and these aspects represent a big issue, they will not allow to make an automatic detection or differentiation between very simple gestures like a Bar and single string pressing.
Even though the sensors perform with reliable accuracy, as they can determine which is the fret with the more activity, the weakness appears when it is about precision, the measurements always be different due to the noise and variability of the system.

Back Neck sensor

It detects precisely the position of the thumb, the range of the values go from 0 to 30 cm, as that is the length of the fretboard from the nut till the beginning of the body. Figure 33 shows an example of the position of the finger while pressing the string 6 in the sixth fret, in this case the sensor was very accurate and precise in determining the thumb position but when quick moves were done by the finger, the transitions of the slider weren't very smooth.

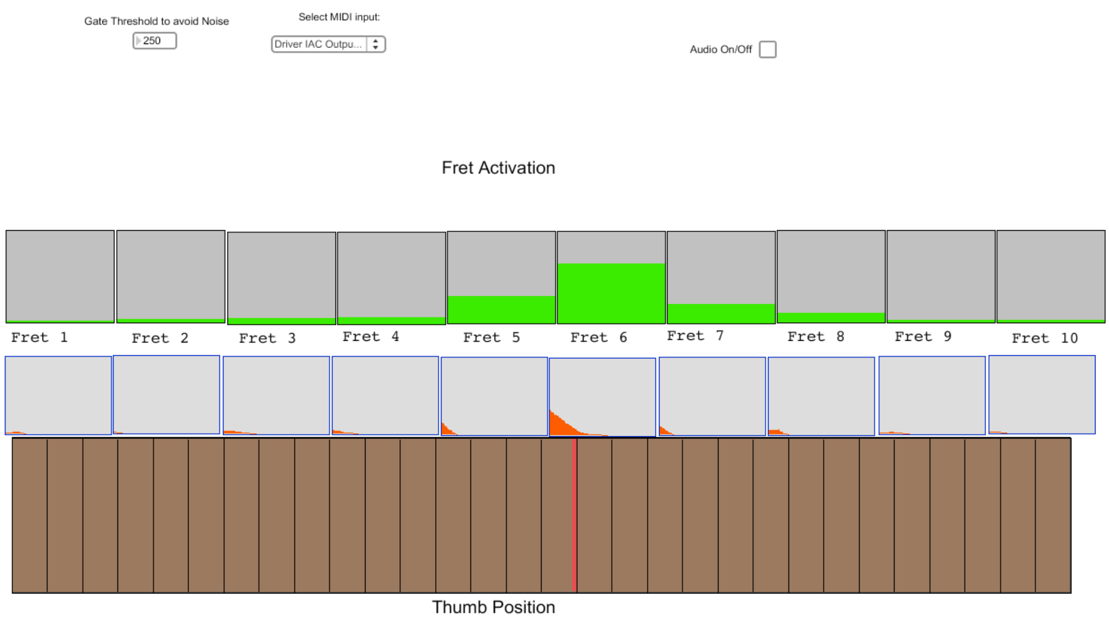


Figure 33. Pressing the string 6 on fret 6.

Another problem with this sensor, is that sometimes the guitar player does not press the sensor due to its own technique of playing , even tough the classic guitar style suggests a parallel position with the second finger, in our tests this was not always happening. A wider sensor or using two sensors could solve this problem.

[14] Reproducibility: Similar to repeatability but for long-term measurements by different people and under different conditions.

After the changes made to the prototype, we can say that the improvements made to the model, and its performance have not been outstanding and it has problems inherited from the original prototype.

The comparison made in this section, shows that these home made capacitive sensors, should not be used with the aim of capturing gestures, not only because of the imprecision, but because of the fragility (tape has to be replaced due to bad contact).

The research made by Guitar Lab, capturing certain left hand gestures [2] and doing an automatic categorization of fingering position [1], is a great job thinking about the limitations denoted, but it is clear that the system could not go further, a lot of errors came, when trying to identify a Bar articulation and a single finger string pressing in real time, also fast movements are not well captured by the guitar due to the low sampling rate, and the biggest problem is that we cannot distinguish which string is played.

5.2 Re-orientation and applications

The initial aims of this thesis, were to contribute to the Guitar Lab project, by complementing the model for gesture acquisition in classic guitar, add some improvements and continue with experiments to retrieve information from guitar left hand gestures.

In this point of the dissertation, the goals of this theses were not able to be fullfilled and a new out come emerged from this results. Thinking about one of the desires of Guitar Lab of using the model for artistic purposes, and considering all the research about gestures and gestural controllers done in the Literature review, we decided to walk a different path, and forget about the possible problems that a model like ours could represent to scientific purposes, therefore we study the possibilities of creating a new musical interface or an extended instrument with the model created.

The model showed accuracy in detecting the fret with the higher activity with a high resolution, if we could manage to improve the repeatability, reproducibility and Dynamic error[15], applications could be found.

Therefore the most important thing will be the mapping of the values thrown by the sensors, lowering the resolution will reduce the dynamic error and we could add an offset creating a higher floor for the sensitivity of the sensors, with a shorter range the accuracy of detecting the higher pressure in a fret is not compromised, as the sensors have low repeatability a dynamic threshold could be set according to the maximum value obtained.

