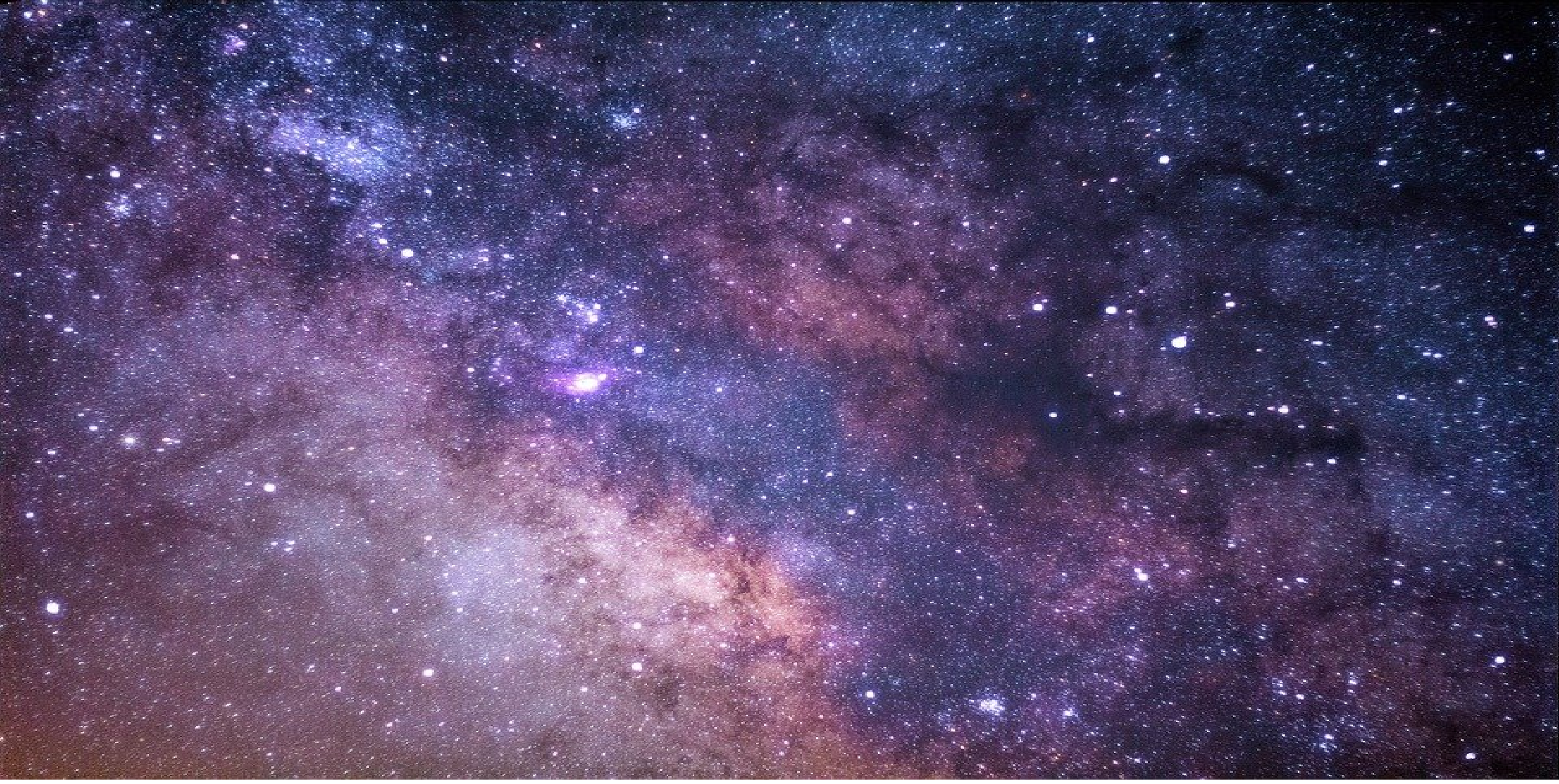

Flying Multi-tonal Zither

Development of a new interface for musical expression

Marco González Pérez

Sound and Music Computing, 2020

Master's Thesis

STUDENT REPORT
AALBORG UNIVERSITY

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Abstract:

Since the creation of the MIDI protocol and the first synthesizers, the large majority of digital musical instruments have been keyboard-based. This approach has therefore helped expand the musical possibilities of keyboard players, given that they only need a MIDI keyboard and a computer to start making music. However, this approach has usually been framed within the western tonal system, which has sometimes led to some musical limitations. This Master's Thesis is aimed at creating a new digital musical instrument allowing the same level of expressiveness as string instruments (vibrato, slide, picking...) and having the flexibility provided by controllers usually found in keyboard synthesizers. Moreover, this project explores how different scales from different cultures (such as equal tempered scale, polychromatic scales and microtonal scales) can be integrated within the same device in order to create a flexible and versatile instrument.

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Preface

Music Interaction (also referred as Music and Human-Computer Interaction) is the scientific field which studies the design, implementation, evaluation and analysis of interactive systems that involve computer technology for musical activities [6]. This project follows that methodology in order to create a new interface for musical expression.

The name of the instrument, "Flying Multi-tonal Zither", reflects how this project was influenced by the German instrument "Zither" and several tonal systems of different cultures. The instrument is designed so as to propose a new approach when it comes to develop new synthesizers and MIDI controllers. In fact, this project tries to bring a new digital musical instrument to string instruments players.

All source code and documentation is available at GitHub[1], where you can also find a video demo of me playing the instrument. It is distributed under the MIT license.

Aalborg University, December 18, 2020

Marco González Pérez
<mgonza19@student.aau.dk>

[1] https://github.com/Marquets/SMC-Master-Thesis

Chapter 1

Introduction

Some studies have proved that people from all around the world are becoming similar from a cultural point of view. In this regard, sociologists seem to agree that, as a result of globalization, some aspects of our lives, which are becoming more culturally similar, are being homogenized. In addition, compared to the past century, human interactions don't know geographic frontiers. By using the Internet, people are able to communicate whenever they want to and regardless of the country in which their counterparts are located. [9]. Although this phenomenon is a matter of concern for some citizens, it is undeniable that it has enabled to enlarge the cultural knowledge of many people. As a result, the world has witnessed a period in which people can discover new cultures by just doing a quick search on the Internet.

Even before the creation of the Internet, the world started a slow race to become a more globalized planet. As a result, musicians were able to discover new musical elements from other cultures. Back into the 60's, one good example of this phenomenon would be illustrated by The Beatles. The English band travelled all around the world sharing their music with the world and creating the first ever stadium tours. In the mid-1960's, when the band was one of the most celebrated and influential rock groups of popular music, they began to use musical elements and instruments from Asia in their songs. These influences came primarily from India, where George Harrison started to learn how to play the sitar and recorded it in the new songs of the Beatles [15]. A more recent example of this phenomenon could be the King Gizzard and the Lizard Wizard's Flying Microtonal Banana (2017) album in which every song was composed in a 24-note per octave tuning. The songs were originally composed by using a baglama, a Turkish instrument, and then, in order to record the album, the band decided to refret all their guitars and other instruments. The band was therefore inspired by traditional Middle Eastern music and applied these new tunings to their more familiar instrumentation of psychedelic rock. [3].

These examples show how globalization is helping musicians to broaden their musical options and their creative limitations by exploring new tonal systems from other cultures. However, in some cases, this exploration into new tonal systems might be a bit complex to materialize given that it requires to make some adjustments to instruments so as to let the players play with those tunings.

As amateur musicians and string instruments players, this has always intrigued us and we have always been willing to explore into tonal systems beyond the 12-TET. In addition, as Sound and Music Computing students, we have always been motivated by the idea of building a new gestural instrument so as to overcome some limitations found by amateur music producers when exploring into new tonal systems.

Consequently, this Master's thesis aims at creating a new digital musical instrument allowing the same level of expressiveness as string instruments and having the flexibility provided by controllers usually found in keyboard synthesizers. Moreover, this project explores how different scales from different cultures (such as the equal tempered scale, polychromatic scales and microtonal scales) can be integrated within the same device in order to create a flexible and versatile instrument.

Chapter 2

Analysis

In this chapter, several points will be discussed regarding the state of the art and the design requirements chosen in order to determine the direction of this project. Firstly, the interaction goals of the instrument will be defined. Secondly, a list of examples of old string instruments and new interfaces, which served as an inspiration for this project, will be provided. Finally, the final problem statement and an enumeration of the design requirements will be presented.

2.1 Interaction Goals

As mentioned in [10], in order to design a new digital musical instrument, one typically needs to take into consideration not only technical aspects but also what kind of interaction the instrument is going to provide its users with. So as to provide an overview of the interaction goals of this project, Birnbaum's seven-axis diagram shown in [10] was used.

From the interaction perspective, the instrument designed for this project includes the following features:

- Role of Sound: the instrument should allow users to have a high degree of expressiveness while playing it.
- Required Expertise: the instrument should target string instruments players and users that know how to play music with MIDI controllers.
- Musical Control: users should be able to have "note-level" control in addition to some sound design controllers.
- Degrees of Freedom: the device should provide some degrees of freedom in terms of playability and sound design.

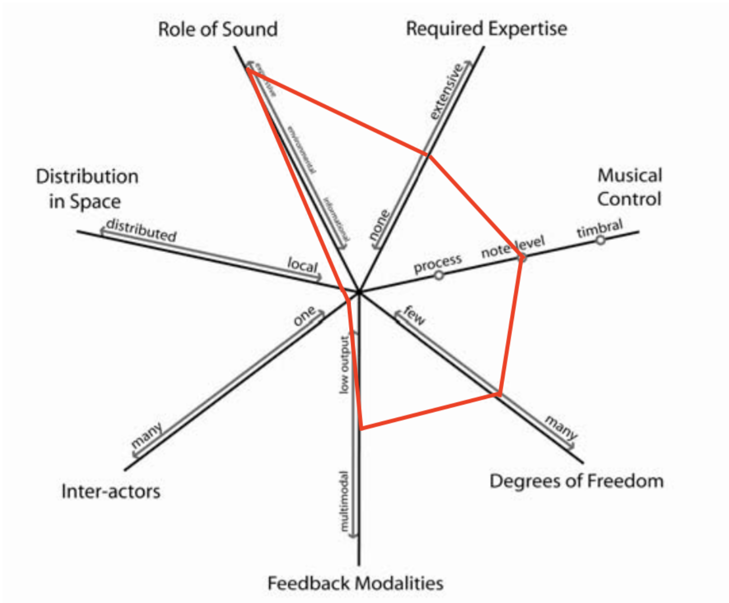


Figure 2.1: seven-axis diagram from Birnbaum for the Flying Multi-tonal Zither

- Feedback Modalities: the main primary communication (perception) channel should be the auditory channel. Some tactile feedback might be added in order to improve the instrument's feedback.
- Inter-actors: the instrument should be meant to be played by one user at a time.
- Distribution in Space: the instrument should be distributed within a single device.

