THE XT SYNTH:

AN EXPRESSIVE MIDI CONTROLLER FOR STRING PLAYERS

Submitted by

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ABSTRACT

This paper describes the concept, design, and realization of two iterations of a new musical instrument called the XT Synth. The development of the instrument came from the desire to maintain the expressivity and familiarity of string instruments, while adding the flexibility and power usually found in keyboard controllers. There are different examples of instruments that bring the physicality and expressiveness of acoustic instruments into electronic music, from "Do it yourself" (DIY) products to commercially available ones. This paper discusses the process and the challenges faced when creating a DIY musical instrument and then subsequently transforming the instrument into a product suitable for commercialization.

Author Keywords

Synthesizer, MIDI Controller, Strings, Human Computer Interaction, NIME

1. INTRODUCTION

The XT Synth[1] is a new musical instrument with continuous polyphonic pitch control, augmented with force sensitive resistors, potentiometers and rotary encoders. It has a 3D printed body and LED lighting on a transparent top acrylic layer. It began as a synthesizer, but is now a MIDI controller. The instrument features familiar techniques translatable from string instruments, specifically the guitar and violin family. Its visual component (see Figure 1) adds another level of expressivity, where light patterns are created in addition to the sonic elements. The XT Synth is an ongoing project, currently in the design stage of its second iteration. This paper discusses what the XT Synth was, what it is, and where it is going. This paper will illustrate how the process of iterating between different prototypes affected the development of the XT Synth.

Generally speaking, for this paper, new instruments can be broadly separated into two categories: instruments that have a translatable performance technique from other instruments and instruments with such a specific technique that can't be translated from other instruments. Traditional instruments have well-established performance techniques and usually belong to a family of instruments. Instruments like the harpsichord, violin, or guitar, feature performance techniques that are translatable to other instruments of their family. For example, certain guitar techniques are easily translated to the mandolin, such as picking and fretting techniques. On the other hand, some new musical instruments do not easily translate their technique to any other instrument, because they have a unique design, thus a unique technique. Novelty comes with a price, the more unique the performance techniques of these instruments are, the more distant they become from familiar techniques of existing instruments, and thus from the centuries of refinement embedded within them. One of the factors for the staying power of new instruments is the balance between novelty and established techniques of traditional instruments. The XT Synth attempts to remain in the middle of this continuum. While some of its technique can be translated from string instruments like guitar and violin, it adds novel features with their own techniques for expressive control.

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[1] Videos and pictures of the XT Synth can be found at: www.musiconerd.com/xtsynth

In recent years, novel instruments with continuous pitch control have been found great success, such as the Continuum (Haken & Tellman, 1998) and the ROLI Seaboard (Lamb & Robertson, 2011). Additionally, augmented guitars like the Sensus (Sensus, 2018), from Mind Music Labs, are in production. Such augmented guitars feature a variety of sensors to affect onboard audio processors, but don't attempt to provide MIDI control over synthesizers. The XT Synth seeks to fill the gap between these two ideas. That is, the XT Synth is a continuous pitch controller for string players, augmented with sensors. While most closely aligned with augmented guitars, the continuous pitch control focus intends to make the XT Synth a familiar instrument to other fretless string instruments as well.

The process of creating the XT Synth transitioned from developing a personal project towards developing a commercially viable product. This process affected the design of the each iteration. Features needed to be added and others excluded, not only to satisfy artistic desires, but also to be resilient, inexpensive to build, and easy to manufacture.

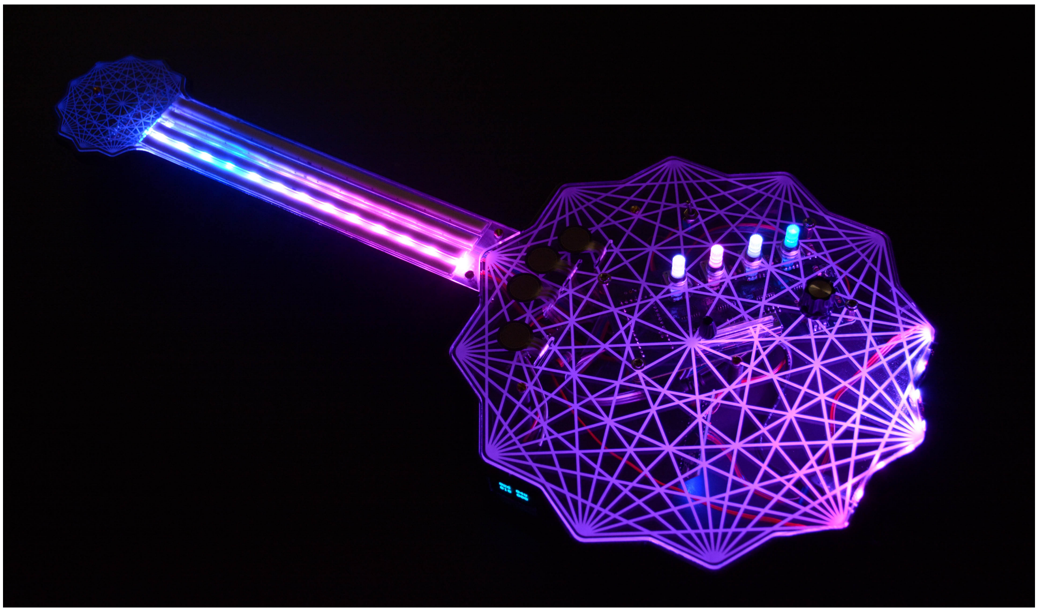

Figure 1. The XT Synth.

The process of creating a commercially viable interface differs drastically in its production process, from the first sketches to fabrication. This paper will, in part, outline the approach used to shift XT Synth from a

DIY instrument to a commercially viable product. It's necessary to say that this an ongoing project, and, as such, a commercial viable product means a product that is: "as finished as possible, ready to be commercialized".

2. BACKGROUND AND MOTIVATION

The main motivation in designing the XT Synth was to create an instrument that could feature a performance technique that is easily translatable from string instruments, like guitar, mandolin and violin; that could have the expressiveness of non-fretted instruments, like a violin, or theremin; and that could be a synthesizer and a MIDI controller.

Most of the MIDI controllers on the market have discrete control of pitch. In other words, pitch is quantized. Discrete controllers are those most often associated with keyboard controllers, where each key sends just one value for note and velocity when it is pressed, or released. Several of these keyboards still have ways of manipulating parameters in a continuous way, like using the pitch bend wheel, or aftertouch. However, this level of expressiveness is still limited. Using a pitch bend wheel for making vibrato is impractical and poorly reflects how the vibrato in an acoustic instrument is actually made. Another problem is that the pitch bend controls all the notes that are being sent on that particular MIDI channel. So, if pitch bend is sent on channel one, all the notes on channel one will be bent. Thus, it is impossible to make different vibratos, or glissandos, for different notes played simultaneously. Such instruments feature MIDI monophonic expression and lack MIDI Polyphonic Expression (MPE) (Midi Polyphonic Expression (Mpe) Specification Adopted, 2018). MPE is a MIDI implementation that allows individual notes to have their parameters, like pitch bend, controlled individually. With MPE it is possible to achieve individual control of each note played, closer to how one plays an acoustic instrument. MPE will be better discussed later in this paper.

The XT Synth was designed to be an instrument with MIDI polyphonic capabilities and with continuous control for pitch and other parameters. It uses hardware and software technologies to enable the translation of performance techniques of string instruments that have been around for centuries into an electronic instrument, with all the possibilities it holds.

There are several MIDI instruments on the commercial market that feature the continuous control of pitch. These include the Continuum and the ROLI Seaboard, to name two. There are also instruments like the Linnstrument (Roger Linn Design, 2018), which is played in a similar manner to a keyboard, but with the form factor of a guitar. These instruments allow full MIDI Polyphonic Expression for continuous control of pitch, pressure, etc., allowing great expressiveness over vibrato, glissandos, volume, and any other control that can be MIDI mapped. However, these instruments are designed with a keyboard technique in mind, making it hard for string players to adapt quickly to it.

