EM Guitar – An Electromagnetically Actuated Guitar

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ABSTRACT
Electromagnets can excite metallic strings, including those on guitars and pianos, causing them to vibrate continuously. This has been used for several projects and commercial products to create unique sounds and ways of playing. However, they are all limited, either in the number of strings or the selection of specific ones to be excited; or in form factor. The EM Guitar solves these limitations by combining an input system, individual electromagnets for each string, and a power source into a single, self-contained package. Multiple strings and individual strings can be excited. The EM Guitar offers a complete package that allows for new methods of playing with its infinitely sustaining notes while still retaining the ability to be played in traditional ways.

Author Keywords
Electromagnet, Capacitive Touch, Guitar

1. CONCEPT AND BACKGROUND
The purpose of this project is to innovate upon previous electromagnetically actuated guitar designs and add-ons to create an electric guitar that is capable of being played without needing to pluck or excite the strings manually, allowing for new ways of playing. This project will improve on these previous projects by attempting to allow the ability to simultaneously excite all six strings of the guitar, enabling a greater range of notes to be played. It also will create a very unique sound compared to traditional methods of playing guitar due to the infinitely sustaining notes and that no picking is required, allowing the notes that are played to not have any of the "attack" that is found with picking, hammer-ons, pull-offs, and other similar playing methods.

This project would be a cooperative instrument with a computer driving the electromagnets based on the input of a human player who is fretting, muting, and selecting the strings. Electromagnets would be used to excite the strings by sending them an alternating HIGH/LOW signal at the correct frequency for the string and the note fretted. When a HIGH signal is sent, the electromagnets would attract the string and when a LOW signal is sent, the string would be released. Alternating between attracting and releasing the string at its fundamental frequency would cause it to vibrate, producing a sound that can be amplified and sent through a speaker.

Since this method relies on attracting the strings with electromagnets, the higher strings may be harder to excite than the lower strings because they are thinner, so there is less material for the magnetic field to interact with. Also, due to the inductance of the electromagnets, there is an upper limit to the frequencies they can be energized and de-energized at, potentially limiting how high of pitch the guitar could play. If possible, all components except the final output signal amplification would be contained either on or within the guitar to create a fully independent package.

Capacitive touch sensors work by detecting the change in capacitance when your body comes in contact with a conductor. This specific touch sensor type was chosen to make the exact location where the touch happens matter less. For the frets, it allows one large pad to be put under the strings for each fret and for a touch anywhere on that pad to be detected. Using traditional buttons would be more complicated and bulkier. A similar reasoning was used for the string selection pads, capacitive touch sensing allowed for inputs without needing to press hard enough to click a button.

2. PRIOR ART
2.1 WPI Projects
The two most direct sources of inspiration for this project were the Marco Magnet Guitar [2] and Eric "Magneto" Clapton [4], two projects created in WPI's MU2301 Making Music With Machines course driving a guitar's strings with electromagnets. Both of them were only able to drive two of the guitar's strings. An oscillating signal was generated at specific frequencies and sent to the electromagnets through an audio amplifier. The location of the electromagnets was limited by the interference with the pickups. If they were too close, then the signal driving them would be picked up and outputted by the guitar. The electromagnets must be between the range of notes that can be fretted and the guitar pickups to excite the strings when they are fretted.

The source of the driving signal in the Macro Magnet Guitar was a set of notes being played by Ableton from a laptop [2]. These were outputted as an audio signal and put through an audio amplifier before being sent to the electromagnets. The idea behind this was that the positive and negative portions of the audio signal would excite the strings better. This assumption was untrue, though as ferromagnetic objects such as the strings are only attracted to magnetic fields, so positive and negative voltages create a frequency doubling effect [7]. The Eric "Magneto" Clapton project used an Arduino to generate digital on-off pulses at various frequencies to drive the audio amplifiers and then electromagnets [4]. This is a similar method to what ended up being used for the EM Guitar.