Digital musical instruments (DMI), also known as gestural controllers, can be classified in several ways. For instance, Atau Tanaka classified gestural controllers into physical or nonphysical controllers [18]. In addition, the following way of classifying DMIs was proposed in [10]:

- Acoustic instruments that are "augmented" by using different types of sensors.
- Gestural controllers aimed at completely reproducing an original acoustic instrument and its initial features.
- Gestural controllers inspired by existing instruments in order to overcome some limitations of the original models. These gestural controllers don't attempt to simulate them exactly.

- New alternate controllers that don't have any resemblance to existing instruments.

The instrument designed for this project could be classified as a new gestural controller inspired by existing instruments. All the existing instruments that served as inspiration for this project are presented hereafter.

2.2 Background

2.2.1 Beyond control and interaction of regular keyboards

The musical keyboard found nowadays in pianos, organs, synthesizers and midi controllers has characterized the Western music for many centuries. However, thanks to the advance of new technologies, new approaches are coming into light in order to offer new ways of expression to musicians. Usually, one of the research questions addressed when creating a musical instrument is therefore how to make sure that it allows a high degree of expressiveness. This lets the player be precise and fluent in his/her performance [6].

In order to design a digital musical instrument with a significant level of expressiveness, research into related instruments was conducted.

Some of the most relevant existing instruments are presented below:

The Roli's Seaboard

The Seaboard is a renovated version of the piano keyboard created by Roli [1]. It offers a smooth feel with a touch-responsive and super-sensitive surface that allows to bend and modulate sounds in ways that make a standard keyboard feel two-dimensional [8]. This instrument brings some similar gestures found in string instruments and gives keyboard players the opportunity to enhance their expressiveness.

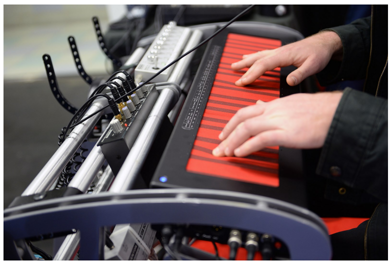
The Continuum Fingerboard

This digital instrument was created by Haken Audio [2] in 1998. The Continuum was conceived as a new type of polyphonic music performance device. Instead of using keys as a traditional synthesizer, it tracks the positions on the x, y and z axes for up to ten simultaneous notes. The performer must place the fingers accurately to play in tune and can slide or tilt the fingers for pitch bend and vibrato [5] (Figure 2.2b). This instrument was an important source of inspiration for this project given

[1] `https://roli.com/products/seaboard`
[2] `https://www.hakenaudio.com/`

the possibilities it offers in terms of expressiveness and playing in different tonal systems.

(a)



(b)

Figure 2.2: The Roli Seaboard (a). The Continuum Fingerboard (b)

2.2.2 New gestural controllers exploring string instruments gestures

The study of gesture is a complex field of research. Many studies have explored gestures in different contexts and the definitions provided vary greatly across researchers. The word gesture usually means the opposite of posture. Gestures are dynamic and they involve general body movements while manipulating an object [10]. As described in [10], DMIs might be the result of breaking apart an acoustic instrument, having a clear separation between the gestural interface and the sound generator. This implies that those parts can be combined in multiple ways while developing DMIs. Moreover, the same gesture used in the acoustic instrument can lead to the production of completely different sounds on the DMIs. Having that in mind, one of the main purposes of this project is to get inspiration from different string instruments in order to create a synthesizer and MIDI controller using gestures usually found in those instruments. Some related projects will be described below.

The LinnStrument

The LinnStrument is an expressive MIDI controller for musical performance created by Roger Linn. Unlike a standard MIDI keyboard, the LinnStrument tracks the position of the player's fingers in five dimensions, enabling musical performance expression found on acoustic instruments [3]. This instrument is a very good example of how the expressiveness of MIDI controllers can be rethought. In addition, the fact of not having a sound engine but only a gestural interface shows how versatile this instrument could be if it was connected to any sort of MIDI synthesizer.

[3] `https://www.rogerlinndesign.com/linnstrument`

Figure 2.3: Roger Linn with the LinnStrument

The Soundplane

New gestural controllers can also be the result of a research aimed at providing expressive controls for performance for new complex sound synthesis algorithms such as physical models. The Soundplane is a digital instrument created by Randall Jones. Jones developed this instrument while trying to answer the following research question: “How can we make a computer mediated instrument with control intimacy equal to the most expressive acoustic instruments?” [7]. The Soundplane has the sensitivity and feel of an acoustic instrument. It tracks a wide range of finger gestures on its walnut playing surface, from a light touch to a very firm press. Unlike a MIDI keyboard, the Soundplane also communicates three dimensions of information, x, y and pressure, over the entire duration of every touch [4].

2.2.3 Inspiration from real string instruments

At the beginning of this project, some research on several types of string instruments from different cultures was conducted. Some of the instruments that were found were an important source of inspiration when it comes to the shape and sound design of our instrument.

[4] `https://madronalabs.com/soundplane`

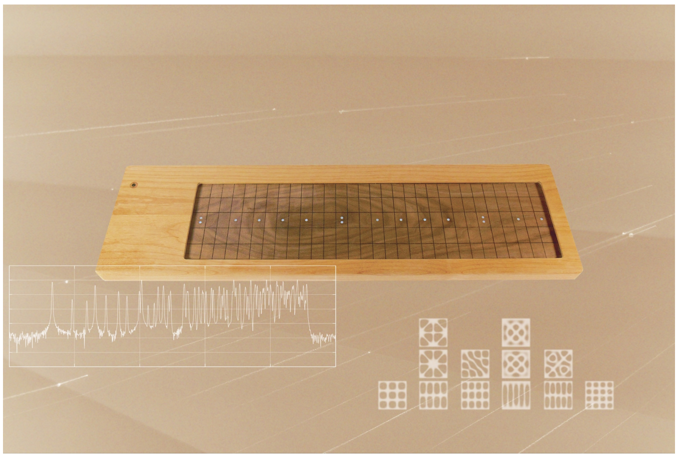


Figure 2.4: The Soundplane Model A

The Guqin

The Guqin is a plucked seven-string Chinese musical instrument (Figure 2.6). Its main characteristics are the following ones:

- 7 silk strings and a resonance box.
- A range of about four octaves, its open strings being tuned in the bass register.
- Sounds are produced by plucking open strings, stopped strings, sliding strings and harmonics.
- In terms of tuning, it uses the relative scale. The user tunes one string as the "standard" and then tunes the others accordingly [5].

Figure 2.5: The Guqin

The Guqin was a source of inspiration not only in terms of designing the body of our instrument but also when it comes to its final sound design.

[5] `https://en.wikipedia.org/wiki/Guqin`

The Zither

The Zither is an ancient German string instrument generally played by strumming or plucking the strings, either with the fingers or with a plectrum. In addition, it is possible to play it by beating the strings with specially shaped hammers. Like guitars, its body functions as a resonating chamber. Its number of strings varies from one to more than fifty [6].

Its body and how its strings are separated into two sections, the fingerboard "fretted" strings and the non fretted strings, influenced the design of our instrument.

Figure 2.6: The Zither

Tom Stone and his Intonation Systems for Guitars

In [16], John Schneider analyzes the whole history of the modern guitar and its evolution throughout the years. One of the most interesting ideas addressed by the book has to do with Tom Stone's intonation system for guitars. Until the 1970's, string instruments using alternative tuning systems had used fixed frets, limiting each instrument to one tuning system. In 1970, Tom Stone announced his invention of a guitar with interchangeable fingerboards.

The interchangeables fingerboards are classified in four categories:

- Pure Intonation series: a form of just intonation.

[6] `https://en.wikipedia.org/wiki/Zither`

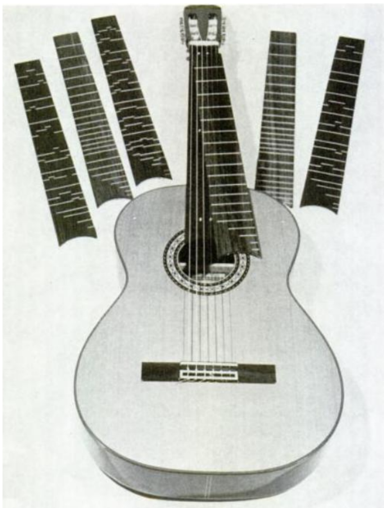


Figure 2.7: A guitar next to some interchangeables fingerboards

- Experimental series: playing around with octaves and harmonics.
- Cultural series: japanese koto scales, east Indian (Hindustani) scales and Classical Arabian scales.
- Historical series: Pythagorean scales, traditional just intonation (7 and 12 tones), quarter-comma mean-tone and of course the equal temperament.

Those interchangeable fingerboards inspired our project so as to introduce different tonal systems into the Flying Multi-tonal Zither.

2.3 Final Problem Statement

How can we create a new gestural controller inspired by existing string instruments in order to keep expressive playing techniques and to overcome some tonal limitations of the original instruments?

2.4 Design Requirements

The design requirements of this project can be categorized into three different categories: functional requirements, non-functional requirements and environmental requirements.

2.4.1 Functional Requirements

The functional requirements are presented below :

- The system should react in real-time (<10ms latency) to user input.
- It should provide flexible control over playing techniques and general musical attributes found in string instruments.
- The connected device should be able to interpret user inputs and produce a corresponding sound.

In addition, it has to be noted that the instrument has three main sections: a multi-touch section, a rubber cord stretch section and common controllers.

Multi-touch section

It should be able to:

- generate notes and semitones in different tonal systems (equal well-tempered, cultural system - japanese, indian or arabian - and pythagorean scales).
- interpret different user inputs and produce sounds and/or midi for each input.
- modulate the sound with a series of finger gestures controlling vibrato, pitch-bend/slide and picking.