Closely related instruments to the XT Synth, employing violin techniques or violin-inspired techniques, include Dan Overholt's Overtone Violin (Overholt, 1998), Suguru Goto's Super Pal (Pierrot & Terrier, 1997), and Charles Nichols' vBow (Nichols, 2003). Those instruments have a known technique, like the violin's, technique but also have a variety of augmenting sensors. This allows for violinists to perform with electronic sounds, but still using a familiar performance technique.

Two of the closest examples to the XT Synth's implementation of continuous pitch control are David Vorhaus' Kaleidophon (Berg, 2017), invented in the 1970's and the Artiphon's Instrument 1 (Instrument 1, 2018), launched in 2015. The Kaleidophon has four ribbons, mounted on a drainpipe. These four ribbons are played using the left hand technique of a guitarist. This instrument controls an analog synthesizer by sending voltages associated with the position of the fingers upon the ribbons. The Kaleidophon never became a commercial product. The Artiphon's Instrument 1, however, became a successful example of a commercial MIDI controller that combines the playability of string instruments with continuous controllers and MIDI Polyphonic Expression. The Artiphon has sensors that act like strings, and actuators that can be used to "pluck" the strings, plus other features. The Artiphon was designed (for better or worse) to be consumed by the masses. It is an instrument that was made to be functional, with a simple design. While the Artiphon and the XT Synth share several characteristics, the Artiphon looks to be more a music production tool, while the XT Synth is a performance tool, although both can do both.

Non-fretted instruments are known for being hard to play and not providing instant gratification. One can think about the beginning violin student and the sounds emitted. This steep learning curve can cause a great deal of frustration for beginners. However, instruments that are hard to play tend to offer a high ceiling for virtuosity, given time. Instruments that are really easy to play, on the other hand, often sacrifice flexibility for certainty. The XT Synth leans to the side of flexibility, giving room for expressivity and virtuosity. The XT Synth is not easy to play like some electronic instruments, for example a Novation Launchpad (Launchpad, 2018). With a Launchpad a press of a button can play an entire song! While the song is played perfectly, the performer has no expressive control over the playback. The ceiling of virtuosity is low. The XT is closer to an acoustic instrument, where practice is needed to perform the instrument properly and such practice offers the reward of freedom of expression.

Although the XT Synth has no frets, in its software it has a quantization method that allows the performer to hit the right notes the first time the finger touches the neck, while still allowing vibratos and slides. The quantization is a trade off between flexibility and learning curve, the more flexible it gets, the harder it is to play. The quantization can be switched on and off, leaving to the player to decide.

After conceptualizing the functionality of the XT Synth, the design was considered. As a guitar player, my first sketches leaned towards guitar designs. Guitars are instruments that come in a wide variety of shapes. This is particular true with electric guitars. Choosing the shape of a guitar is more than choosing a type of sound, it also tells something about your style, your personality. In this sense, visual aesthetics are important. The visual aspect of the instrument implies something even before it is played. Different expectations are set if a Gibson Flying V, or a Fender Telecaster is on stage. Guitar shapes tend to vary, having their own “personality”, while MIDI controllers tend to be neutral, being visually similar to each other. I decided that the XT Synth should have its own visual “personality”. It should have its own unique form factor. The inspiration for its design came mostly from the spiritual and psychedelic movement from the late 50s and 60s. More about the XT Synth's design will be discussed later in this paper.

The first prototype of the XT Synth was built rapidly in two weeks. The prototype featured the typical weaknesses of prototypes, such as: components soldered with wires on solderable breadboards; fragile enclosure; various elements were not structurally secure (even glued with super glue!). There were various glitches, which will be discussed later. The less than polished aspects of the prototype can be seen in figure 2, such as the wires sticking out from the body of the instrument.

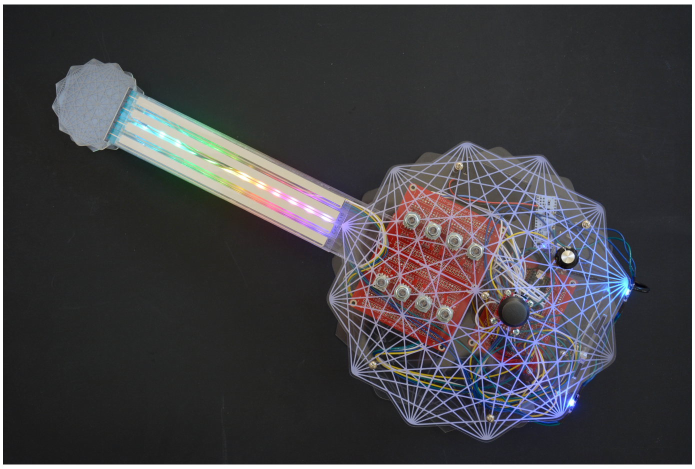

Figure 2. The XT Synth in the light.

The original goal of the XT Synth was to be a personal project. However, the first presentation of the prototype XT Synth generated surprisingly strong interest from the online community. This led me to transform it into a commercially viable product. Without experience with mass produced products (at all), this was to be a learning experience. The making process needed to be drastically faster, the instrument itself much more durable, and its features, design, and components needed to be rethought to reduce expense while maintaining quality. With that in mind I made a second prototype. It featured a 3D model for the enclosure, custom Printed Circuit Boards (PCB) were made, and a reimagining of its sensors and features. Lessons learned and technical and philosophical aspects of making the XT Synth will be discussed later in this paper.

2.1 Vibrato and Electronic Music

Expressive elements of performance are hard to come by in electronic music. Small variations of musical parameters, usually provided naturally on acoustic instruments, are absent on electronic instruments, specifically the small variation of pitch known as vibrato. While it is possible to perform vibrato in several ways on an electronic instrument, it lacks the same quality and physicality of an acoustic instrument. In fact, vibrato was the first motivation for building this instrument. Vibrato is a common technique in acoustic instruments, but it is still a secondary subject of most electronic instruments. Because of that, it is important to recognize the importance of the vibrato in acoustic music and its past and future role in electronic music.

2.1.1 The Vibrato

Vibrato is "A regular fluctuation of pitch or intensity (or both), either more or less pronounced and more or less rapid. The Italian term 'tremolo' is also occasionally used for vocal vibrato" (Moens-Haenen, 2001). It is a common technique present in most vocal, or instrumental performance, assuming the instrument is capable of such pitch modulation.

Violin vibrato has been used for centuries. It have been alternately called a plague, or life-giving and charming. It was something that was used as an embellishment, but in the first decades of the twentieth century, it became an integral part of the violin sound, when it became more and more present.

Much can be said about why this shift occurred. In the chapter "Violin Vibrato & the Phonograph (Katz, 2004), this phenomena is seeing as a consequence of the phonograph. Before the twentieth century, vibrato was advised to not to be overused, the "heart" of the expression was the bowing, not the vibrato. The increase of the vibrato was really noticed in 1910 and in 1916 vibrato was considered indispensable.

Analysis of several recordings reveals an increase in the vibrato throughout the first two decades of the twentieth century, but why? Changes in construction of the violin, put more weight on the shoulder of the performer. This could have given the left hand more freedom to perform the vibrato. Other considerations could be the adoption of metal strings, where the vibrato was used to soften the sound, among others. But none really give a clear explanation of why it became the standard. For Katz, recordings were the main reason why. One reason is that due to the poor quality of the recording the vibrato helped to accommodate the sound. The vibrato also helped to obscure imperfect intonation, which is more noticeable in a recording; and it could give a better sense of the performer's performance, because one's body expression was not going to be seen by the audience.