2.2 Commercial Products
One commercial product that uses electromagnets to excite a guitar's strings is the EBow [3]. It takes in the frequencies the string it is above is vibrating at and excites the string using those frequencies, creating a feedback loop. This allows for many unique sounds to be produced, although it is limited to only playing a single string at a time, preventing it from doing power chords or other chord shapes. The Sustainiac [10] is another commercial product that allows for new ways of playing a guitar with electromagnets. It replaces the neck pickup of a guitar and excites the strings with the signal recorded by the pickups to allow notes to be sustained for a long period of time. The Sustainiac can only enhance existing string vibration, so it cannot get the strings vibrating from being stationary without a player. The Sustainiac can excite chords, but the sound ends up being dominated by only a few notes rather quickly [10].

2.3 Other Projects
An example of an electromagnetically actuated instrument that is not a guitar is the Magnetic Resonator Piano [6]. It is a system that can be installed in a grand piano that excites the strings when the corresponding key is pressed. Due to the way it senses the key position, it can perform crescendos from silence, harmonics, and pitch bends. The main limitations are that it only enhances a

section of the piano's full range, it requires a grand piano to install in, and extra space is needed for the controller and power supply.

3. REQUIREMENTS

3.1 Timbre

The main timbral requirement is the infinite note sustain that electromagnetically actuated string instruments are known for. There is also a requirement for no noise to be picked up from the excitation signal and outputted from the guitar. Some noise may be present in the final amplified sound, but that would be due to white noise being boosted and it is very difficult to remove completely from the sound. The first timbral requirement can be realized by programming the Arduino in such a way as to continually output the requested signal as long as that combination of buttons is pressed. The programming for this can be achieved by having the Arduino output a unique set of signals for each input state the guitar can be in and continue outputting those signals as long as that input state is maintained. The low electrical noise requirement can be accomplished by using piezo pickups rather than the guitar's standard electromagnetic ones. Piezo pickups work by detecting the mechanical movement of the strings, rather than the movement of a ferromagnetic material in a magnetic field. This makes them not susceptible to electromagnetic interference, eliminating the issue of the excitation signal being detected by the pickups. The magnetic fields generated by the electromagnets would be detected by traditional guitar pickups and overpower the signal from the strings.

3.2 Time

The main time requirement is responsiveness, meaning that the guitar can respond to player inputs in about 200 ms. By using the tapping or hammer-on techniques, the string can be started to vibrate manually, and the signal can sustain the note afterwards. This can be realized by ensuring that the electromagnets are strong enough to get the strings vibrating in a short amount of time from rest.

3.3 Pitch and Dynamics

The pitch requirements are for it to be able to excite specific frets on specific strings, in other words, play the requested note. The tuning of the strings would be controlled by the guitar's normal tuning lugs and the intonation can be adjusted at the bridge. Also, multiple strings should be able to be excited simultaneously with different frets as their note targets. Pairing up fret and string button presses in the code could allow for multiple strings to be excited at the same time on different frets. Since the fret sensors do not differentiate between strings, this must be accomplished in programming. There are two main methods of doing so, assigning every string to the highest fret currently pressed, or assuming that the strings are always pressed in some predetermined shape and splitting up the frets between strings accordingly.

There should be control over the loudness of the instrument, whether by changing the amount of current sent through the strings or electromagnets using a potentiometer or by adjusting the volume through a speaker with a pedal or amplifier. The volume control can be used to help equalize the volume between the different strings, especially between the high and low ones. The low strings are excited much better by the electromagnets than the high strings, likely due to their increased size. Articulation could be controlled by the human player, either with fretting techniques like hammer-ons and slides or by using a pick.

3.4 Appearance and Use

The finished product should appear similar to a guitar, although there will likely be buttons and other electronics on the outside. The electronics also could be put inside the body if enough space is made. LEDs could be added to indicate what frets or strings are being pressed.

The guitar could either have a cooperative interaction with humans or be fully controlled by one. In a cooperative mode, a human would select what fret is being played while a program chooses the string or strings. In a fully controlled mode, a human would choose the combination of both frets and strings, playing it akin to an instrument.

3.5 Excitation

The excitation requirements for the EM Guitar are that the electromagnets should be driven by a 5V square wave with a variable duty cycle to adjust the volume. For actuation, the height of the electromagnets under the strings should be variable. The structural requirements are that a 3D-printed mount will be made for the electromagnets to fit in the space beneath the strings. This may require modifications to the pickguard. Some of the electronics may also be able to fit in the space beneath there as well.