Rubber Cord Stretch Section

It should be able to:

- vary the tuning of the Multi-Touch Section.
- produce notes and drone sounds.

Common Controllers Section

The Common Controllers Section contains controllers (an overall volume patch selector, a patch selector, a tonal system selector and controllers to change and modulate the sound of the instrument) that affect the whole system.

2.4.2 Non-Functional Requirements

When it comes to the non-functional requirements :

- String instruments players should be able to play the instrument.
- The device should be ergonomic and should be able to be held in three different ways (flat, “guitar” and “harp”).
- The device should provide some kind of tangible feedback when it is played.

2.4.3 Environmental Requirements

The environmental requirements for this project are defined according to two different environments:

Physical environment

- The system is designed for indoor use.
- The system will be used in a semi-noisy environment.

Technical environment

- The product will run on a Teensy 4.0 and a Teensy Audio Shield.
- The device should be able to communicate with other digital instruments using the MIDI protocol.
- The user input should be translated using 4 SoftPots linear potentiometers with 3 conductive rubber cord stretch sensors (used for note generation) and force sensitive resistors made of cupper tape and velostat (used for sound modulation).

Chapter 3

Design & Implementation

In the following chapter, the design and implementation stages that shaped our first ideas into the final prototype are explained in 6 sections. Firstly, section 1 will describe the inspiration taken from the state-of-the-art. Section 2 will analyze the design process used in this project. Then, in sections 3, 4 and 5, the technical, musical and aesthetic choices that were made will be exposed. Finally, in section 6, the prototype developed as a result of the previous choices and which led to the final version of our instrument will be explained.

3.1 Inspiration

As mentioned in chapter 2, this project took inspiration from the following existing instruments:

- **The Roli Seaboard**: the interface brings to the standard midi keyboard some similar gestures found in string instruments in order to enhance the performer's expressiveness. This instrument was very inspiring for the design of our MIDI and synthesizer oriented to string instrument players.

- **The LinnStrument**: it was very interesting to find an existing instrument based on acoustic instruments that shows how versatile an instrument of this kind can be. The LinnStrument was helpful in making design decisions so as to develop our instrument.

- **The Guqin**: as this project tries to explore ways to enlarge the tonal possibilities of MIDI controllers and synthesizers, a large research was conducted so as to find world musical instruments. The Guqin was an important source of inspiration in terms of sound design and musical gestures.

- **The Zither**: this German instrument attracted our attention because of its shape and its disposition of strings which are both reflected in the aesthetics of our instrument.

- **Tom Stone's Intonation Systems for Guitars**: Tom Stone and his interchangeable fingerboard gave us some clues about how to display the different tonal systems chosen for our project.

As described by Overholt in [13], the goal of creating a new gestural controller is to define a framework and an approach for developing a powerful gestural interface for music performance and composition. In other words, the goal is to allow humans to be musically expressive through the use of advanced technologies.

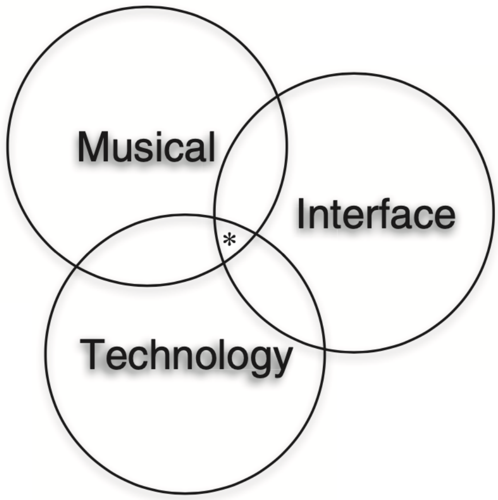


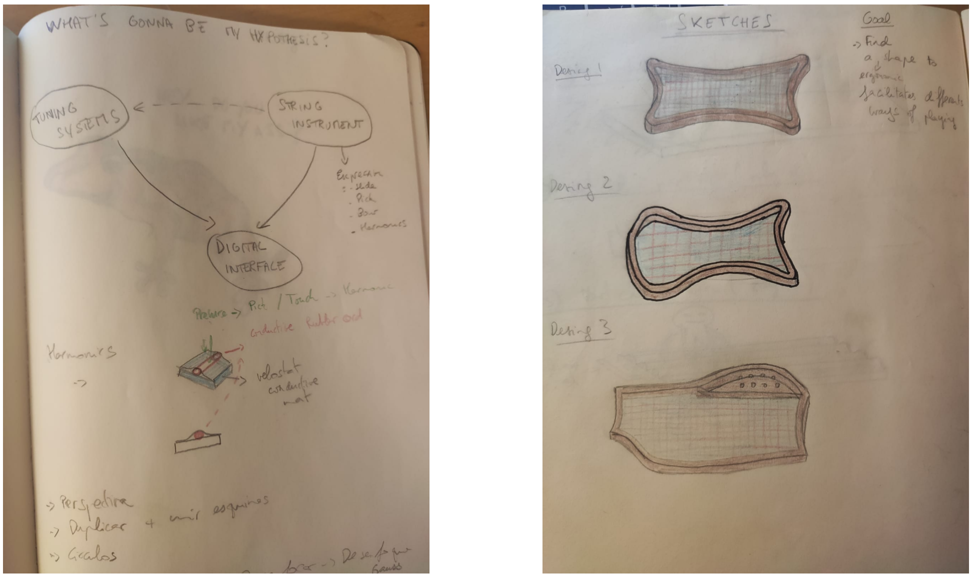
Figure 3.1: This figure taken from [13] explains what approach should be followed when developing new gestural controllers. In this regard, new technologies are used and combined with an interface so as to provide an expressive device for music performance and composition.

The main characteristics of the above mentioned instruments were a source of inspiration not only for creating the framework in which our instrument is placed but also for trying to overcome some intrinsic limitations found in acoustic instruments. For instance, when it comes to the Tom Stone's Intonation System, this project tries to overcome the tonal limitation found in string instruments by integrating several tonal systems within the same device. In this regard, Overholt explains in [13] that the mere fact of blending human skills and machine capabilities can result in a level of expressiveness that can be near or even surpass that of traditional acoustic instruments.

3.2 Iterative Design Process

From the beginning of this project, an iterative process was followed in order to design the instrument. In fact, the main concept of the instrument was settled from the early stage of the project. However, in order to start shaping more in detail the instrument, some new ideas were soon put on the table: the number of gestures from string instruments that were going to be featured, the tonal systems that were going to be used and the kind of sound design that was going to be provided with.

The initial concept relied on the use of a DIY pressure sensitive matrix presented like a mat so as to have a continuous sensitive surface to play the notes. The instrument would look like a framed mat inspired by the ATV's aFrame instrument [1]. Nevertheless, it was decided to completely change that initial concept because the research conducted on real string instruments made us change our mind and go for a more look-alike string instrument version. In addition, it has to be noted that drawing inspiration from some acoustic instruments, such as the Guqin or the Zither, seemed to be more adequate when it comes to designing a new instrument which was meant to have some gestures and level of expressiveness related to string instruments. Some of our first ideas and sketches are shown in figures 3.2a and 3.2b.



(a) (b)

Figure 3.2: First (a) and Second (b) design iterations

One particular characteristic usually found in several string instruments is that they can be played by holding them in several ways. For instance, guitars can be

[1] http://www.aframe.jp/

played either while standing up by using a strap or while sitting on a chair. In addition, guitars can be played either by using the regular playing techniques or by using a slide such that the guitar is played as a lap steel guitar. This specific characteristic of guitars also influenced our choices when designing our instrument. Indeed, this led us to look for an ergonomic shape for our instrument in order to make it possible to hold it in different ways.

(a)

(b)

Figure 3.3: Different ways of playing guitar

3.3 Technical Choices

3.3.1 Why Teensy?

Teensy is a "*is a complete USB-based microcontroller development system, in a very small footprint, capable of implementing many types of projects. All programming is done via the USB port.*"[2]. This microcontroller development board is compatible with Arduino software and libraries that offer a great versatility when implementing audio projects. In addition, it can be upgraded by using an audio shield so as to add high quality 16 bit, 44.1 kHz sample rate (CD quality) audio. Moreover, the audio shield supports not only stereo headphones and stereo line-level output but also stereo line-level input or mono microphone input [3]. As a result of all the versatility offered by Teensy and the audio shield, it was decided to use this board for developing our instrument.

[2] `https://www.pjrc.com/teensy/`

[3] `https://www.pjrc.com/store/teensy3_audio.html`

3.3.2 Why Teensy's Audio Design Tool?

Another good reason for using Teensy as a microcontroller development board was its Audio Design Tool. Teensy is provided with a powerful audio library (oscillators, sound effects, sound analysis...) which became the DSP engine of our project. Teensy's Audio Design Tool lets users easily draw a diagram in order to design the sound processing part of their projects. Moreover, the design tool can generate some code in order to integrate it into the Arduino editor [4]. In this regard, one of the synthesizers of our instrument was implemented by using this design tool. Figure x shows the diagram produced with it:

3.3.3 Why Faust?

Faust (Functional Audio Stream) is a functional programming language for sound synthesis and audio processing with a strong focus on the design of synthesizers, musical instruments, audio effects, etc. It targets high-performance signal processing applications and audio plug-ins for a variety of platforms and standards [5]. As Faust can be easily used within a Teensy board, it was decided to rely on this powerful programming language to implement a version of the Karplus-Strong algorithm for our project.

3.3.4 Why Softpots and Force Sensitive Sensors

The Softpot is a linear potentiometer made by Spectra Symbol [6]. By pressing down the strip with the finger, the resistance of the potentiometer changes and allows the user to calculate the relative position of the finger on the strip [7]. These potentiometers have already been used in several music projects such as the "XT Synth" made by Gustavo Oliveira, which is another good example of new controllers for string players [17], and this is the reason why we decided to use them for our project. Moreover, in order to provide our instrument with more control and expression over different sound parameters, it was decided to add some force sensitive sensors (FSRs). As mentioned in [14], current technology enables us to easily build force sensitive sensors by using copper tape and velostat, a material made of a polymeric foil impregnated with carbon black so as to make it electrically conductive [8].