Another reason was that the performer would need to play near the horn of the recording device. Due to the primitive recording techniques of the time, the performer needed to either play louder, or stand closer to the recording horn. Standing near to the recording horn risks touching the horn with the bow. Additionally, the sound of the bow in the recordings would be more prominent. Vibrato was used to overcome these obstacles. It would create a louder sound with less noise.

Vibrato has a close relation between sound and physicality. It is an important idiomatic aspect of string instruments and voice, but what about electronic instruments? Although we might categorize "electronic instrument" as a type of instrument, these instruments vary largely, thus, the way their vibrato is produced also varies.

2.1.2 The First Electronic Musical Instruments

The chapter "Electric Dreams: 1900-50" (Katz, 2004) tells us about the main electronic instruments that were invented in the first half of the 20th century. The first electronic instrument to ever make a public appearance was the Telharmonium, created by Thaddeus Cahill. The Telharmonium was the first major event in electronic music, combining the technology of the electricity and the medium of the telephone. He noticed that he could use dynamos to create different pitches, and thus to create music. Not only could this electronic music be performed, but also it could be transmitted down to the telephone lines, being broadcast in different places at the same time. It was clear that the Telharmonium could target a mass market, because it could send music to several different venues, which would pay a subscription. The Telharmonium concerts combined popular orchestral and opera selections along with ragtime.

In 1907, the same year that the Telharmonium was invented, Ferruccio Bussoni published his sketch of a New Esthetic of Music, talking about the future of music relating it with electrical sound sources. In 1913 Luigi Russolo wrote his manifesto The Art of Noises, which stated that new technologies were bringing new sounds to the environment and, with time, machines would be invented to recreate those sounds musically.

The Theremin was invented in 1919 by Leo Theremin and, differently from the Telharmonium, it was compact, simple to use and could be run off a domestic power supply. After many iterations, the instrument became popular and it was used as a soviet propaganda tool to represent the drive for progress. Although the instrument was simple, it was really expensive and hard to play. Besides that, because of 1929 Great Depression no more than 500 units were built. However, it was a historical mark for being the first electronic instrument to be available to the general public.

In 1928 Maurice Martenot patented in Paris an instrument called the Ondes Martenot. It was a complex instrument, which could be played with a keyboard, or with a ribbon, allowing portamento and vibrato. Its sound was comparable to the Theremin, but with more sonic possibilities and easier to play, because it was associated with a keyboard. The Ondes Martenot had more orchestral pieces written for it, like the well-known Turangalîla Symphony (1948) by Messiaen.

There are numeral other instruments that are influential, such as the Trautonium, the Novachord, Solovox, the Ondioline and the Clavioline. A full discussion of these instruments is outside the scope of this paper. However, details concerning them can be found in (Chadabe, 1997).

Perhaps, the greatest influences on current electronic instrument design are Robert Moog's synthesizers of the late 1960s. Initially, Moog synthesizers were not made with a focus on performance, but rather as studio instruments. However, Moog started to think about ways to make an instrument for live performance. The question was: what form should it take? For Vladimir Ussachenvsky, the director of the Columbia-Princeton Electronic Music Center, it shouldn't be a keyboard, because it would be treated as a novelty organ. In the end, Moog chose the keyboard form because it was going to be more marketable and easy to use.

Synthesizer creator Don Buchla was also creating synthesizes and had a path similar to Robert Moog, however he was more interested in the *avant-garde* than in the commercial aspects. He was commissioned by Morton Subotnick and Ramon Sender to build an electronic device that could be used for composition and performance, and which would help to eliminate the laborious process of tape editing. This device became to be the Buchla Series 100 Modular Electronic Music System.

At this time, Moog synthesizers were still big and expensive. The EMS VCS 3 was the first affordable synthesizer, released in 1969. In 1969, Moog started to work on a small performance synthesizer and finally launched what was called as a "compact, moderately priced electronic music synthesizer designed and built for live performance", the Minimoog. Other companies started to launch their own compact and affordable synthesizers as the market for such instruments increased. ARP launched the Odyssey in 1972, and Korg, Yamaha and Ace Electronics (the forerunner of Roland) started to launch their models in the following years.

2.1.3 The Vibrato in the Electronic Music

In the 1920's, the vibrato was an integral aspect of string instruments technique. But, how vibrato would affect the performance technique of the upcoming electronic musical instruments? The theremin was a non-tempered instrument, just like the violin, considered to be extremely difficult to be played in tune. The vibrato, besides being an embellishing artifact, also helped theremin players to play in tune, and became a prominent characteristic of the instrument's sound.

The Ondes Martenot was a hybrid of non-tempered instrument with keyboard instrument. One could play it with keyboard keys, but also with a sliding ring that allowed portamento and vibrato. The instrument featured the ability to toggle back and forth between keyboard control and the sliding ring, which controlled pitch with a ribbon.

Perhaps because of the lack of success in sales, or perhaps partially due to the difficulty of playing in tune, the Theremin discouraged other companies to launch non-tempered electronic instruments. Although modular synthesizers without keys, like the Buchala 100 Series, became popular, the choice of using a keyboard for the portable Moog synthesizers became the industry standard in the upcoming electronic musical instruments.

Playing vibrato in a physical way, as is done on the theremin and on the Ondes Martenot, was lost in most of the synthesizers and MIDI controllers created until the recent years. To produce vibrato, without having a physical way to make it, other electronic techniques were used to emulate the natural sound of the vibrato, or to create different and more extreme sound effects. The process to create vibrato in an electronic system is called “frequency modulation”. This technique consists in modulating the carrier frequency by using another low frequency oscillator.

This way of making vibrato was the standard in most commercial electronic musical instruments until recent years. In 2015, ROLI launched the ROLI Seaboard, an instrument that allowed keyboard players to make electronic music with polyphonic expression, with multiple different vibratos, portamentos, pressure, etc. The product gained great success and media acknowledgement, opening doors for new expressive electronic musical instruments.

The XT Synth enables one to play with a vibrato technique in a similar manner to the left hand violin technique. It allows a level of expressiveness encountered in acoustic instruments and in only a few electronic ones.

3. THE INSTRUMENT

The XT Synth was conceived as an instrument that can be played with a technique familiar to string players, with augmenting sensors for real time sound manipulation. The instrument, at the time of writing this paper, has gone through two prototypes. The most recent iterations in hardware and software will be discussed, along with why some previous ones were abandoned, or changed to the way they are now.

In the following sections, the main features that comprise the XT Synth will be discussed: pitch control - soft potentiometers; parameter control – force resistive sensors, potentiometers and rotary encoders; synthesis; MIDI; PCB design; instrument body design – 3d and 2d design, 3d printing and laser cutting; lights.

3.1 The Synthesis Engine

The first prototype of the XT Synth was a MIDI controller and a synthesizer. The goal was to have an instrument with an affordable embedded digital synthesis engine. The synthesizer feature was later abandoned. The reasons for that will be discussed in this section.

In the past I have tested different boards from the Arduino family (with various libraries) as synthesizers. To decide which board to choose, I looked for: portability; processing power; number of I/Os; number of interrupts; whether it can be recognized as a MIDI class compliant device; and if it has a DAC and/or audio compatible board. For the first prototype I chose the Teensy 3.2 and for the second the Teensy LC.

The Teensy 3.2 is an Arduino compatible board from the PJRC Company. It has a Cortex-M4 microcontroller, with enough power for moderately complex synthesis techniques and it contains one 12-bit DAC. It can generate audio at a 44100hz sample rate. The Teensy 3.x family has an audio library. Code can be generated using the audio library via a GUI (Figure 3). After laying out the synthesizer in the visual workspace, one can export code that can be used in the Arduino IDE.