[15] Dynamic error: the difference between the measurement and the measurand when the static errors are zero.

A patch from the mapping is shown in figure 34. It has 10 inputs and 2 outputs, the inputs are each of the frets and the first output is the fret number with the maximum value and the second output is the value of the sensor.

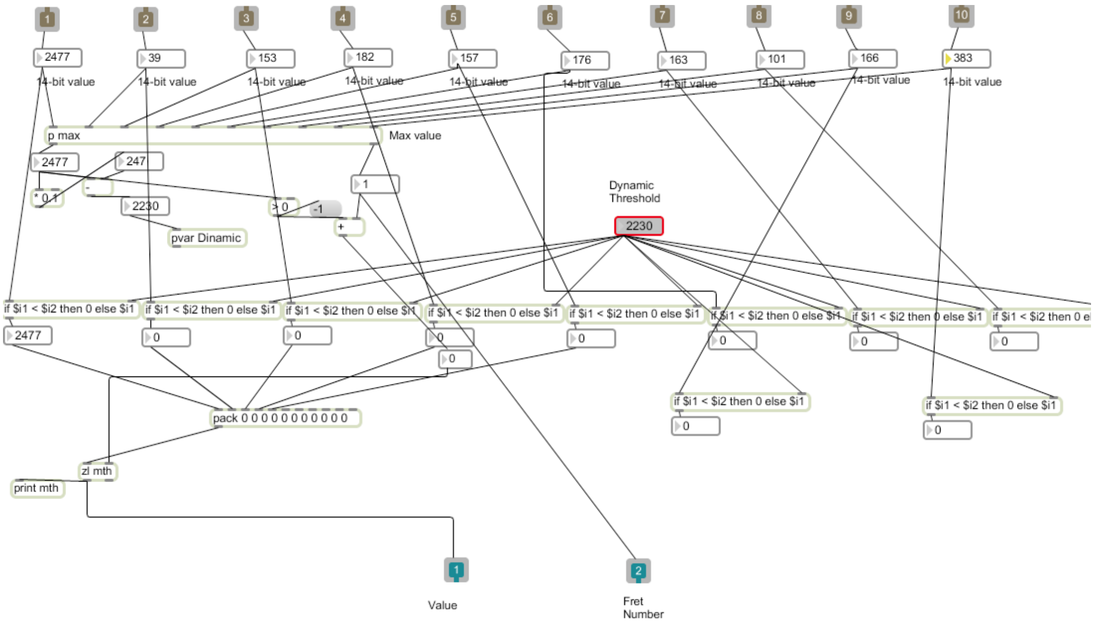


Figure 34.Mapping for choosing the fret with the maximum value.

Consequently the first test with sound was made, a single tone at 440 Hz was directly controlled by the values of the sensor in fret 1, the frequency was incrementing according to the pressure on the fret, each fret had a tone two octaves above the latter.
The Max patch was sonifying only the fret which had the maximum sensor value, this first application was tested by two guitarists, and it worked properly, but the sound was very unpleasant, so the next step was to work in a better sound that could be generated with this hybrid instrument.

Max/Msp allows you to create almost every sound that you can imagine, so the decision was difficult, first of all we decided to work with a guitarist, Javier Hernando. He has been playing guitar for more than 10 years in several bands of Death Metal.
The idea that we conceived together is that the instrument must be configurable in order to have different sounds as presets hence it could adapt to different musical pieces.

The patch for the sound generation is presented in figure 35, it has 3 inputs and a stereo audio output, the inputs are the fret value, fret number and audio control for turning it on or off, the first 5 frets are mapped into oscillators with different effects, figure 35a shows and example of the subpatch [p effect1], and the last 5 frets trigger samples of music pieces figure 35b.