4. PRELIMINARY DESIGN

The design of the EM Guitar can be split into five main components, note selection, signal generation, excitation, music output, and power source. An outline of some of the major components is shown in Figure 1.

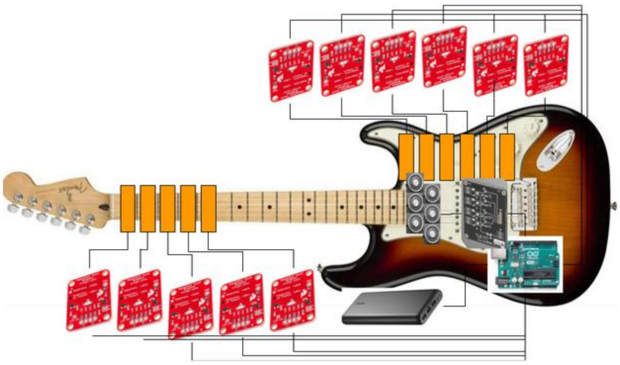


Figure 1. Mockup of the preliminary design. The black lines show connections between components, not specific wires or data signals. The orange rectangles represent the copper tape pads. They are connected to the red SparkFun AT42QT1011 Capacitive Touch Breakout boards. These connect to the teal Arduino Uno. The black circuit board is the MOSFET switching/amplifier circuit, connected between the Arduino and the electromagnets arranged in the grid near the base of the fretboard. The battery bank connects to the Arduino and amplifier board to power them.

4.1 Note Selection

The initial design of the note selection component involved using a set of capacitive touch sensors to detect a combination of string and fret inputs. The SparkFun AT42QT1011 Capacitive Touch Breakout boards were used to detect when a pad made of copper tape was pressed and send a HIGH signal to the Arduino. The same boards would be used for determining what frets are being pressed and what strings are requested to play. A pad for each fret placed under the strings would activate the breakout board when a finger touches it while pressing down a string. With this design, the fret sensors would not be able to determine what string was being pressed at that fret. Having a separate sensor for each string at each fret would enable more accurate determining of the position of the fretting hand but would greatly increase the number of sensors needed. A set of six pads would be placed along the pickguard to allow the player to input what strings they desired to be played. This design would be limited in the number of frets that can be sensed, as an Arduino Uno only has 14 Input/Output pins and six Input pins, for 20 total. Input signals for five frets and six strings, with six outputs for the excitation signals are 17 pins used, limiting future expansion.

4.2 Signal Generation

An Arduino Uno would handle signal generation. It would be programmed to take in the combination of strings and frets that are pressed and output the corresponding frequency to the correct strings. The output signal would take the form of a 0-5V square wave with a 50% duty cycle. A square wave was chosen because it is the easiest to generate with an Arduino. The 50% duty cycle was chosen to allow the string to be attracted for half of the time and allowed to relax for the other half, hopefully causing it to vibrate effectively. The signal would be generated using the PWM capabilities of the Arduino. These signals would then be amplified by using the signal to switch a higher current source with a MOSFET.

4.3 Excitation

There were two options for the excitation method of the strings, using electromagnets or taking advantage of the Lorentz force. The solution involving electromagnets would use a separate electromagnet placed near each string to excite them individually, as shown in Figure 2. A mount would be made to hold them either in one of the existing recesses in the body from the pickups or above the strings. Smaller electromagnets were preferred, both because they would package more compactly and because having a core that better matches the diameter of the string may make them excite the strings better [9]. The Adafruit P20/15 electromagnets were chosen as they are the smallest size Adafruit sells and they are 5V, which makes them easier to drive.

Figure 2. A sketch of the initial design for the electromagnet holders. The final design moved them beneath the strings but kept the same staggered pattern.

Using the Lorentz force to excite the strings involves running current through them in the presence of a magnetic field [7]. Running a changing current through the strings would create a changing force that would then lead them to vibrate. The signal would be applied to the strings at the headstock of the guitar, with the bridge acting as the common ground. Magnets would be placed under the strings in the area where the pickups used to be. Since the Lorentz force does not require that the conductor is magnetic, brass strings would be used to reduce the resistance of the strings and allow more current to flow.