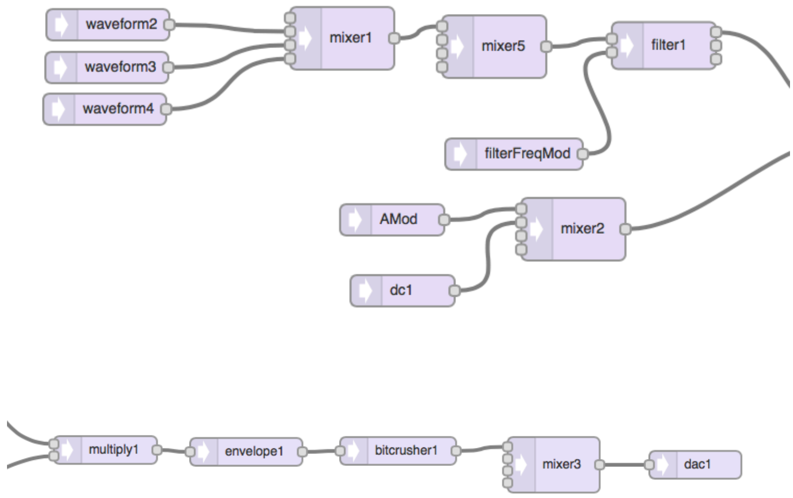

Figure 3. Teensy audio library GUI.

The synth created for the XT Synth contains three different waveforms – sawtooth, square and triangle. It also features filters, modulation, an envelope and a bit crusher. Various musical parameters can be changed through the rotary encoders and potentiometers.

The Teensy audio library features waveforms that are not bandlimited. This was a major problem, since aliasing was audible. Because of that, some time was invested on creating bandlimited waveforms for the Teensy audio library. A bandlimited sawtooth was coded and used with the Teensy audio callback. The technique used was the "polynomial transition region" (Ambrits & Bank, 2013). Having achieved a bandlimited sawtooth wave, a square wave was generated using two sawtooth waves with one wave phase inverted and delayed by a time less than the period of the waveform.

Unfortunately, sound quality was disappointing. The DAC quality is low. Glitches happened from time to time and the floor noise was distractingly audible. A better DAC could be used, or even an analog system could be built, but this was not economically viable. The synthesizer has been abandoned (for now) and the instrument simply functions as a MIDI controller[2].

[2] A video where the XT Synth is used as a synthesizer, where the glitches can be heard, can be seeing here: https://www.youtube.com/watch?v=0mDZeFKfs98&t

No longer needing to use all the power of the Teensy 3.2 for synthesis, I decided to use the Teensy LC for the next prototype. The Teensy LC is less powerful than the Teensy 3.2, but also less expensive. The LC (low cost) model, while less powerful, is powerful enough for MIDI and can be recognized as a MIDI device, just like the Teensy 3.x family.

3.2 Pitch Control

3.2.1 Hardware

To detect finger position on the neck of the XT Synth, four soft potentiometers are used. A soft potentiometer changes its resistance accordingly to the position of the finger on the ribbon. The soft potentiometer is read in an analog pin of the Teensy. The analog pins have a 10-bit resolution, and thus a soft potentiometer is able to produce 1024 values. So in a 200mm ribbon, there is a resolution of approximately 0.2mm.

The soft potentiometer requires a pull down resistor to avoid its floating behavior output. Using a 1-3k resistor as the pull down resistor, its voltage is pulled down. Without touching the soft pot, the output measured is around 2-5 – in a 0-1023 range. Given this information a threshold is set. If the threshold is exceeded, it means that the soft potentiometer is in use.

In the first prototype, four Spectra Symbol 200mm soft potentiometers were used (part number SP-L-0200-103-3%-ST). They have 200mm in length and 20.32mm in width. Problematically, this width creates a spacing too wide compared to the distance between two guitar strings. To solve this issue they were cut to about 12.7mm. This made the playability better, but added time to the assembly and the cuts was not perfect.

For the second prototype a better solution was found, which was using the Spectra Symbol Thinpots. The Thinpots are like a normal soft potentiometers, but thinner. It was used four Thinpots, which instead of 20.32mm, have 10mm of width. This made the playability better, however, it was still very hard to hit the sensors in the right place. I quite often hit between two sensors. There was no tactile feel, like a guitar, just a flat surface with the soft potentiometers on it. Thus, it was decided that a tactile feel needed to be added in order to play the instrument correctly.

I experimented with sticking different materials on top of the sensors. Using a foam double-coated tape, with another normal tape on top (so the fingers don't stick to it) worked surprisingly well. A future step will be designing my own tactile "strings" for the XT Synth.

3.2.2 Software

The goal with the XT Synth was to create an instrument that could perform glissandos and vibratos, just like a fretless instrument, but also could be easily played in tune, like a fretted instrument. However, non-tempered instruments imply a steep learning curve, as playing in tune is much harder than with fretted instruments. For the XT Synth, a system was implemented that quantizes the notes, like in a fretted instrument, but also allows microtones, vibratos, glissandos, etc., like a fretless instrument. This way, it has the expressiveness of a fretless instrument, like a violin, but it is easy to play like a fretted one, such as a guitar.

In order to perform vibrato, glissandos, etc., over MIDI, a system using pitch bend was created. One of the challenges was how to translate the pitch bend into the desired pitch in the synthesizer, since pitch bend is not global, it can go from one half step to many octaves, depending on how the external synth is configured. Different solutions were implemented, which will be discussed in the following sections.

3.2.2.1 Pitch Bend Basics

Before discussing how the pitch bend was implemented, it is important to understand how MIDI and pitch bend works. With a few exceptions, every MIDI message is comprised of three bytes (8 bits each). There are messages like "note on", "note off", or "control change", "pitch bend" and "after touch". Each of these messages has three bytes, and each byte, or part of the byte, represents something different.

The first byte, called the Status Byte, has its first bit always being "1". Its next three bits represent the MIDI message type, like "note on", "control change", "pitch bend", etc. In the case of pitch bend, the three bits are “110”. The last four bits of the Status Byte are for the MIDI channel, thus giving a total of sixteen possible channels. So the Status Byte of a pitch bend message in channel one is “11100001”.

The next two bytes are data bytes. Both start with “0”, the remaining seven bits are used as a value for the message, so there are a total of 128 possible values (7bit resolution). With a “note on” the first data byte will tell the note number and the second the velocity. With “control change”, the first data byte will tell the CC number and the second the CC value. With pitch bend, both data bytes are used together, as one number, extending the pitch bend resolution. The first data byte is called LSB (Least Significant Byte) and the second MSB (Most Significant Byte). Together they allow pitch bend to have a 14bit resolution (16384 possible values). Different from velocity, pitch bend is not related to a specific note, but to a whole channel. Having just sixteen channels available, there are only sixteen different possible pitch bends available at the same time. Each pitch bend will affect all the notes of that specific channel, a problem that is solved implementing MPE (MIDI polyphonic Expression), which will be discussed later in this paper.

3.2.2.2 The MIDI Library

The “Arduino MIDI Library” was used for sending MIDI from the Teensy board. The library does most of the low level work, making it much easier to use the MIDI protocol with a microcontroller. With the Teensy boards it is possible to use the MIDI library as USB MIDI, which makes it trivial to make the Teensy an USB-MIDI class compliant device.

There are different ways of sending pitch bend with the MIDI library, using different types of arguments, such as *doubles*, *ints*, or *unsigned ints*. In figure 4., the pitch bend function using *ints* is shown.

```
void MIDI_Class::sendPitchBend ( unsigned int  PitchValue,
                                 byte          Channel
                               )
```

Send a Pitch Bend message using an unsigned integer value.

Parameters:

- **PitchValue** The amount of bend to send (in a signed integer format), between 0 (maximum downwards bend) and 16383 (max upwards bend), center value is 8192.
- **Channel** The channel on which the message will be sent (1 to 16).

Definition at line 288 of file MIDI.cpp.

```
{
    send(PitchBend,(PitchValue & 0x7F),(PitchValue >> 7) & 0x7F,Channel);
}
```

Figure 4. The MIDI library pitch bend reference.