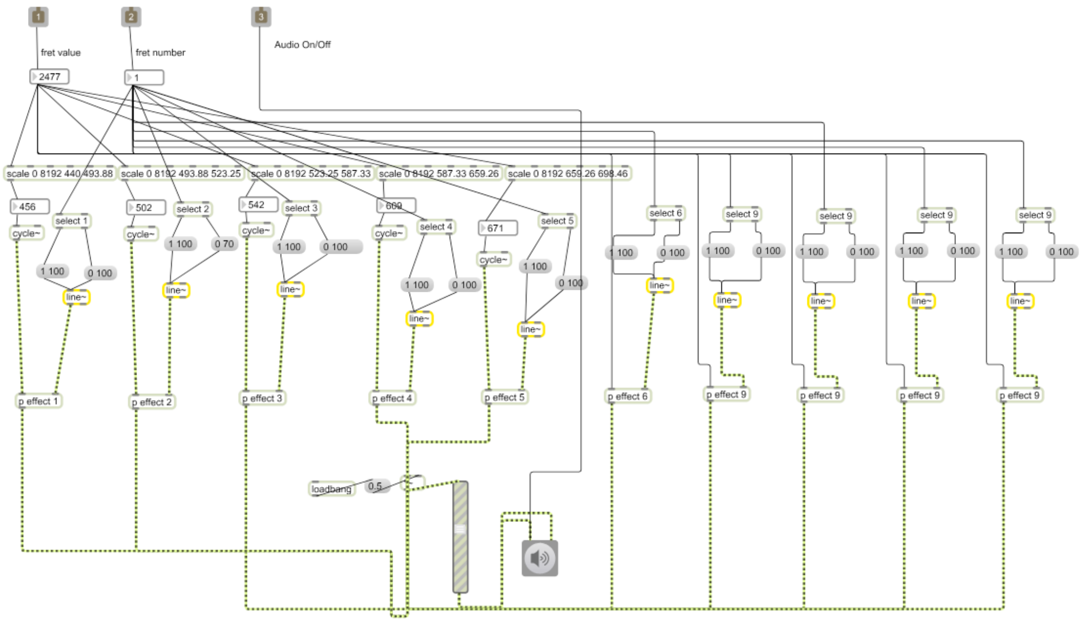
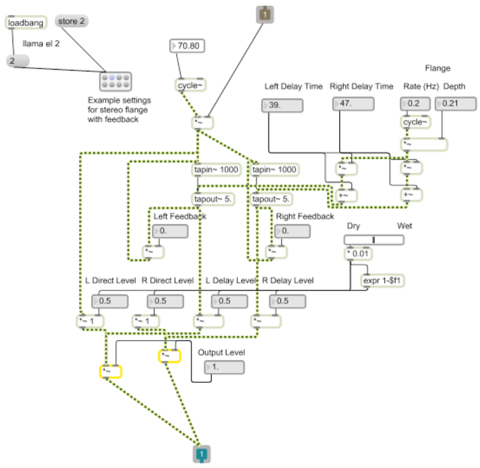


Figure 35.This patch pick the values of the fret and takes them to individual subpatches for independent sonification.



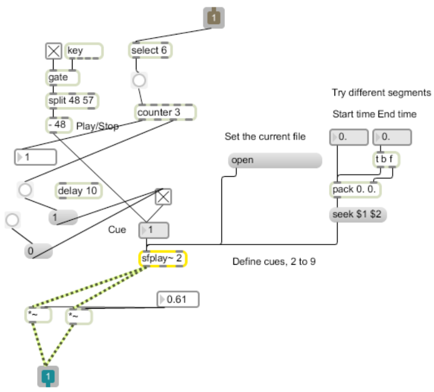


Figure 35a.Flanger effect sub patch [p effect 1]. **Figure 35b**.Subpatch for getting sound samples.

These were the final settings that we did for the sensor sonorization , the next step was to adjust the levels of effects and samples. Once we were satisfied with them, Javier started doing a jamming session, a test recording was done on the 23rd of June and it can be seen in YouTube under the name of Guitar Gesture Controller.

Conclusions

At the outset of this dissertation there were two goals established. The first goal was to improve the prototype for gesture acquisition, we can say that this goal was partly fulfilled, improvements were made to the prototype, the connections of the sensors were optimized, and a complementary sensor was added to the model. The primary problem was the crosstalk, and it was not eliminated, in consequence, the second goal failed completely, with a lot of noise induced and variations on the measurements, the prototype could not be used for further gesture analysis than the ones made by the GuitarLab (Classification of finger positioning and descriptions of Bar, Chromatic Note, Grace Notes and vibrato articulation).

A lot of learning came after doing this thesis there are several aspects that must be denoted in order to achieve a good gesture analysis if the approach is made with sensors:

1.- The sensors must be non-intrusive to the performer, in our case there was no problem, all the guitarists that used the prototype felt comfortable.
2.- The sensors must be direct sensors and ideally absolute sensors, in our case they were direct but not absolute that is why the measures were done in relative capacitance units, ideally measurements should give an absolute physical scale.
3.- If you want to have full description of the gesture, you must cover different approaches in order to analyse them, some examples of our case: Hammer on(Force and position) Bending(Position and string deformation).In this dissertation, the capacitive sensors detected the presence of a finger, even when it was not touching the fret, also the pressure applied on each fret was described by higher values in the sensor output, the problem was that you could not create a value frontier or threshold that could classify or differentiate between pressured or non pressured fret.
4.- An important thing that should be taken in to account is the sample rate, and it will depend on how fast is the score or the gesture to analyse. In our case we could not achieve to analyse gestures or scores with our model, but GuitarLab 's analysis showed in [2] that at 35Hz it was difficult to analyse vibrato, which has rate between 5 and 6 Hz.
5.- This is the last point added to this guideline, and is merely a suggestion, by adding a Motion Capture system you could be able to describe accompanist gestures, a very good result was obtained by Norton in [11] who could achieve to describe not only arm articulation , he also described behaviour of the fingers .

The main legacy of this research is the review of guitar gesture analysis, there is not too much out there where you can grasp ideas or information about capturing guitar gestures with sensors, the main contributions in this field come from Motion Capturing, sensors are every where and constantly adapting and evolving according to the needs of different industries (e.g. biomedical, instrumentation and control, mobile devices), sooner or later there will be enough elements to make a better analysis than the ones presented in this dissertation, and this document will be valuable for people interested in this subject.

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