[4] https://www.pjrc.com/teensy/gui/

[5] https://faust.grame.fr/

[6] https://www.spectrasymbol.com/

[7] https://www.spectrasymbol.com/product/softpot/

[8] https://en.wikipedia.org/wiki/Velostat

3.3.5 Why Rubber Cord Stretch Sensors?

Rubber cord stretch sensors were used in our project so as to simulate regular strings. This carbon-black impregnated rubber behaves in a very similar way as the FSR and it is often used to measure force. In our project, these sensors trigger notes when they detect that the cord has been stretched [9].

The use of Sofpots, FSRs and Rubber cord stretch sensors allow our musical instrument to have gestures similar to those of string instruments as well as some features found on synthesizers and midi controllers:

- **Slide and Vibrato**: thanks to Softpots, the instrument is not only able to track the finger position in order to trigger the notes but also to slide through the notes in a continuous and similar way as is the case for string instruments.
- **Picking**: The rubber cord gives the player the tactile feedback usually perceived when picking a string of an acoustic instrument.
- **Velocity control**: FSRs were a great add-in to our instrument so as to have control over the velocity of the notes triggered. In fact, the player has the possibility to control the force with which a note is played.
- **Sound Parameter control**: in addition, with the same FSRs, the player is able to control some parameters commonly found on synthesizers such as the cut-off frequency of a filter and a pitch bend.
- **Midi Mapping**: finally, when the instrument is working as a midi controller, the user can choose to map the first FSR to any midi parameter of a digital instrument or DAW.

3.4 Musical Design Choices

3.4.1 Why being inspired by string instruments?

As musicians familiarised with string instruments, synthesizers and midi controllers, it was considered that it could be very interesting to mix both worlds in order to create an hybrid instrument.

When it comes to string instruments such as guitars, they offer a great level of expressiveness given that the player can control several characteristics of the notes with hand gestures (pitch-bend, vibrato, slide...). In addition, a large range of string instruments are used in different cultures with different tonal systems. However, there are few string instruments that make it possible to play in different

[9] `https://www.adafruit.com/product/519`

tonal systems without having to retune the strings or to put additional frets on their fingerboards. Furthermore, even though we can find nowadays some midi controllers inspired by string instruments, this is not the common rule for instrument companies, which still use the keyboard as a regular standard.

As a result, this project tries to overcome the string instruments' tonal limitations while integrating their gestures within a midi controller and a synthesizer. On a more general note, the development of new interfaces for musical expression, string instruments as well as world music were related to our research interests and were therefore the driving force that led us to develop our instrument.

3.4.2 Sound Design

The instrument was not meant to be designed only for a specific music genre. Therefore, many of the sound design choices were oriented towards letting create music that could suit several genres. For this purpose, the device has 2 different synthesizers designed to provide the instrument with an intuitive and simple sound engine.

- On the one hand, it has a Simple synth inspired by the Sequential Circuits Prophet 600 (Figure 3.4)). This synth is a subtractive synthesizer with only 2 oscillators whose waveforms and pulse widths can be modified by the user. In addition, this synth lets the user detune slightly the oscillators between them. Moreover, by pressing the FSRs, the user controls the cut-off frequency of a filter.

Figure 3.4

- On the other hand, it has a Karplus-Strong synth. As explained in [4], the Guqin can be easily modeled by using the Karplus-Strong algorithm. Given that the Guqin was an important source of inspiration for our project, it was coherent to add a sound engine in our instrument so as to simulate the Guqin.

3.4.3 Tonal systems

In the context of this Master's thesis, the word "tonal" refers to two different concepts: intonation and timbre. From a musical point of view, intonation means the pitch in which a tone is played 'in tune' or not [10]. On the contrary, the timbre is related with the harmonic content that characterizes the sound of a specific instrument. In fact, those harmonics are responsible for letting people distinguish a C chord played on a piano from the same chord played on a guitar. Given that the user can play with different sounds in our instrument, it can be said that it can produce different timbres. In addition, it was decided to implement several intonations in order to let the user play in different tuning systems from different cultures. As a result, this means that the user is able to choose how the notes are displayed along the softpots. This is, in the end, equivalent to adding or removing frets on string instruments. The tuning systems that were chosen for this project are shown in figure 3.8:

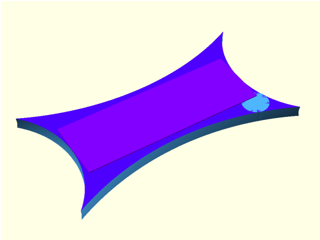
Intonation	Number of notes per octave	Explanation
Equal Temperament	12 notes	The equal temperament is the tuning system used in Western Music, which approximates intervals by dividing an octave (or other interval) into notes that are all the same distance apart.
Pythagorean Tuning	12 notes	The Pythagorean scale is any scale which can be only constructed from pure perfect fifths (3:2) and octaves (2:1).
Grama system or "Shruti"	22 notes	This system is usually found in Indian music. "Shruti" means the interval between two notes where the difference between them is perceptible.
Quarter Tone (24-TET)	24 notes	Quarter tone has its roots in the music of the Middle East and more specifically in Persian traditional music. It divides the octave into 24 notes separated each by 50 cents and has 24 different pitches.
Polychromatic tuning	Range of frequencies	This intonation doesn't make any sort of division of the octave but offers a full range of frequencies. It is usually found on fretless string instruments.

Figure 3.5: List of tonal systems

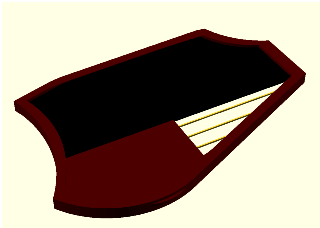
[10] https://trainer.thetamusic.com/en/content/intonation-and-tuning

3.5 Interface and Visual Design

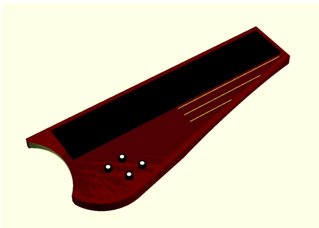
3.5.1 Searching for an Ergonomic Design



(a)



(b)



(c)

Figure 3.6: 3D models of the instrument ordered from the first to the last design

It was an important design choice for this project to make an ergonomic design so as to enable the user to hold the instrument in different ways. After a process of doing sketches and 3D models with OpenSCAD [11], it was decided to use the design presented in figure 3.6c. Thanks to this design, players can hold the instrument in 3 different ways as explained in section 3.2. The following pictures explain visually how users can play the instrument.

(a)

(b)

(c)

Figure 3.7: 3 different ways of holding the instrument

It has to be noted that the final design was highly inspired by the Zither, which

[11] `https://www.openscad.org/index.html`

has a similar shape compared to that of our instrument but cannot be held in different ways. The Zither's shape gave us indeed a clue to design the shape of our instrument in an ergonomic and versatile way.

Regarding the dimensions of the device, we chose to make the instrument as thick as regular guitar bodies (4 cm) and with a length of 60 cm. These dimensions were appropriate to hold the instrument with both hands and were also determined by the length of the softpots. Finally, the bottom of the instrument presents a "U" shape that can be fitted on a person's leg as shown in 4.2a.

3.5.2 Control mapping and Grouping

Once the shape and size of our device were determined, we started an iterative process in order to choose where the controllers were going to be located in the device. Subsequently, decisions were made about how to map each controller with the player inputs.

Control mapping

Our instrument uses a one-to-one mapping and a one-to-many scheme. Some controllers modulate a single parameter but others modulate several ones. For instance, the softpots and the stretch sensors send the raw data to Teensy which is in charge of translating the analog input into notes. When it comes to the FSRs, the mapping changes depending on the mode selected by the user (Simple Synth, Karplus-Strong Synth or Midi Controller). The following table explains how the mapping works in each case.

	Simple Synth	Karplus-Strong Synth	Midi Controller
FSR nº1	Mapped to the cut-off frequency of the filter (one-to-one)	Mapped to the pitchbend (one-to-one)	The user can choose to map the FSR to any parameter from a VST (one-to-one)
FSR nº2	Mapped to the cut-off frequency of the filter and the velocity of the notes (one-to-many)	Mapped to the velocity of the notes (one-to-one)	Mapped to the velocity of the notes (one-to-one)

Figure 3.8: Table explaining how the mapping works with the FSRs

The rest of the controllers are potentiometers that are mapped to the synth parameters (waveform, pulse width and fine) and to others general parameters (volume, synth selector and tonal selector).

Control grouping

The controllers of the device can be grouped into 3 categories:

- **The Fingerboard**: the softpots and the FSRs that make it possible to enter the notes and to modulate the sound, respectively.
- **The Harp**: the stretch sensors that trigger some fixed notes.
- **The Pickguard**: the controllers placed in this group modify the most general aspects of the performance (volume, tonal systems, synth selector, waveforms...).

3.5.3 Labelling

Nº of controller	MIDI Controller	Subtractive Synthesizer	Karplus-Strong Synthesizer
1	MIDI CC(1) Modulation Wheel	General Volume	General Volume
2	MIDI CC(2) Breath Control	Patch Selector	Patch Selector
3	MIDI CC(7) Volume	Pulse Width OSC 2	
4	MIDI CC(11) Expression Controller	Waveform Selector OSC 2	
5	MIDI CC(71) Timber / Harmonic Intensity	Waveform Selector OSC 1	Pluck Position
6	MIDI CC(74) Brightness	Detune	Body Size
7	MIDI CC(75) Decay Time	Pulse Width OSC 1	Body Shape
8	MIDI CC(76) Vibrato Rate	Tonal Selector	Tonal Selector

Figure 3.9: Labelling and Table with parameters.

Since this instrument targets people that are familiarised with synthesizers and midi controllers, the general parameters are labelled using numbers (1 to 8). Each of the numbers appear on an additional table that shows the name of each parameter in each mode (MIDI, Subtractive Synthesizer and Karplus-Strong SYnthesizer). In addition, this decision was taken so as to keep the aesthetics similar to the ones usually found on vintage synthesizers and midi controllers.

3.6 Physical Prototype

3.6.1 The body of the instrument

After creating the 3D design of our instrument, the next step was to build the body of the device in the university lab. In order to do this, it was decided to use hardboard, an engineered wood product, which was cut thanks to a laser cutter.