3.2.2.3 Note per Note Pitch Bend

Different solutions were implemented to control pitch with pitch bend. One solution was to use a "note per note" pitch bend method, which is similar to how it is done in a keyboard, with a pitch bend wheel. The concept consists of bending the pitch of one note into the next one, note per note. First, the strings are quantized in x number of notes, for example twelve notes. When the finger hits the string, if it is between B and C, the distance between the previous and the next note is calculated in percentage. If the finger is in a 25% position, closer to the B, the following formula will be applied: "PbAmount = ((PbRange/2) * percentage)) + PbRange/2". Whereas "PbAmount" is how much pitch bend will be sent. "PbRange" is the pitch bend range, which is 16384. "PbRange" is divided by 2 because we just want to bend the pitch up. Everything is summed with "PbRange/2", because we want to start at the middle of the pitch bend value. Greater than that "PbRange/2" means bend the pitch up and less than that would be bend the pitch down. And "percentage" is the distance to the next note in percentage. So: PbAmount = (8192 * 0.25) + 8192, this way the pitch bend amount would be 10240.

When reaching the next note, a "note on" with the next note is sent and its equivalent pitch bend, which would be 8192, zero pitch bend. To make this to sound as one continuous glissando, the synth must be in legato mode and the next "note on" needs to be sent before the "note off" of the previous note, in order to be performed a legato. This, in theory is a great solution, but not practically. There's a perfect glissando, but at every note change, there's a slight jump, or click in the sound, making this method not suitable for this project. This result is due to the serial nature of MIDI and thus not a problem that can be overcome without changing protocols.

3.2.2.4 One Pitch Bend for All

Since there's an audible click when changing from one note to another, the alternate method implemented always sends just one "note on" per string, and changes the pitch bend along the string according to the finger's position. For example, one string will always send the midi note D, then, it will be sent an amount of pitch bend depending on where the finger is. The problem with this approach is that pitch bend is relative, it doesn't have an absolute pitch value. If in the synth being used, has the pitch bend configured to bend the pitch in two half steps, the whole string will be equivalent to just two half steps. As such, every synth needs to be configured always with the same pitch bend range, which will dictate the string range.

3.2.2.5 Fretted Vs. Fretless

One of the goals of the XT Synth was to be able to perform glissandos and vibratos, like a fretless instrument, but in a way that would be easy to play in tune, like a fretted instrument. The solution to this problem was to quantize the note the first time the finger hits the string, leaving it free to do any sort of glissando after that.

In order to achieve this the following algorithm was used: The pitch bend range is divided in equal parts, according to the number of "frets" needed, and the value for each "fret" is stored in an array; after the finger hits the string, the offset from the next "tuned" note is calculated; finally, this offset continues to be added to the pitch bend while the finger is on the string. In this way, the pitch is always offset by the same amount while the finger is on the string. So, if the finger hits the string between two "frets", to slide to another note, in order to tune, the finger will need to stay, also, between two frets. That's a tradeoff of using this system, whereas hitting the first note in tune is easy, but sliding to another note in tune requires more listening than muscle memory.

3.2.2.6 MIDI Polyphonic Expression (MPE)

As discussed before, pitch bend is global to every MIDI channel, so using strings on the same channel would make the pitch bend to affect all the strings at the same time. In order to solve this problem, every note needs to be assigned to its own pitch bend channel. A solution, recently popularized by instruments such as the ROLI Seaboard, is the MIDI Polyphonic Expression (MPE). According to the official MIDI website "Prior to MPE, expressive gestures on synthesizers—such as pitch bending or adding vibrato—affected all notes being played. With MPE, every note a musician plays can be articulated individually for much greater expressiveness. In MPE, each note is assigned its own MIDI Channel, so that Channel-wide expression messages can be applied to each note individually. Music making products (such as the ROLI Seaboard, Moog's Animoog, and Apple's Logic) take advantage of this so that musicians can apply multiple dimensions of finger movement control: left and right, forward and back, downward pressure, and more." (Midi Polyphonic Expression (Mpe) Specification Adopted, 2018)

That's a simple implementation for the XT Synth, however not every software supports MPE. A list can be found in the MPE webpage (Midi Polyphonic Expression (Mpe) Specification Adopted, 2018). Software that supports MPE will listen to all MIDI channels and will parse each channel to a different voice of the synthesizer. If the software doesn't support MPE, this needs to be done manually. One needs to open four instances of the synthesizer on the different MIDI channels to which the XT Synth is sending. This is more CPU intensive and more time consuming, but it also opens for different sounds and configurations for every string.

3.2.3 Soft Potentiometer issues

Although soft potentiometers are fairly accurate, they have some issues. Some problems could be fixed in code, others required an adaptation in the playing technique.

3.2.3.1 Soft Potentiometers are not linear

Soft potentiometers don't have a linear response, neither do they have a perfect logarithmic response. Therefore, it is impossible to linearize its response using simple equations. Also, data sheets do not contain the response curve of the sensor. The solution was to measure every *x* mm and then scale the values in such a way as to linearize the soft potentiometers in software. I measured the values at every 5mm in the ribbon and then used a function to map those values into a linear scale. I used Evan Kale's "multimap" function, which can be found in his "3D Print Arduino MIDI Controller" tutorial (Kale, YouTube video). After linearizing the values, it was possible to divide the string in equal parts, making it much easier to work with the soft potentiometers.

3.2.3.2 Soft Potentiometers Can Just Read One Position at Time

Soft potentiometers can just read one position at time. Although it might sound like an obvious statement, this becomes a problem while trying to play the XT Synth like one would play a guitar. While on a guitar one note per string can be played at a time, the other fingers tend to rest on the same string, with no side effect. Using a soft potentiometer, this can't happen. If one rests another finger in the same string, the sensor will output a value that doesn't correspond to either one, but something in between them. The solution is making sure that one just plays with one finger at time, or releases the other finger as soon as possible, in case of legatos.

3.3 Controllers

3.3.1 RGB Rotary Encoders

One of the ways of controlling the XT Synth parameters, or just sending MIDI CC, is using the RGB rotary encoders. Rotary encoders are digital components that don't have an absolute position like potentiometers, however, one can tell if it was turned counterclockwise or clockwise. An advantage of a rotary encoder is that it can be used for controlling several different parameters, using it in different banks, since it simply increments or decrements, instead of giving a number related to its absolute position. The tricky part is keeping track of which number it's outputting at the moment, since it doesn't provide visual feedback.

RGB encoders are capable of providing a form of visual feedback by mapping values into colors displayed by the rotary encoders themselves. Each encoder has a color that ranges from blue (minimum) to red (maximum). One can tell (roughly) the values by the rotary encoders by their color. These rotary encoders also have push buttons, which are used for changing banks, and transposing octaves. The encoders used were "Sparkfun Rotary Encoder – Illuminated (RGB)".

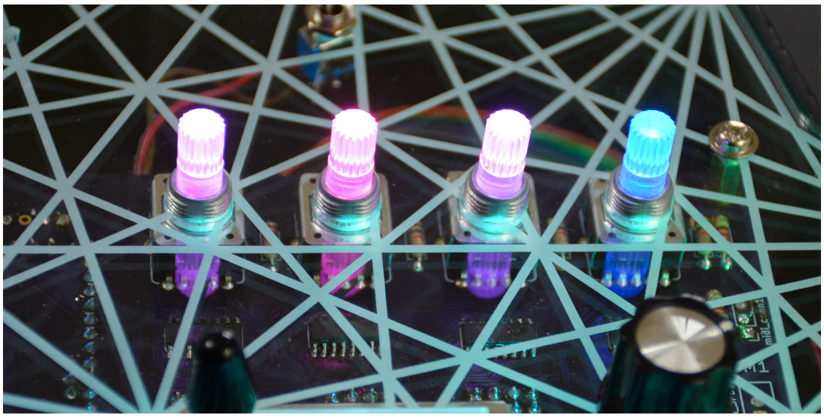

Figure 5. Illuminated rotary encoders.