The electromagnet approach is simpler and proven while using the Lorentz force is more novel. There have been several examples of instruments using the Lorentz force to excite strings. One is a guitar design patented by George Breed in 1890 [1]. This design was limited by the technology of the time, especially in generating string enough magnetic fields. A piece of music created with the Lorentz force is "Music on a Long Thin Wire" by Alvin Lucier [5]. This piece involved a string stretched across a room and exciting it in various ways, including by the Lorentz force. There are several downsides to the Lorentz force. The first is that the strings need to remain electrically isolated from each other, except at the bridge. This is difficult due to the metallic frets on the guitar and conductive copper pads placed below the strings on the frets. Also, the current running through the wires will heat them, changing their tuning. Given how sensitive to the tuning of the strings the electromagnets were discovered to be, this likely would have made it very difficult to get a consistent sound by using the Lorentz force.

From initial testing of using the Lorentz force to excite the strings, only high harmonics were excited, leading to a sound quality that was not preferred. The strings did not get hot enough to burn, but they were getting noticeably warm and out of tune. Also, the magnets were strong enough to change the resting position of the strings, causing them to have inconsistent heights and interfere with the frets when played. For these reasons, exciting the strings using an array of electromagnets was chosen for the final design.

4.4 Audio Output

Due to the nature of an electric guitar's standard pickups, the signal sent to the electromagnets will be picked up by them and output from the guitar. If the electromagnets are within about six inches of the pickups, the signal sent to them will completely overpower any signal the pickups get from the strings. To avoid this, piezo pickups can be used, which generate the output signal from the guitar by measuring the movement of the strings directly. The signal from a piezo pickup can be weaker than from traditional electromagnetic pickups, so a preamp or signal booster pedal may be required depending on the amplifier used.

4.5 Power Source

Since both the Arduino and electromagnets can be run on 5V, a battery bank for charging electronics such as phones can be used to provide a self-contained power source. Most common battery banks are rated to 2A or more output on a single USB header, with slightly higher total amperage ratings. Since the P20/15 electromagnets are rated to 0.22A at 5V, six of them would have a max current draw of 1.32A. The actual draw would be lower than this, as they will be energized and de-energized according to the excitation signal and it is unlikely that all of them will be one simultaneously. The Arduino would not draw much more than this either, so using one USB port to power the electromagnets and one for the Arduino would stay within the current limits of the battery bank. One note about battery banks is that some of them will stop supplying current after a period of inactivity and depending on the battery bank, this period may be too short, or the current draw of the idling Arduino and one or zero electromagnets may not be enough to prevent it from turning off. The Anker PowerCore MetroEssential 20000 5V battery bank has been confirmed to work.

5. FINAL DESIGN

5.1 Aesthetics

The EM Guitar is meant to still function as a normal guitar while also adding extra functionality to it. Because of this, it was designed to not be very bulky or add too many extra systems on the outside of the guitar. With this in mind, in the final design, the electromagnets were mounted under the strings so that the guitar could be played as a normal guitar. This mounting location leaves the strings open for picking. Along with electromagnets, the MOSFET board driving them would be mounted under the pickguard to decrease clutter for mounting positions on top or the sides of the guitar. For ease of access and testing, the Arduino UNO, battery supply, and any capacitive touch I2C boards were mounted on top of the guitar by existing holes for the pickguard or with hook and loop tape.

5.2 Note Selection

For the final design, the Adafruit 12-Key Capacitive Touch Sensor Breakout - MPR121 - STEMMA QT was chosen to detect what frets are being played and for strings. This was chosen instead of the previous boards as they contain 12 inputs for capacitance touch sensing while also being able to communicate through Inter-Integrated Circuit (I2C) to allow for future expansion for the number of frets that can be detected by adding more boards. The I2C communication allows multiple boards to be daisy-chained together, providing many capacitive touch inputs, while only taking up a few input pins on the Arduino.