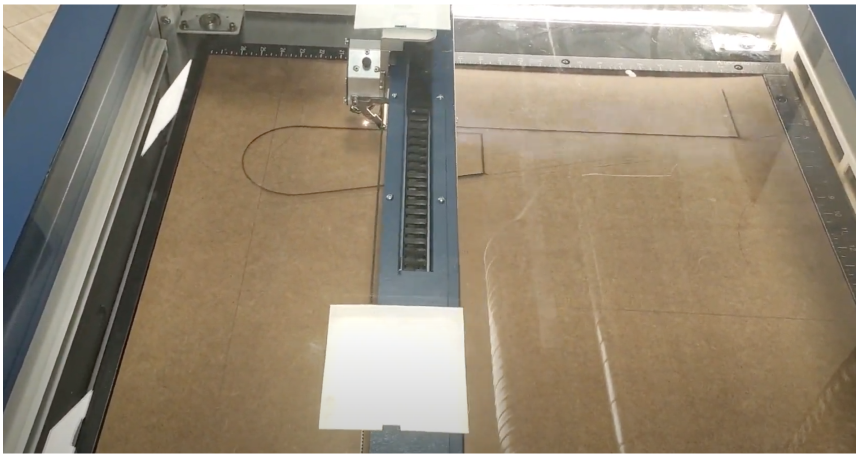


Figure 3.10: Picture of the laser cutter cutting the material

10 layers were cut following the shape designed in the 3d model and taking into account the space needed for all the circuit components, such as the softpot and the Teensy. The next stage was to glue the 10 layers together and paint the body. Finally, 4 holes were drilled for the signal output, the midi output, the power supply and the micro-usb port of the Teensy.

3.6.2 The Fingerboard

The Fingerboard is used by the performer to trigger the notes of the instrument. This section is composed of 4 softpots, having each of them 2 FSRs, which allow the player to use some hand techniques found in string instruments such as the slide and vibrato. Each softpot was set over a layer of foam in order to improve the tactile feedback created by the instrument. Figure 3.12 explains how the softpots and FSRs were built together.

Thanks to this configuration, the user is not only able to trigger the notes (X-axis) but also to modulate the sound of the instrument while pressing the FSRs located below the softpot (Y-axis). In an early stage of prototyping, it was found that each FSR required a transimpedance amplifier circuit (figure 3.13) given that, without it, the signal provided was a bit low in order to achieve the expected functionality.

Figure 3.11: The body's final look

Figure 3.12: Disposition of the FSRs beneath the softpot

3.6.3 The Harp

The Harp is composed of 3 rubber cord stretch sensors. Each of these sensors trigger one single note as an acoustic harp would do. This section is placed next to the Fingerboard and its main functionality is to let the user harmonise and accompany its performance while he plays with the Fingerboard. In order to simulate a string instrument, the 3 rubber stretch sensors are attached to real tuning heads that were taken from an old ukulele.

3.6.4 The Pickguard

This section is in charge of offering some knobs that control some parameters of the synthesizers and the general parameters of the instrument. Regarding the Simple Synth, the user can change the waveform and the pulse width of the 2 oscillators. In addition, it can detune both oscillators by using the "Fine" controller. When it comes to the Karplus-Strong synthesizer, the user can control the gain, the pluck

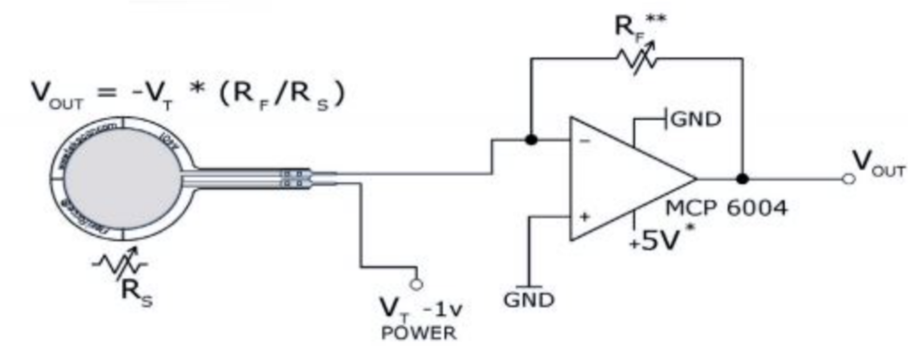


Figure 3.13: Schematic of the transimpedance circuit used

position, the shape of the body simulation and its scale.

3.6.5 The Circuit

Before building the entire instrument, the circuit was modeled and tested by using only one softpot with 2 FSRs and a stretch sensor. In addition, all the code was tested by using this prototype of the circuit. After having achieved the required results, the final circuit was designed. For the final prototype of the circuit, everything was soldered thanks to a stripboard. Given that the Teensy 4.0 doesn't have many analog inputs available when using the audio shield, two 16 channels multiplexers were required in order to be able to connect all the sensors and potentiometers in the board. Figure 3.14 shows the block diagram design of the final prototype.

3.6.6 The Simple Synth in Depth

As stated previously, this subtractive synthesizer is a straightforward synth with only 2 oscillators and a band-pass filter. Subtractive synthesis is a type of synthesis where the harmonics of an audio signal are attenuated by a filter so as to alter the timbre of the sound. This method of synthesis is commonly associated with the technique analog synthesizers from the 60s and 70s, in which the harmonics of simple waveforms, such as sawtooth, pulse or square waves, were attenuated with a voltage-controlled resonant low-pass filter [12]. In our device, the player can modify the cut-off frequency of the filter by changing the pressure of his finger on the softpot along the X-axis. This means that when the user puts more pressure into the FSR nº1, as shown in figure 3.12, the cut-off frequency increases. In contrast, when that happens with the FSR nº2, the cut-off frequency is reduced. As a result,

[12] `https://en.wikipedia.org/wiki/Subtractive_synthesis`

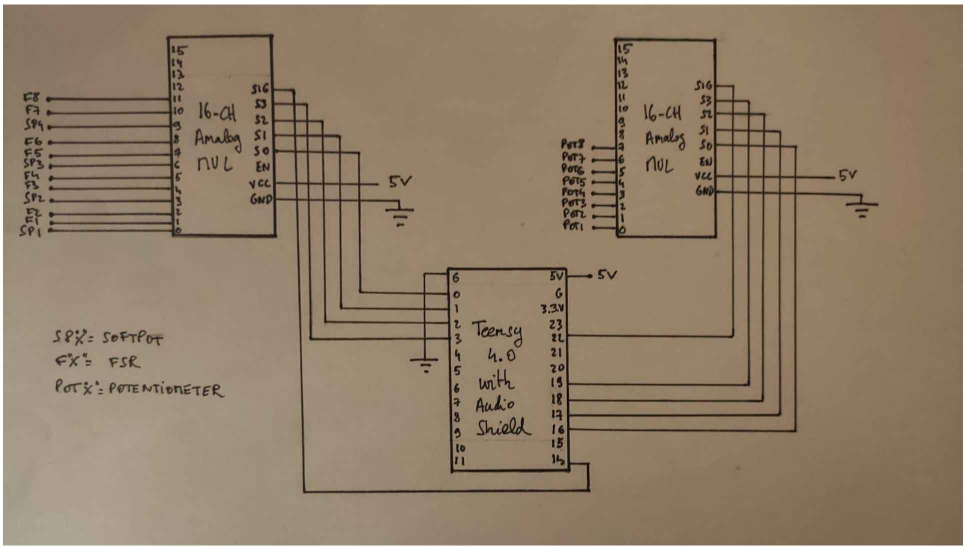


Figure 3.14: Block diagram design of the final prototype.

if the player tilts up and down its finger, it can modulate the sound in a way similar to a Wah-Wah effect pedal. The Simple synth of our instrument was implemented with Arduino and the Audio System Design Tool. In addition, in order to let the user play with the different tonal systems, the following calculation was made so as to get the frequencies produced when pressing the softpots in any of the tonal systems offered:

$$F = f * IntervalRatio$$

Figure 3.15: Picture explaining the process to calculate a note

In this equation, F is the final frequency produced when the player presses the softpots and f is the starting note which is multiplied by the interval ratio of the chosen tonal system. This means that, in order to play every corresponding note in every tonal system, a starting note has first to be chosen for each softpot. This starting note could be related to the one produced by an open string plucked on acoustic instruments. For our instrument, it was decided to use an open tuning similar to the one found on a bass: E A D G. In addition, our instrument uses a layout for notes called the "Fourth String Layout" by Roger Linn which again follows the same layout as a bass guitar [13]. Moreover, depending on the tonal

[13] https://www.rogerlinndesign.com/support/support-linnstrument-fourths-layout

system chosen, the softpots are divided into the interval ratios. For instance, if the player presses a softpot in the middle, this position has its corresponding interval ratio and the starting note is then multiplied by the ratio so as to produce the corresponding note in that specific tonal system. This methodology was used not only for the Simple synth but also for the Karplus-Strong Synth.

3.6.7 The Karplus-Strong Synth in Depth

Given that this project was not aimed at digitally replicating a string instrument as accurately as possible, it was decided not to use a complex physical model in order to model the sound of a string. Consequently, we used the Karplus-Strong algorithm to simulate the sound of a string. This algorithm consists of a short excitation, usually a burst of white noise, being output and simultaneously fed back into a delay line L samples long. Moreover, the output of the delay line is fed through a filter whose gain must be less than 1, at all frequencies, in order to maintain a stable positive feedback loop. In fact, the filter can be a first-order lowpass filter. Finally, the filtered signal is simultaneously mixed back into the output and fed back into the delay line. In order to implement this algorithm, a Faust code was integrated within the Arduino code where some additional features were added such as letting the player choose the body shape and scale of the simulated string instrument.

The Midi Controller in Depth

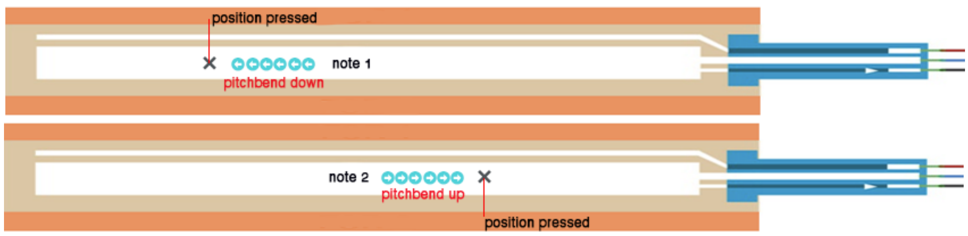


Figure 3.16: Picture explaining the process to calculate a midi note

When it comes to implementing the Midi Controller part of our instrument, we first tried to divide the softpots into midi notes. Consequently, depending of the number of octaves chosen, several notes could be played by pressing in different positions over the sofpots. This method worked well but its main problem was that it did not enable the vibrato gesture given that the notes were displayed in a discrete way instead of being continuous. In order to solve that, another method was implemented. Firstly, we set a fixed note in the softpots so as to make it possible that, regardless of where the user presses the softpot, the system only sends that note via the MIDI protocol. Secondly, in order to display the other corresponding notes, the fixed note was placed in the middle of the sofpots. When the user presses above or below that position, the instrument uses the pitchbend midi message to generate the corresponding note. The pitchbend midi message is a value generated within the range from -8191 to 0 to produce "down" pitchbend and within the range from 0 to 8191 to produce "up" pitchbend. Finally, in order to let the user play different tonal systems, we divided this pitchbend range in as many divisions as the tonal system requires.