Another feature that was implemented to track the encoders' values, banks and octaves, was the use of an OLED display. The display shows the MIDI control change value (CC) stored in each encoder, the number of the bank that is on, and the octave transposition (Figure 6).

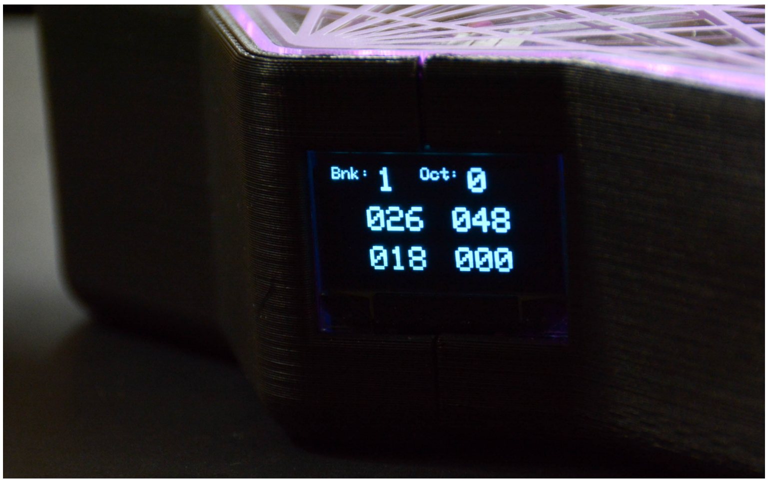

Figure 6. OLED display.

For reading the encoders, the Encoder library (which comes with the Teensy library) was used. It allows one to easily read the values of the encoder, rewrite them, etc., leaving the complications of efficiently reading the encoder to the library.

An important caveat about rotary encoders is that they require pins with interrupts, to work properly. If one tries to read the turning of a knob of an encoder by simply reading the digital pins, it is probable that several readings will be missed, since the code will not be fast enough to catch all the on / offs sent by the encoder to the digital pins. To solve this issue, a mechanism is needed that interrupts the code and reads the encoder every time it changes its state. This is possible using “interrupts”, which are present on some pins of different microcontrollers. In the code it is possible to know if a pin with an interrupt has changed its state. If that happens, the code will stop (it will be interrupted) and run a specific function. After that it will continue from where it stopped. The encoder library takes care of this functionality, so the only thing that needs to be done, regarding the interrupts, is to simply attach the encoder terminals to pins that have interrupts. This was another one of the reasons of choosing a Teensy board, it has enough pins with interrupts for this project (each encoder requires two pins, so, eight pins with interrupts).

3.3.2 Potentiometers

Potentiometers are analog components that, contrary to rotary encoders, have an absolute position. These are ideal to control parameters that are most often manipulated, such as volume, or a filter cutoff frequency. Besides that, they have a physicality that feels more natural than rotary encoders, due to their lower and upper limit.

In the first prototype, one rotary potentiometer and one XY joystick were used. The joystick has a spring that always pulls the handle to the middle. The x-and y-axes were divided in two, 0 being the value in the middle. Thus, the joystick sends 0-127 left, 0-127 right, and also up and down, sending different MIDI CCs. However, because of this, the resolution of each of the possible movements was divided by half. On top of that, the chosen joystick didn't perform satisfactorily. It only seemed to work well near the zero position. Due to this reasons the joystick was excluded from the next prototype.

For the second prototype, the rotary potentiometer was maintained and a slider potentiometer was added.

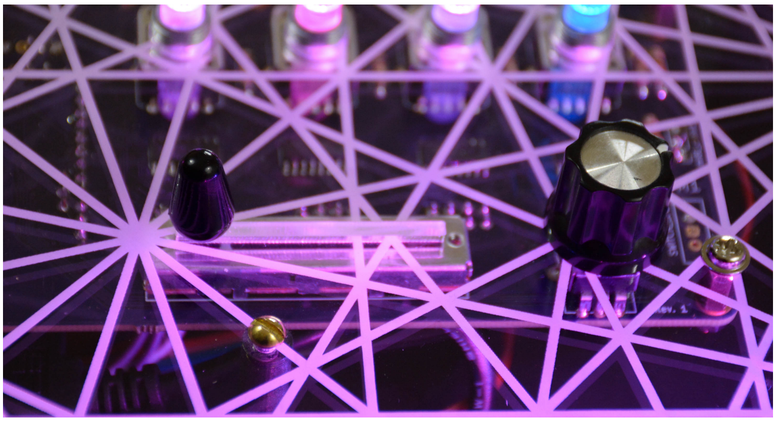

Figure 7. Potentiometers.

Both worked as expected, with a 10-bit resolution, which was then converted to 7-bit MIDI. My intention was to use it mainly to control a low pass filter cutoff frequency, or as a volume control. With 7-bits to represent a range of approximately 18k hertz, there is not enough resolution for having a smooth transition between frequencies, mostly in the lower spectrum. So, I decided to send pitch bend with the potentiometer, instead of MIDI CC. Pitch bend can be also used to map any parameter, it doesn't need to control pitch. As mentioned previously, pitch bend has a 14-bit resolution, giving a much bigger resolution than MIDI CC. With higher resolution, pitch bend works well to control filter cutoff frequencies, or volume.

In the second prototype it was added a slide potentiometer. The idea behind the slide potentiometer is that it can be used in a familiar way for guitar players. One can move it up and down, as one picks with a guitar pick. Although it can be mapped to anything, controlling volume, or cutoff, seems to be the most idiomatic gesture.

3.3.3 Force Sensitive Resistors (FSRs)

FSR, or Force Sensitive Resistor, is a sensor that changes its resistance according to the amount of pressure applied to it. The reasons I chose to add these sensors are: it is easy to manipulate several of them at the same time, giving a multidimensional control over the sound; and because they can be used as velocity sensitive triggers for each string, enabling one to "pluck" a string with the right hand.

Figure 8. Force Sensitive Resistors.

In order to use the FSRs in two different ways, an on/off switch was added to the circuit, in order to have two modes. In the first mode, each of the four FSRs send MIDI CC, which can me mapped to any parameter in the synth/DAW. In this mode, notes are triggered just by hitting the strings with the left hand. In the second mode, the FSRs can trigger each of the strings. If one doesn't use the left hand while hitting the FSR, it will play an "open string", but if one finger is in one of the string, it will only be triggered after the FSR is hit. Also, in this mode, the FSR is programmed to send aftertouch, after the "note on" allowing another level of expressiveness with this continuous control.

3.4 The Printed Circuit Board (PCB)

In the first prototype, due to time constraints, no custom PCB was designed. Instead, solderable breadboards were used and several wires. Solderable breadboards can be used just like normal breadboards, but with the components soldered to it. It took a large amount of time to solder everything, which would make it time consuming to build another instrument like this. In order to make the building process much faster I decided to design my own PCB. In fact, three different PCBs were made, which all connect to the main PCB.

The main PCB was made in a way to accommodate the Teensy LC, the rotary encoders, potentiometers and IDC connectors (ribbon cable connectors), to connect with the other PCBs and other components. The Teensy doesn't have enough pins, in order to accommodate all the LEDs of the encoders, so two bit shifters 74HC595 smd (surface-mount device) were used, and for the analog components two analog CD4051 multiplexers were used.