As shown in Figure 3, copper tape for each string connects to a capacitance sensor tied to each electromagnet in the programming. The order for each note from left to right is Low E, A, D, G, B, High E. The placement and order were thought out as they are close enough to the strings that a guitarist can switch from strumming to using the electromagnets and the order of the tape feels intuitive to play. The copper strips on the fretboard are used to map frequencies based on which note is also being played at the same time. By fretting a note and pressing the pad for the corresponding string, the Arduino knows what frequency to send to the electromagnet under that string.

Figure 3. Final design product for the EM Guitar. Left shows copper tape on the first 5 frets of the guitar with soldered wire by the neck coming down to the 1st capacitance touch board. This leads to a 2nd capacitance touch sensor via I2C which senses the string capacitance copper tape and communicates to the Arduino UNO.

5.3 Signal Generation and Coding

To actuate the strings, the electromagnets must be pulsed at the right frequency. To do this, the Arduino Uno receives I2C signals via the capacitance touch boards that tell which strings to play and what frets are being held down. Each single note is mapped to a frequency that was originally calculated but also tuned to work best with this system. Due to inaccuracies in the intonation of the guitar and frequencies of the excitation signals, the frequency required for a given fret is off from the theoretical frequency that note should be. Strings 1-4 have a duty cycle of 50% while the 5th and 6th strings have duty cycles of 30% and 20% respectively. The Low E and A strings were chosen to have a lower duty cycle since they are louder when resonating than the higher strings. To parse the I2C signals, the input is compared to a bit that corresponds to the location of the pin and whether it is on or off. This checks to see whether each string or fret is pressed. Once a string is detected, it looks to see what the highest fret detected is and plays the corresponding frequency. Instead of using a PWM library, the internal clock is checked to see if the correct amount of time has passed since the state of that output pin was changed to switch it again, creating a signal similar to a PWM one. This was chosen as the Arduino Uno has a limited number of unique PWM signals it can output, preventing all six strings from being played simultaneously. To view the code, view the GitHub repository in Appendix A.

5.4 Electromagnets

Once the Arduino Uno knows what note to play, it sends the frequency to pulse the corresponding MOSFET to the set string. Two Mosfetti 4 Channel MOSFET Driver Boards are used to control the electromagnets since there are 6 of them. The signal from the Arduino is used to cause the MOSFETs to switch to a higher current 5V supply from the battery bank. The electromagnets chosen are the Adafruit P20/15 Electromagnets which fit into a custom 3D print mount under the strings (Figure 4). Spacers (Figure 5) are placed between the electromagnets and the base of the mount to adjust their height, so they are the proper distance from the strings. The mount with electromagnets added and leads routed is shown in Figure 6. The SolidWorks part and STL files are in the GitHub under the CAD and Machine Files folder found in Appendix A.

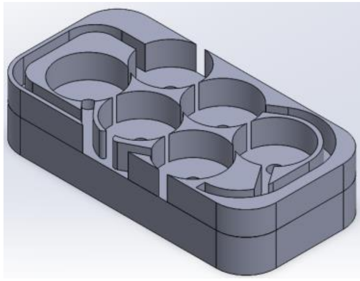


Figure 4. Isometric view for 3D printed Electromagnet mount. This is custom fit to slot under the pickguard into the neck pickup and for the wires to wrap downwards.

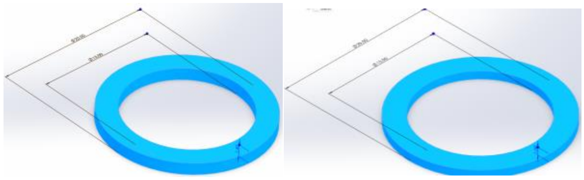
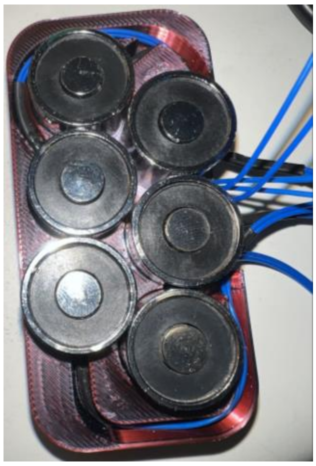


Figure 5. Isometric view for custom 3D printed spacers to add adjustable heights for each electromagnet. They both have the same inner and outer diameters at 15 mm and 20 mm, respectively, but have different depths for additional spacing points. The depths are 1.5 mm (left) and 1 mm (right).