Chapter 4

Evaluation

4.1 Evaluation Method

Young and Murphy [20] propose a methodology to evaluate digital musical instruments (DMI) in terms of three main aspects: functionality, usability and user experience.

Functionality refers to the technical abilities of the DMI, i.e. what they are able to do and how well they do it. Usability refers to the users' awareness of how well the DMI reach their goals as well as the level of learnability, efficiency and satisfaction of the DMI. Finally, the user experience refers to the users individual opinions on different aspects of the interface design [20].

The evaluation of our instrument was conducted by taking that methodology as a reference point. In addition, it has to be highlighted that the evaluation procedure was primarily aimed at getting valuable information about possible deficiencies in the current design of our instrument so as to improve it in the future.

The final problem statement of this Master's thesis was revisited in order to ensure that the main aspects of our instrument were going to be evaluated.

*How can we create a new **gestural controller** inspired by existing string instruments in order to keep **expressive playing techniques** and to overcome some **tonal limitations** of the original instruments?*

4.1.1 Data Collection: Functionality test

First tests while playing the instrument

When the implementation of the instrument was finished, several tests were conducted in order to evaluate its functionality. These tests consisted of playing the instrument connected to Ableton and checking whether every component was working properly.

Overall, most of the instrument's components worked as expected. Nevertheless, some errors were found. Firstly, some of the potentiometers didn't work at all. Indeed, two of them didn't respond so it was decided to replace them. However, the new ones didn't work either. In addition, it was noticed that the rest of the potentiometers were not mapped correctly when used as controllers for the two synthesizers.

Given the time constraints and the fact that the errors that were identified weren't an impediment to conduct the evaluation, they weren't fixed but we consider that they could be addressed when improving the instrument in the next iteration. The errors seemed to have something to do with how the multiplexers were wired into the Teensy 4.0. In fact, several analog inputs are used by the Audio Shield to process audio data. Since some of those inputs were used to connect some of the multiplexer's control pins, it is highly probable that both signals were interfering with each other. In the future work section, an explanation will be provided on how to fix these errors. Finally, as a final design choice, it was decided to not use the rubber cord stretch sensors given that after some testing they were not such a big feature for the instrument and they seemed to not be adequate to hold the instrument in several ways.

Latency test

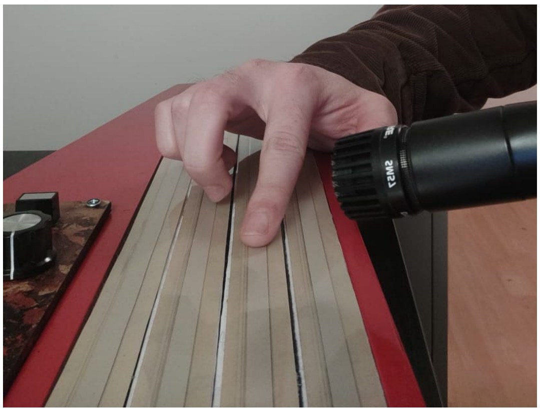
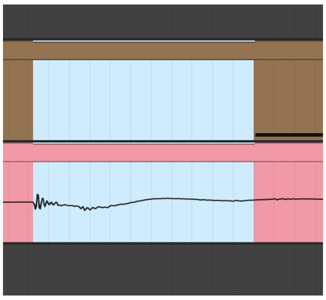


Figure 4.1: Picture of the latency recording set.

The signals from a microphone situated next to the softpots of the instrument as well as the signals from the jack output of the Teensy 4.0 were connected to separate inputs of an audio interface. Moreover, the micro-usb port of the Teensy was connected to a computer in order to conduct the latency test.

Each of the 4 softpots was pressed in several positions at intervals of approximately 1s. The resulting audio file was recorded into Ableton and the time intervals between the finger press and the sound production were measured individually.

The average latency obtained by using the MIDI mode was 5 ms. Moreover, when measuring the two synthesizers, the instrument gave a result of 22ms for the subtractive synthesizer and 6.3 ms for the Karplus-Strong synthesizer. The latency of the MIDI mode and that of the Karplus-Strong synthesizer were therefore lower than the 10 ms latency threshold mentioned in [19], while the latency of the subtractive synthesizer was slightly above that threshold. However, this last synthesizer seems responsive enough to be played and the latency is nearly unnoticeable.



(a)

Figure 4.2: One example of the intervals measured from the MIDI mode.

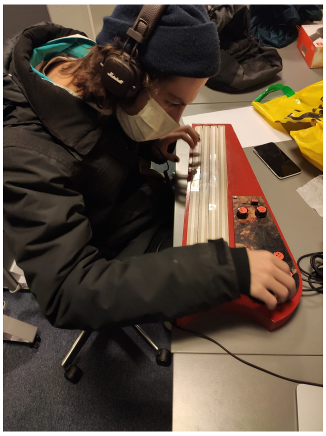
4.1.2 Data Collection: Usability test

After testing the functionality of the instrument, it was time to conduct the usability test by relying on external testers. Given the impossibility of finding people specialized in playing our instrument, which is by nature a new one, it was decided to rely on the following categories of experts to conduct the evaluation: NIME experts, string instruments players, music producers familiarized with the use of MIDI controllers and synthesizer and musicians familiarized with different tonal systems.

Expert evaluation was carried out over 10 sessions, each of which lasted between 30 minutes and 1 hour. The 10 solo sessions were carried out over 3 days on the Aalborg University Copenhagen campus. Each session was held in a study room, in a relatively quiet environment, where the set up consisted of the device connected to an audio interface, a computer and a pair of headphones to let the tester play the instrument without any disturbance. 10 experts were chosen as the sample size for the usability test, based on the research paper [11]. The age of the experts, their field of expertise as well as details about which session they took part in can be found in Table 4.4.

The usability test consisted of an heuristic approach where participants were asked to discover the instrument by themselves. At the beginning of the evaluation, the participants were only asked to perform two tasks. Firstly, they were asked to hold the instrument in the position they thought it would be the most

(a)



(b)

Figure 4.3: Two of the participants testing the instrument.

comfortable for them to play it. Secondly, they were requested to start playing the instrument by themselves and try every aspect of the instrument (the MIDI mode, the synthesizers, the knobs, etc).

In some sessions, the expert's performance was recorded in order to have some audio samples so as to analyse the extent to which each participant was able to make music with the instrument. In addition, considerable notes were taken during each evaluation session and two forms were filled out by all participants. One form was used to get qualitative feedback regarding the usability of the device. As proposed in [20], the other one was used to assess usability by using the System Usability Scale (SUS) [2]. The SUS is a Likert scale comprising 10 questions that each measures the degree of agreement with a 5-point scale, where "0" and "5" correspond respectively to "Strongly Disagree" and "Strongly Agree". The final score, a number between 0 and 100, gives an approximation of the device usability. In our

Participant nº	Age	Expertise	Took part in
1	40-50	NIMEs / Music Producer	Session 1, Day 1
2	20-30	Music Producer	Session 2 , Day 1
3	30-40	Music Producer / String instrument player / Musician familiarized with several tonal systems	Session 3, Day 1
4	20-30	NIMEs / Music Producer	Session 4, Day 1
5	20-30	NIMEs / Music Producer	Session 5, Day 1
6	30-40	Music Producer / String instrument player / Musician familiarized with several tonal systems	Session 6, Day 2
7	20-30	Music Producer	Session 7, Day 3
8	20-30	Music Producer/ Musician familiarized with several tonal systems	Session 8, Day 3
9	20-30	Music Producer / String instrument player	Session 9, Day 3
10	30-40	NIMEs/String Instrument Player	Session 10, Day 3

Figure 4.4: Table showing age, expertise and session of each participant.

form, in addition to the SUS 10 questions, it was decided to add an extra question that measures the degree of agreement with an "adjective rating scale" as proposed in [1]. In this regard, Bangor et al. [1] indicate a strong correlation between the adjectives and the SUS scores, thus enabling researchers to map the SUS scores to an adjective spectrum from "Worst Imaginable" to "Best Imaginable".

The form that was used to get qualitative feedback and the audio samples of some experts' performances can be found in the appendix of this document and the Github repository respectively [1].

4.1.3 Data Analysis: Usability Test

Since the large majority of the data obtained after the evaluation was qualitative, the analysis of the data consisted of finding correlations between the participants' feedback and their expertise.

Scoring SUS

The original 10 questions from the SUS were scored according to their respective guidelines [2]. The adjective rating scale used in the 11th question of our form was converted into a 7-point scale as in [1] (i.e. "Worst Imaginable" was converted into 1 and "Best Imaginable" into 7). Subsequently, we tried to determine whether there

[1] `https://github.com/Marquets/SMC-Master-Thesis`

was a correlation between the scores of the original 10 questions from the SUS and the scores of the 11th question.

4.2 Results

4.2.1 Usability Test: Qualitative data

The results are presented according to the main aspects that were evaluated in each session:

What is the best way of holding this instrument?

- 7 participants, who were music producers, said that they preferred to play the instrument by lying it horizontally on the legs or on the table. 2 of them, who were also string instruments players, pointed out that that way of holding the instrument was similar to the one used to play a lap steel guitar.
- 1 string instruments player preferred to play the instrument like a harp.
- The 2 remaining participants preferred to play it like a guitar.