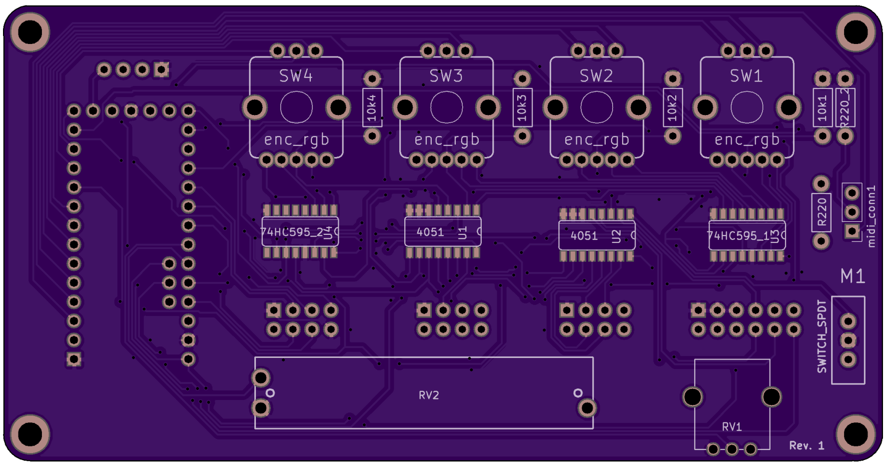

Figure 9. Main PCB.

3.5 Design

3.5.1 Visual Aesthetics

How the XT Synth looks, along with how it sounds, is important. Visual aesthetics in musical instrument design have always played an important role. The performance is both a visual and an auditory experience (Dobrian, 2001). Having a visually interesting looking instrument greatly contributes to our appreciation of the performance.

When a guitarist goes to the stage with a Les Paul guitar, or with a Flying V, it implies something, something different for each of them. Different expectations are set simply because of the visual form of the instrument. The design brings personality to the instrument and recontextualizes the instrument as, not just a tool, but also a piece of art itself. In the following section, the aesthetic underpinnings of the XT Synth are discussed.

3.5.2 A Homage to the Psychedelic Culture

The chapter "The Spiritual Absolute in the Visual Music Film" (Mollaghan, 2015) discusses the transition between the strict absolute formalism of the visual music of artists like Viking Eggeling, Hans Richter and Norman McLaren, to a form of art that could function not only at the formal level, but also at the spiritual level.

Artists like Jordan Belson, John Whitney and his brother James Whitney, were all living on the West Coast, and shared ideas that went beyond the pure art of making visual music films. John and James made a couple films together, for example "Variations on a Circle" (1941-42) and "5 Film Exercises" (1943). But it was in the late 50s that this new "scene" started to appear. At this time people saw the space race between the United States and Russia, and were made more aware of the cosmos. The mysteries that lie in the universe became of great interest of the public. Also, a taste for eastern religions, such as Buddhism and practices like Yoga became more popular in the US.

Jordan Belson, James and John Whitney, among others, presented a series of concerts, called "Vortex Concerts" in the Morrison Planetarium, in San Francisco, starting in 1957. In these concerts they would present their works in order to evoke a "mystical experience", which would appeal directly to the senses of the viewer, in an immersive experience, with several projectors, lights and sound. They believed that this experience could help achieving higher states of consciousness. Also, psychedelic drugs, which were also known for giving mystical experiences, were an integral part of the whole philosophy of these artists. They produced works such as: James Whitney, "Yantra" (1957); James Whitney "Lapis" (1966); John Whitney, "Permutations" (1966); Jordan Belson "World" (1970).

At this time, notions of transcendence, awakening and the sublime were bounded with music. The philosopher Kant says that the sublime happens when we face something that is so much stronger, or larger than us, that we feel powerless, or small. But we also experience a great feeling of pleasure, happiness and understanding. The sublime is our response to something that is too overwhelming for us to comprehend.

In the Vortex concerts, the artists looked for an experience that could give a sense of the sublime. Several projectors, speakers and lights, came together in an overwhelming stimuli for the senses. Nowadays, it is hard to think about a big electronic music festival without a massive apparatus for visual effects. In fact, many of the present electronic music festivals, like the psytrance ones, have a lot in common with the Vortex Concerts of the late 1950s. An overwhelming amount of sound and visuals evoke a "spiritual awakening" through the trance, through the sublime.

My intention with the XT Synth's design is not evoking a sublime, spiritual experience, but it is my homage to those artists, to that culture, that have great impact in my artistic work. As the main shape of the instrument I chose a "sacred geometry" form. Sacred geometry has a strong relationship with math. Its shapes are created through the juxtaposition of other shapes following a certain ratio, making them visually pleasing. The use of math to create art is something that electronic musicians are used to, which perhaps creates a sense of connection between the sacred geometry and the type of instrument that the XT Synth is.

The last aspect is the luminescence of the instrument. It also follows the aesthetics of the sublime in art, the overwhelming. My intention was to make the instrument as bright and colorful as possible. This idea came from my experiences in the Burning Man festival. A current festival that is an example of an overwhelming experience, full of art, and room for self-discovery. There, visual arts are mostly full of lights and colors, which had a major influence on how I wanted the XT Synth to look.

3.5.3 Construction

In this section aspects about the XT Synth enclosure construction are discussed. Design and construction decisions were not only made based upon creative choices, but also upon time and financial constraints, and material and fabrication equipment availability. The instrument has two prototypes at the time of this paper.

3.5.3.1 The First prototype

The first prototype had the time constraint of being designed and built in two weeks. With the available material, equipment and manufacturing experience that I had at the moment, I decided to create everything in a 2D design and later laser cut it in acrylic. All the design was made in the software Inkscape and was printed in a laser cutter in the local Fablab.

One of the ideas behind using acrylic, instead of another material, like wood, is the effect that can be achieved when applying light to an acrylic engraved surface. This technique is usually used in signs, where light is applied in the edge of the sheet, facing inwards. This way, the engraved part glows. Although this is a pretty common technique, I haven't seen this been used in an instrument before, so I gave it a try. The result was good. However, attaching the lights to the right place was difficult, I had to super glue them on the acrylic. I also put an LED strip inside the neck, so that the neck was also illuminated.

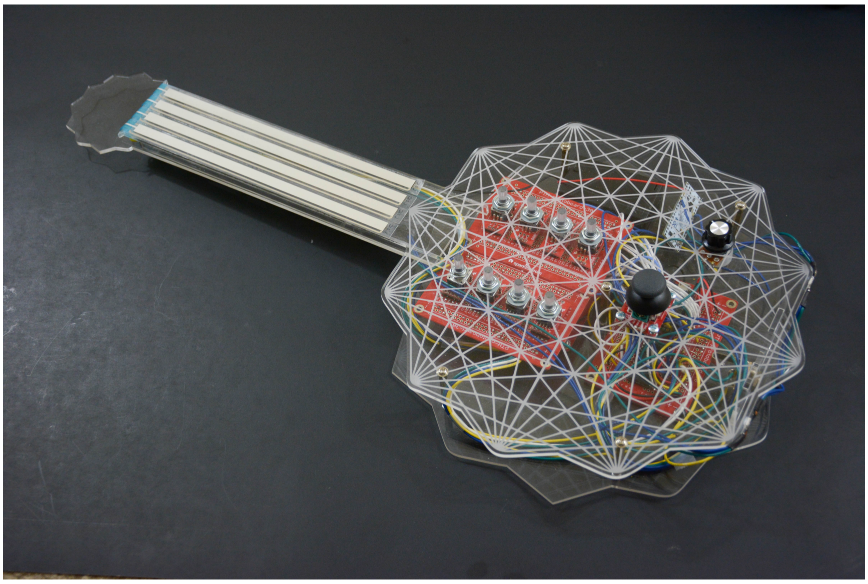

Figure 10. The first prototype.

The acrylic body fulfilled my objective of making the first prototype, but was far from ideal. The biggest flaw is its weakness. It is very fragile and it can break at any moment. It also doesn't have any enclosure for the sides, exposing all the wires. With all those flaws in mind, I decided to go for a 3D printed version.