5.5 Music Output and Effects

The pickup used is the P1-1AR MODERN 2-1/16 INCH SADDLE FOR STRAT which is a piezo pickup. This was chosen as stated in the Preliminary Design section for the mechanical characteristics. Since the piezo pickup is quieter than a traditional pickup, the required amplification that is needed will be a little higher and is required to be able to hear it. The electromagnets give a more unique sound to the guitar when played while also acting as a physical sustainer to any notes being played. If the driven electromagnet frequency is higher or lower than the resonant frequency, then the sound will start

Figure 6. Top-down view of assembled 3D print electromagnet holder with electromagnets installed.

oscillating at a higher and lower volume which creates a slight Wah pedal effect. Another attribute this gives is that it allows the guitarist to be able to tune the strings to the set frequency for each electromagnet. While sound can be heard with just an amp, the clean tone plays it out as a normal ringing sound instead of the normal attack that you have when picking. The electromagnetic-driven notes benefit from distortion and other effects. These types of effects can improve the sound, as the clean sound is sparse due to the lack of attack when playing with just the electromagnets.

5.6 Power Source

The Anker PowerCore MetroEssential 20000 5V Battery Bank is used to power all the electronics. The Arduino UNO is powered directly by the power bank which powers the capacitance touch boards while the MOSFET boards are powered separately via another port on the power bank.

6. EVALUATION

6.1 Methods

To evaluate the final design of the EM guitar, it was compared to the requirements and goals established earlier.

6.2 Results

In terms of the aesthetic goals, the final design meets them. It has the silhouette of a guitar and has electronics attached to the outside of it. There are some LEDs that light up when specific strings are played, but they are not very bright and some of them are partially covered up. The sonic object requirements are also met, as it uses the piezo pickup to output to an amplifier. For excitation, the strings are driven with a 5V square wave at varying duty cycles depending on the string. If the duty cycle was set too high, or the frequency sent to the electromagnet matched the strings resonant frequency too well, the amplitude of the string's oscillation would be too high, and they would strike the frets. This was avoided by a combination of reducing the duty cycles of some strings, intentionally using a slightly off frequency in the code, or slightly changing finger position.

The actuation requirements were partially met. The distance between the electromagnets and the strings is adjustable, it just is difficult as it requires taking the mount out of the guitar, which involves loosening the strings and taking off the pickguard. For the realization of the final design, no material under the pickguard needed to be removed to fit the MOSFET boards under them. Sections of the pickguard around the electromagnets did need to be removed, though. The timbral requirements were met as the guitar can infinitely sustain notes. The electromagnets can excite the strings in such a way that there is no attack to the sound, creating a soft sound when played with a clean tone.

Specific fret and string combinations can be played, meeting the pitch requirements. The intonation of the guitar is inaccurate, either due to it being set up wrong or because the guitar is not made well. This is compensated for when determining what specific frequency should be played for each fret-string combination. For dynamics, the volume of the strings can be changed by adjusting the duty cycle of the signal, but it cannot be done on the fly and must be changed in the code. The volume of the guitar through an amp or speaker can be adjusted through the amp or a pedal board. The EM Guitar is fully human controlled, the current programming is not able to play without direct human input.

Overall, the EM Guitar is easy to use, as the USBs just need to be plugged into the battery bank, and it starts working. Sometimes the capacitive touch boards get stuck and don't update the state of certain sensors, although this has been mostly fixed by adjusting the thresholds of when the capacitive touch boards report a touch. Also, the play needs to make sure that their finger is touching the copper tape on the fret as the sensors are not able to detect just the string pressing into them. The power bank turns off after a few minutes of not using the electromagnets, but the button on it just needs to be pressed to turn the system back on.

7. MODIFICATIONS TO THE FINAL DESIGN

7.1 Note Selection and Coding

The number of frets with touch sensors on them was increased from four to 12 (Figure 7), allowing the EM Guitar to play an entire octave on each string with the electromagnets. 12 frets were chosen as the MPR121 capacitive touch boards used have 12 inputs. Increasing the number of frets only involved placing more pieces of copper tape and then soldering and crimping wires to them.