Visual and Physical Design

- Generally, the visual design and appearance of the instrument got positive feedback by all participants: *"it's cool and strange"*, *"Beautiful design, very intriguing"*, *"resembles an acoustic string instrument"*, *"Layout fine played like a lap steel guitar, can also be played like a cello"*.
- Most participants found the instrument a bit heavy. Some of them stressed nevertheless, as something positive, the fact that the instrument was quite sturdy despite being a prototype.
- When it comes to the ergonomics of the instrument, the participants who were music producers considered that the upper part of the fingerboard was a bit thick and that notes were hard to reach with the left hand. Nevertheless, they highlighted that the instrument was ergonomic when played horizontally on a surface.
- Overall, participants found that the labelling proposed was good. However, one of the NIME experts suggested that, as a future improvement, a LED display could be used as a menu to show the parameters mapped to each knob.

Sound Design and Midi Configuration

- Regarding the mappings of the device, NIME experts found them interesting but considered that it would take a little bit of time to master them. Regarding the softpots, some NIME experts suggested that the FSRs could be used to detect if the softpots were pressed in order to avoid some glitch sounds. In addition, one of those experts proposed to make the mappings work with every VST plugin, given that the instrument only works with VST plugins thanks to a pitchbend parameter control.
- When asked about the number of sound engines the instrument should have, the participants who were music producers generally agreed that the instrument should only have one, instead of having the subtractive synth and the Karplus Strong synth. They argued that this would provide the instrument with a "unique personality". Moreover, one of them stated that quality should be prioritised over the number of patches.
- When it comes to the synthesis capabilities of the instrument, more diverse opinions were put on the table. On the one hand, the participants who were music producers found that the Karplus Strong synthesizer sounded good and that the parameters chosen for this synthesis were appropriate. One of them specified that the sound produced was "full and crips" and similar to the sound produced by "shamisen" Japanese string instrument. On the other hand, NIME experts found that the options offered by the subtractive synthesizer were a bit limited given the actual set of controllers. This synth was considered to be "a bit bland needing some sound effects and modulation".

Tonal Systems

- 3 out of the 10 participants were familiar with several tonal systems. Among those 3 participants, two of them were string instruments players and stated not only that the instrument was adequate to be played on the different tonal systems provided but also that they could feel the difference between the different tonal systems when they were playing the instrument.
- In contrast, the other 7 participants were only familiar with the 12-TET. When asked if they found it easy to play with the other tonal systems, some said that it was hard given the absence of visual frets to let them know the notes they were playing. However, one of them also stated *"it seemed easier to play as if everything I did was pleasing"*.
- When asked about what kind of music they thought this instrument could be good at making music for, a large range of genres were mentioned: intelligent

dance music, pop music, ambient music, electronic music and psychedelic/experimental rock music.

Musical Gestures

When it comes to musical gestures, all participants identified musical gestures from string instruments while playing the instrument and agreed on the fact that the instrument enabled the player to make those gestures with a high level of accuracy. Moreover, some string instruments players said that the gestures were very responsive and one of them even added that the instrument enabled the player to make those gestures in an easier way because, given that his hands were free, it was for instance possible to slide between bass notes and melody notes at the same time.

Additional Comments

Additional comments from the participants are listed below:

- *"Instrument feels too sensitive for a keyboard player without experience on fretless instruments" "Hard to play with tonal systems since I have no experience with non 12-TET" - NIME expert and music producer.*
- *" A bit hard to play at the first place, would need to get used with the instrument" - Music producer and string instruments player.*
- *"I recommend to add a LED screen for labelling and parameter control" , " sensors are a bit glitchy" , "Definitely looks like a real instrument and with a few fixes and improvements, it could be very playable" - NIME expert and music producer.*
- *"I suggests an on-board display of various systems-pointers for the notes" , "Once some technical issues are resolved, I believe this instrument gonna have a warm welcome among instrumentalists" , "Stronger characteristics: Design, intuitive to play and working as midi controller" - Musicologist and string instruments player*

4.2.2 Usability Test: The SUS Score

Usability Scores

Based on the original 10 questions from the SUS, the Flying Multitonal Zither scored on average 70.20 ("Good" in the SUS Scale) with a standard deviation of 8.99.

In addition, it was found that there was a negative correlation between the scores of the original 10 questions from the SUS and the scores of the 11th question, $r = -0.4$. By mapping the SUS scores to the adjective spectrum (e.g. Figure 4.6) by

SUS Score

	X (odd numbers - 5)	Y(25 - even numbers)	(X+Y)	SUS Score (X+Y)*2.5	Adjective Rating from SUS Score	User-Friendly Question	User-Friendly Score
Participant 1	10	10	20	50	Awfull	5	Good
Participant 2	16	17	33	82,5	Excellent	5	Good
Participant 3	14	14	28	70	Good	5	Good
Participant 4	13	18	31	77,5	Good	5	Good
Participant 5	12	16	28	70	Good	6	Excellent
Participant 6	15	13	28	70	Good	6	Excellent
Participant 7	14	15	29	72,5	Good	6	Excellent
Participant 8	14	16	30	75	Good	5	Good
Participant 9	15	17	32	80	Good	5	Good
Participant 10	14	13	27	67,5	Okay	5	Good
FINAL SUS SCORE (AVERAGE)				70,2627950321679	Good	5,26315789473684	Good
Standard deviation				8,99073597284078		0,483045891539648	

Figure 4.5: Table showing the SUS scores and Adjective rating scores of each participant [1].

Bangor et al. [1], we can indicate that 6 participants rated the instrument with adjectives that were different compared to their SUS results.

However, if we take the average SUS score of the 10 participants and the average adjective rating score of the 10 participants separately, the usability of the instrument can be considered to be "good". Moreover, the average SUS score of the 10 participants falls within the "acceptable" category on the acceptability range.

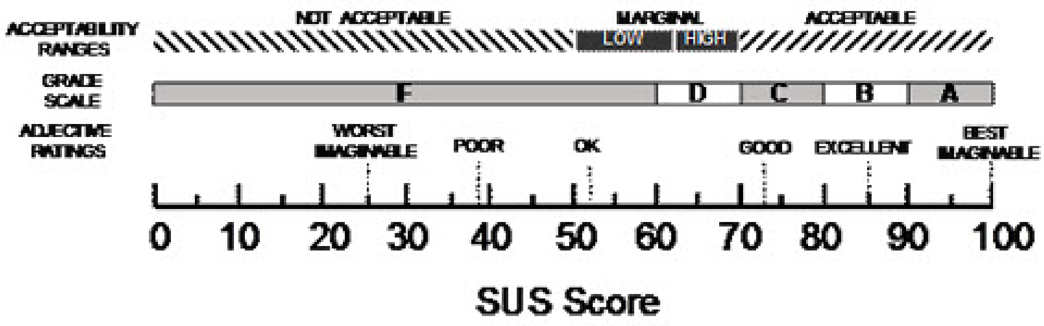


Figure 4.6: The adjective spectrum by Bangor and colleagues [1].

Chapter 5

Discussion

5.1 Evaluation method

As mentioned in [12], it is clear that the most important stakeholder in the process of designing a digital musical instrument is the performer. In this regard, any instrument will prove to be a failure unless it can successfully translate the musical intent of the performer into sound in a reliable way.

Based on that reasoning, we decided to rely on different skilled musicians, who were experts on different fields related to sound and music computing, in order to conduct the evaluation of our instrument. Even if the evaluation didn't take into account their level as musicians, it has to be noted that all participants but one were amateur performers, the remaining one being a professional musician. In addition, it was deemed important not only to get feedback from string instruments players but also from music producers that didn't necessarily play any kind of string instrument. Indeed, it was considered that both categories of experts were well positioned to try to search out the expressive limits of a new instrumental design, especially one that tries to bring the expression from string instruments to the framework of digital musical instruments.

Some might say that a more in-depth evaluation could have been undertaken. However, from our perspective, the main goal of a musical instrument is to be able to make and perform music. Having that in mind, the evaluation method that was followed seemed to be relevant and adequate.

5.2 Design implications

After testing the functionality of the instrument, it was noticed that some of its components weren't working as expected. In addition, some participants highlighted that some features of the instrument were a little bit "glitchy". According to them, several notes were sometimes triggered when one single position of the softpots was pressed. Moreover, the functionality test showed that some of the knobs weren't working well due to the multiplexer connections.

Any future version of the Flying Multitonal Zither should therefore address those issues by refining the wiring of the circuit.

Finally, even if having a more realistic string synthesis is a more significant technical challenge and one that was beyond the aim of this Master's thesis, the instrument might be modified in the future so as to only have the Karplus-Strong algorithm or an advanced physical model synthesis.

5.3 Usability Implications

After having analysed the results of the evaluation, some points can be made about the development of the instrument.

Overall, based on the qualitative data gathered and the average SUS score of the Flying Multitonal Zither, it can be said that this first prototype is acceptable from a usability perspective. Most of the functionalities of the instrument were positively perceived by the participants. In addition, its visual design got very positive comments. The instrument was perceived by some participants as an actual real instrument that resembles an acoustic string one. Moreover, it was considered to be ergonomic when played horizontally on a surface. Nevertheless, in order to get additional feedback about the physical design chosen for our instrument, a more in-depth evaluation should be conducted. This evaluation could focus on whether proprioception, which is the sense of self-movement and body position in charge of training our muscle memory, arises when playing the instrument. In this regard, testing sessions aimed at analyzing to what extent the device is a learnable instrument could be conducted [1].

Regarding the musical gestures from string instruments that the instrument was supposed to let the player make, the participants agreed on the fact that the instrument enabled the player to make those gestures with a high level of accuracy. In addition, the general tonal limitations of string instruments seem to have been overcome given that the participants who were string instrument players familiar with several tonal systems considered that the instrument could be adequate for playing music in those tonal systems. It is also interesting to note that, generally speaking, it was a little bit challenging, for musicians that were only familiar with the equal temperament system, to play melodies in other tonal systems without having the feel of being "out of tune".

When it comes to the sound design and midi configurations, participants approved at least one of the synthesizers of the instrument and were satisfied with the midi capabilities of the instrument. In addition, it was generally pointed out

[1] `https://en.wikipedia.org/wiki/Proprioception`

that the instrument should have no more than one synthesizer and work as a midi controller. These comments will be taken into account for the next design iteration since it seems a good idea to try to make sure that the instrument has a unique sound and personality.