3.5.3.2 The Second Prototype

Knowing that I would have more time to build the second prototype, I decided to learn how to make a 3D model for the instrument, to later print it in a 3d printer. The design was made the in the Fusion 360 CAD software (Figure 11) and printed in a 3D printer in the local Fablab. The instrument was designed in four different parts (not counting the electronic components): body, neck, body top and neck top (Figure 12).

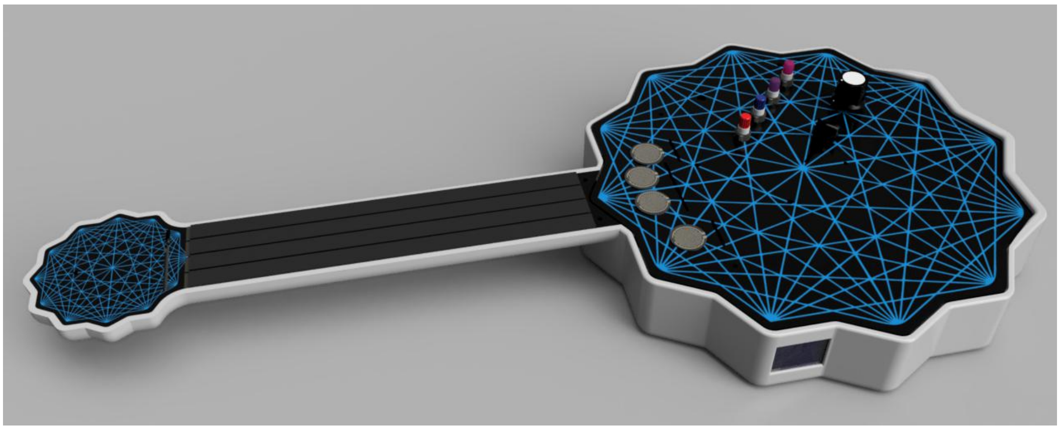

Figure 11. 3D model of the second prototype.

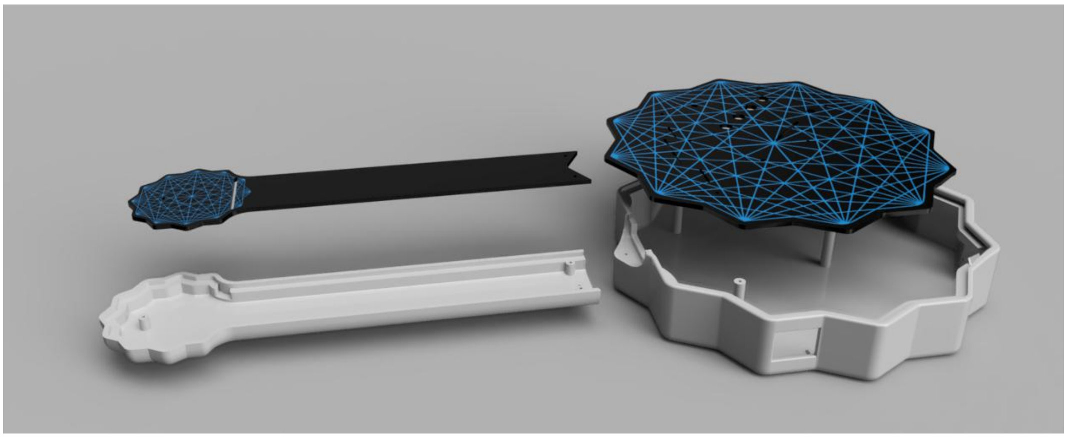

Figure 12. 3D model of the second prototype separated in its 4 parts.

This prototype looked much more “clean” and professional. It is sturdier and it is designed to accommodate the LED strips in the right place. I also kept the idea of an engraved acrylic sheet on top to keep the light effect. There are several adjustments to be made, but that’s for the next prototype.

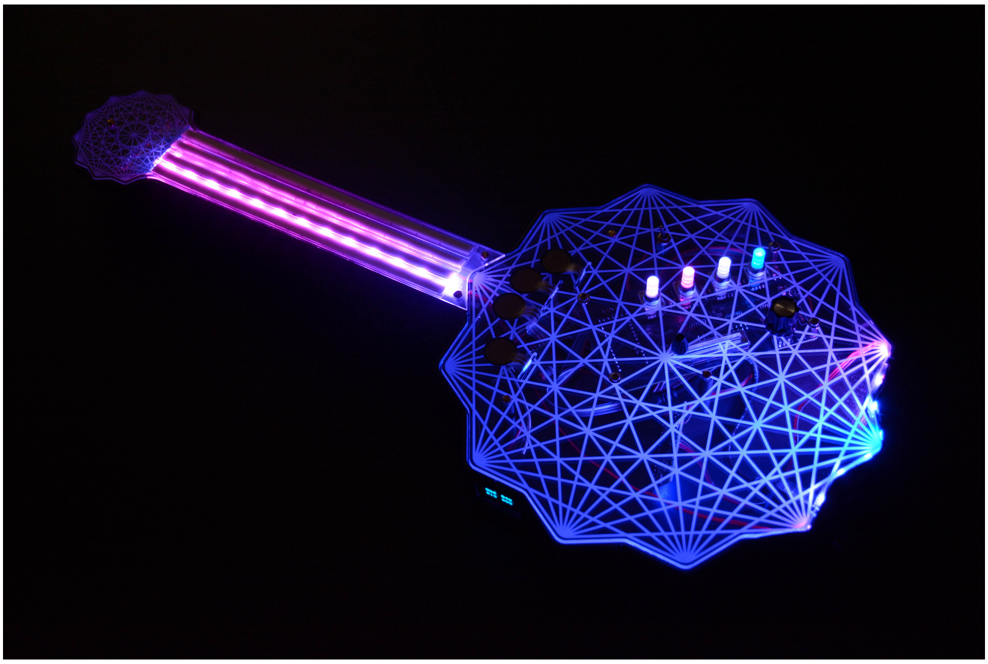

Figure 13. XT Synth light effect.

4. WHERE IT IS GOING

From the first to the second prototype the XT Synth presented a big improvement. The building process went from more than a week to two/three days. However, for being commercialized that it is still too much time. Also, due to the use of 3D printer and 3D printing material, the costs are still high.

There are still several improvements and corrections that need to be made, mostly in the body design. Several parts didn't fit and required a lot of work after they were done. The next steps will be correcting and improving the design, adding a custom tactile surface for the neck, and building a mold so new units can be manufactured faster and cheaper.

5. CONCLUSION

The XT Synth is an ongoing project. It is a new musical instrument, a MIDI controller. It is an instrument that allows string players to make electronic music without having to learn a whole new performance technique. The XT Synth uses continuous controllers for controlling pitch and for modulating other parameters of the sound. It can translate left hand techniques from instruments such as guitar and violin, making it a good candidate for a novel controller for string players.

It was born from the desire of being a personal project and changed its path, with the intent of making it a commercially viable product in the future. With that in mind several changes were made from the first prototype to the second. The first prototype was built only with acrylic sheets and its circuit was built with solderable breadboards and lots of wires, besides its main components. This made it not only look unfinished, but it was also fragile and unreliable. However, the results were satisfactory enough to inspire me to build a next, better, version. Also, the XT Synth "went viral" on the Internet, being shared many times over the social networks and being featured in several specialized websites.

The second prototype presented a much better finish and was easier to build. It gained a 3D printed body, custom PCBs, and new features, which gave it more power, better playability, and made it more visually pleasing.

The XT Synth had its first performance at the Root Signals Festival, at Georgia Southern University, on February 22nd of 2018, with its first prototype. The second prototype had its first performance at the finals of the Guthman New Musical Instrument Competition, at Georgia Tech, on March 8th of 2018.

Videos and more info about the XT Synth can be found at the following webpage: www.musiconerd.com/xtsynth

6. ACKNOWLEDGMENTS

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