Figure 7. Final EM Guitar prototype with added frets and increased electronics space.

The code for assigning the notes each string plays was upgraded in its capabilities. The new capabilities allow the EM Guitar to now play different frets on different strings. The code works by pairing up the lowest fret pressed to the lowest string being played. The next lowest fret is then matched to the next lowest string. This continues until no more frets are being pressed, in which case the other strings are assumed to be fretted at the highest fret pressed. This allows for power chords and other similar shapes to be played, drastically improving the musical capabilities of the guitar. Single notes can still be played, allowing for both chordal and lead playing.

7.2 Electronics Under the Pickguard

As shown in Figure 7, there are additional frets added and storage for the main electronics below the pickguard. Another minor change was that the electromagnet holder 3D print had too tight tolerances around the wire guides. To fix this in a version 3, I would suggest enlarging the initial area where the edge of each electromagnet hole into the respective wire guide to help with the wire epoxy tolerancing. To fit all the main electronics other than the battery under the pickguard, a manual mill was used to pocket out most of the area while also using a Dremel for finishing. A hole was drilled into the side of the guitar to allow the fret wires easy access to the capacitive touch sensors. Finally, a custom pickguard was created using clear Acrylic to be able to see all the electronics in the guitar (Figure 8). For the custom pickguard, a public GrabCad file [8] was modified by adjusting the holes. The .DXF and .AI files are in the GitHub under CAD and Machine Files folder found in Appendix A.

Figure 8. Above view of the pocketed-out areas under the pickguard and an older version of the clear pickguard.

7.3 Future Modifications

Several future improvements could be made. One would be to have a sensor under each string at each fret so that the controller would know exactly what fret each string is being played at. This would eliminate the complicated and limiting logic mapping the set of fret and string inputs together. This could be accomplished with a separate pad or similar sensor under each string, which would require 72 sensors for 12 frets, or some sort of matrix that is scanned through, which could drastically reduce the number of sensors needed.

Another modification could be using a touch screen or pressure-sensitive sensors for selecting the strings. This would allow for increased dynamic range, as the finger's position of the screen or pressure on the sensor could be mapped to volume, allowing for crescendos or decrescendos. The same measurement could instead be used to intentionally change the frequency sent to the electromagnets, creating a sort of pitch bend effect or exciting different harmonics.

Adding a way for the controller to detect the exact frequencies that are being played would enable it to adjust the signals driving the electromagnets to match those, eliminating the need to precisely tune the guitar and frequencies for each note. This could be accomplished by running a Fourier Analysis on the output signal and determining what notes are being played.

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9. APPENDICIES

Appendix A: GitHub Repository

Appendix B: BOM

Item	#	Individual Price	ID	Link
Electric Guitar Kit	1	$82.99	B08TBZZN3K	Amazon.com
Adafruit 12-Key Capacitive Touch MPR121 - STEMMA QT	2	$7.95	1982	Adafruit.com
P1-1AR MODERN 2-1/16 INCH SADDLE FOR STRAT	1	$75.00	P1-1AR	Brennerusa.com
Arduino Uno R3	1	$27.60	A000066	Amazon.com
Mosfetti 4 Channel MOSFET Driver Board	2	$9.95	5757	Adafruit.com
Adafruit P20/15 Electromagnet	6	$7.50	3872	Adafruit.com

Anker PowerCore MetroEssential 20000 5V Battery Bank	1	$61.99	B07SQ5MQ6K	Amazon.com
Right angle USB A to B	1	$6.74	B0B74BMCBB	Amazon.com
USB A to 5.5x2.1 mm Barrel Jack	1	$2.75	2697	Adafruit.com
JST SH 4-pin to JST SH 4-pin	1	$0.95	4210	Adafruit.com
JST SH 4-pin to female headers	1	$0.95	4397	Adafruit.com
1-inch Copper tape	1	$5.99	B0C1442K27	Amazon.com
Dupont 2.54mm crimping kit	1	$37.99	674862314898	Amazon.com
Clear Acrylic Plexiglass Sheet ⅛” Thickness, 18”x24” Size	1	$11.67	PLA-010-022	BuyPlastic.com
Custom 3D Print Parts	1	~$1.00	N/A	Appendix A