Finally, the negative correlation that was found between the scores of the original 10 questions from the SUS and the scores of the 11th question could be considered to be a bias since the instrument only got a poor score ("Awful" and "Okay") in the SUS coming from the assessment of two participants despite the fact that those two participants had chosen the adjective "Good" to rate how user-friendly the instrument was. In any case, if we leave aside that potential bias, the negative correlation could be explained by the fact that those two participants weren't too honest when answering the 11th question. Another alternative explanation could be that they filled out the SUS form having in mind the actual prototype but they answered the 11th question having in mind the final version of the instrument.

Chapter 6

Conclusions & Future Work

This iteration has enabled us to gather evidence in order to provide an answer to the final problem statement of this Master's thesis *"How can we create a new gestural controller inspired by existing string instruments in order to keep expressive playing techniques and to overcome some tonal limitations of the original instruments?"*. The evaluation of the instrument has indeed been useful for identifying some design issues as well as the strongest features of the instrument.

As a starting point, it can be asserted that the usability of our instrument was generally well perceived by the different experts. Indeed, the analysis of the results shows that experts generally enjoyed the instrument and found it adequate for playing music in different tonal systems. In addition, our goal of creating a gestural controller seems to have been achieved given that the participants identified musical gestures from string instruments while playing the instrument.

The instrument seems nevertheless to be more appealing for musicians familiarized with the tonal systems that the instrument allows to play with. Moreover, one participant highlighted that it would take him some time to get used to the instrument. This could be explained by the fact that the instrument is presented as a fretless instrument, without visual cues that would let the performer see the notes' divisions of each "string". In any case, this doesn't seem to be a big issue given that learning how to play any kind of instrument always requires a certain level of practice.

Regarding the sound design, the sound processing options offered by the instrument let us determine the next steps that should be taken in further iterations. Since most of the participants agreed on the fact that the instrument should only have one sound engine and that the Karplus-Strong synthesizer was really interesting, we should try to ensure that, in the future, our device has a good physical model synthesizer. Along with it, the MIDI controller would not disappear in future designs given that it was one of the most valued features of the instrument.

When it comes to the design issues, some design deficiencies were highlighted by the participants such as the weight of the device. Insights were also obtained regarding the softpots which were sometimes perceived as triggering notes that were not pressed. Moreover, the functionality test let us detect some problems with the knobs. We will explain how those issues could be tackled in the future in the next section.

Overall, we therefore consider that we have been able to create a new digital musical instrument that allows the same level of expressiveness as string instruments and has the flexibility provided by controllers usually found in keyboard synthesizers.

6.1 Redesign and technical fixes

The next step of this project will be to redesign some aspects of the current prototype.

Firstly, a new version of the body, with less layers of wood material, will be built in order to make the instrument lighter and more comfortable when played in different positions. Moreover, given that the rubber cord stretch sensors were not used in the end, the space that was originally assigned for them will be reduced in order to make the fingerboard less thick and more accessible to play the lower notes of each softpot.

Secondly, the technical issues that were identified during the whole evaluation will be addressed:

- Multiplexer connections: when it comes to the two potentiometers that didn't work and the bad mapping obtained on the synthesizers, it is highly probable that the multiplexer in charge of managing the 8 potentiometers connections interfered with the audio pins of the audio shield. In order to solve this issue, the solution will consist in connecting the control pins of the multiplexer in charge of managing the 8 potentiometers and the control pins of the multiplexer in charge of the sensors to a same bus connected to 4 digital inputs of the Teensy. The connections will be similar to the ones shown in figure 6.1.

- Softpots: these types of potentiometers are known to be a little bit problematic if they don't lie on a completely flat surface. Even if we were aware of this problem when the prototype was built, it was hard to obtain a completely flat surface and we decided to lie the softpots on the FSRs and some foam. In the next prototype, the above mentioned issue will be addressed by adding an extra layer of thin layer of plastic between the FSRs and the softpots.

- PCB Design: in the current design, several strip-boards were used to connect every part of the circuit together. In the future, the circuit could be upgraded to a designed PCB.

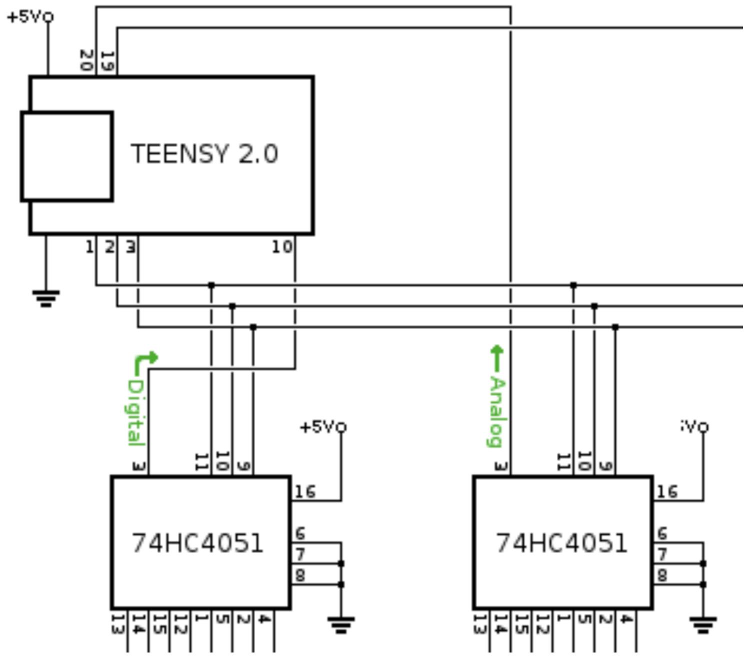


Figure 6.1: Future connection of the multiplexers to the teensy.

6.2 Future work

After redesigning some aspects of the current prototype and fixing the technical issues that were identified, the following improvements could be made:

- LED display for showing parameters values: instead of using the labelling proposed for the current prototype, a LED display could be added to the instrument so as to show the name and value of the potentiometers. In addition, the display could also be used to show in real-time the notes or the chords that the player is playing.

- LED strip to signalize the layout of the notes of each tonal system: since some of the experts complained about the absence of frets that would show the division between notes, a LED strip could be placed on the center of the instrument and along the height of the fingerboard in order to display different color arrays for each tonal system. The LED strip could have a configuration similar to the one used in the LinnStrument shown in figure 2.3.

- Having a more realistic string synthesis: even though the Karplus-Strong algorithm was generally pleasant enough for the participants, the instrument could be upgraded so as to make sure that it has a more realistic string synthesis. In order to achieve that, a micro-controller, more powerful than the Teensy, would be needed, such as the Raspberry PI, in addition to conducting research aimed at choosing a physical model for the instrument.

- Adding Aftertouch: Aftertouch is a MIDI data sent when pressure is applied on a keyboard after a key has been struck and as long as it is held down or sustained [1]. Given that the Teensy is fully functional with the MIDI protocol, adding Aftertouch could be easily done by adding some lines to the actual code of the instrument.

- Adding MIDI messages to create lightning shows: in order to improve the user experience, and since the device is a midi controller, it would be possible to envisage that, by playing the instrument, a lightning show would be created. Indeed, the musical gestures made by the player with the device could be mapped to MIDI messages that could potentially control some lights. This improvement would give the instrument a completely new perspective that could enhance the user experience.

[1] https://www.sweetwater.com/insync/aftertouch/

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Appendix A

User Questionnaire Interview

A.1 Welcome

The Flying Multi-tonal Zither is aimed at creating a new digital musical instrument allowing the same level of expressiveness as string instruments(vibrato, slide, picking...)and having the flexibility provided by controllers usually found in keyboard synthesizers. Moreover, this instrument explores how different scales from different cultures (such as well-tempered scale, polychromatic scales and microtonal scales) can be integrated within the same device in order to create a flexible and versatile instrument.

All the information acquired from the participants in this questionnaire will be only used for examination purposes.

A.2 Participant's information

- What's your name?
- How old are you?
- Which of these expertises are you more familiar with?
  - Electronics [ ]
  - NIMEs design [ ]
  - Music producer familiarised with the use of synthesizers and midi Controllers [ ]
  - String instrument player (guitar, violin, sitar player...) [ ]
  - Musician familiarized with other tonal systems than 12-TET [ ]

A.3 Visual and Physical Design

- What did you think of the Flying Multi-tonal Zither when you first saw it?
- What do you think of this layout?
- Do you think this instrument is ergonomic?
- What do you think of the size and weight of the device?
- What are your opinions about labelling the controllers?
- Do you have any additional comments towards the visual design of the instrument?

A.4 Sound Design and MIDI configuration

- How can we improve the mapping between controllers and parameters?
- What do you think about the default sounds the instrument can play?
- How many different patches do you expect from an instrument like this?
- What do you think of the midi possibilities offered by the instrument?
- What do you think of the synthesis possibilities offered by the instrument?

A.5 Tonal Systems

- Are you familiar with other tonal systems than the 12-TET?
- If yes, is this instrument adequate to play in those tonal systems?
- If not, was it hard for you to play on those you were not familiar with?
- Did you notice any difference on the display of the notes when you change between the different tonal systems?
- What kind of music do you think this instrument would be cool to use for composing?

A.6 Musical Gestures

- Which musical gestures, from string instruments, are you able to perform with this instrument?
- How good do you think this instrument lets you perform those gestures?
- Do you miss any musical gesture from string instruments?

A.7 User's Experience

- If you could add any feature(s), what would it/they be?
- Was there anything about the instrument that felt like a mistake or a bug?
- Do you have any final comment do you want to add regarding your experience with this instrument?

Appendix B

Bill of Materials

Part	Components needed	Qty.	Manufacturer
Body	- Hardboard (wood product) - Wood Glue - Spray paint	- 10 sheets (1000 x 700 x 4mm) - 1 Bottle of 500ml - 2 Aerosol Spray (400ml) (Red and Black)	 - Fixer - Belton
Fingerboard	- Softpots - Copper tape - Velostat - Foam	- x 4 - x 1 - 2 sheets (280mm x 280mm)	- SpectraSymbol - 3M (Tc) - Adafruit Industries LC -
Pickguard	- 10K Ohms Potentiometers - Knobs	- 8 potentiometers - 8 Knobs	- WL - Taiss
Micro Controller and other Components used	- Teensy 4.0 - Audio Shield D - Multiplexer 16-Channels	- 1 board - 1 board - 2 boards	- PJRC - PJRC - Sparkfun
Connectors	- MIDI In port - Jack female input - power supply female connector	- 1 connector - 1 connector - 1 connector	

Figure B.1